EXECUTIVE SUMMARY

FCS-ATOMIC

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1. FCS-ATOMIC FRAMEWORK

The evolution of space technology has allowed ESA to consider new possibilities for challenging and groundbreaking mission that impose new and complex requirements and constraints both on the ground and space mission segments.

In the ground segment the Flight Dynamics System (**FDS**) is responsible for controlling the spacecraft and designing the operations required for a successful mission. These can range from programming and executing reaction wheel off-loadings to perform orbit determination, and compute manoeuvre for orbit maintenance or even trajectory re-optimisation, passing by guiding the spacecraft's attitude. In this respect, one of the most challenging and successful was ROSETTA – this highly challenging mission managed to deliver a lander to a small body in a highly uncertain environment which required fast and agile ground interaction with the spacecraft systems. The ground operations achieved on this mission by the FDS are considered as a high standard to be followed by the succeeding missions. The FDS has, however, its limitations. It relies on communication links and data processing that may require a non-negligible time which deteriorates the navigation solution when this is used to command the spacecraft. This can be particularly challenging for mission at far ranges from Earth.

The spacecraft's Guidance, Navigation and Control (**GNC**) system – responsible for providing the translation and rotational status of the spacecraft, correct its trajectory along its nominal path, and control the Six Degrees Of Freedom (6DOF) motion – can assume new levels of autonomy taking some of the burden off the FDS system. This enables both reducing the mission cost and improving the spacecraft's navigation performance which reduces mission risk. This autonomy has been considered in the past for the Marco Polo mission and is currently being assessed for the Phobos-SR (formerly known as PHOOTPRINT) and the AIM missions. The GNC system, however, cannot run completely independently from ground and requires some level of interaction between the FDS and the GNC.

The study of the **hybridization of the use of the FDS with the spacecraft's GNC** as well the optimal interface point between the two systems has been performed on the most recent ESA mission studies such as the AIM and the Phobos-SR missions. The goal is to find the optimal strategy for achieving the mission goals within the available resources which often relates to the spacecraft navigation performance, mission cost, spacecraft mass, or technology readiness.

These studies, however, tend to be performed early on the mission based on very preliminary assumptions, with no solid navigation analysis, leading to sub-optimal strategy choices on which the systems design rely on.

The present activity (**Flight Control System Assessment Toolbox for Optimal MIssion Cost and performance, FCS-ATOMIC**) aims at filling this void, by developing a framework that simulates both the FDS and GNC systems, which together make the Flight Control System (FCS), and the possible interactions/hybridization between them.

1.1. FCS COMPONENTS AND INTERFACES

In Figure 1-1 the FCS high-level FCS component breakdown is presented that will serve as the basic reference for the FCS component identification.

Although one may feel tempted to include solely the GNC and FDS systems in the FCS that would lead to a short sight of what the whole FCS encapsulates. The general high-level FCS component breakdown is divided into space and ground segment. The on-board GNC will be part of the former while the FDS is integrated in the ground segment, as a part of the mission operations centre. Other components on the space or ground segments impacting on the OB GNC or the FDS performances are also described.

In the space segment one may find the OB GNC, divided into its three main modules – navigation, guidance, and control – due to their natural importance for the OB GNC. Furthermore, there are also present the sensors and actuators and the telemetry, tracking, and command system (TT&C) responsible for communicating with Earth; two systems with large impacts on the GNC and FDS performances. Other SC systems would be the power, thermal, and avionics. The importance of the latter is highlighted due to the importance of the on-board computer (OBC) on the GNC system where it should be able to provide the computational power that it demands. The larger these demands are, the larger will the cost, mass, and power consumption of the OBC be. The payload instruments are described separately from the other sensors as these can either be operated for navigation, by the FDS or GNC, or for science/data by the Payload Data Operations Centre depending on the current authority on the operations timeline.

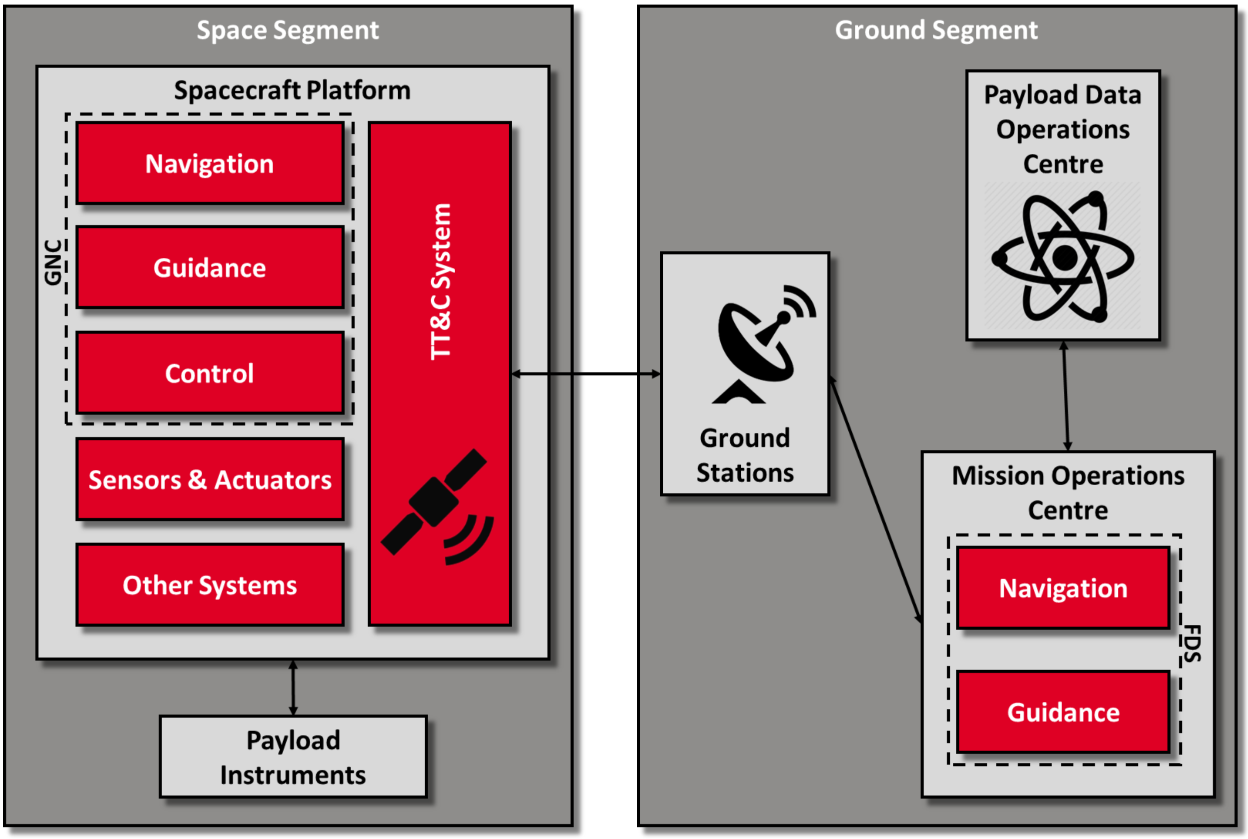


Figure 1-1: Detailed Component and Interface Breakdown

In the ground segment, one can find the three main entities – the ground stations, the mission operations centre (MOC), and the Payload Data Operations Centre. The first, the ground stations, are responsible to set a communication link with the space segment as well as perform tracking activities on the spacecraft (most usually, range, Doppler, tracking, GNSS and ΔDOR measurements). The MOC, where the core of the FDS is located, is responsible to perform the navigation and guidance of the SC when the FDS authority is defined in the mission timeline. Furthermore, other operations such as operator checks, go/no-go flags, command generation are also performed in the MOC. The Payload Data Operations Centre is responsible for operating the payloads during defined payload operations periods. This last entity can assume different roles depending on the mission at hand and its objectives. A particularly relevant example would be the Science Operations Centre (SoC) in case of a science missions where they can iterate with the MOC for important parameters for the orbit determination of the SC such as shape models, ephemerides, or other dynamical parameters estimated by derivation from the obtained scientific data.

The goal of this activity is to develop a framework that integrates and defines the FDS and GNC systems (which together compose the Flight Control System or FCS) and the respective interfaces to assess the feasibility of future missions based on a set of realistic and detailed assumptions.

The framework allows performing the trade-off of different strategies in early mission phases in terms of optimal authority sharing between the ground and space segments ("task sharing") that proves the mission feasibility and/or improves the mission performance or reduce costs.

Quantifying such performance can be as varied as evaluating the spacecraft mass, navigation performance, mission cost, mission safety, complexity, or science return.

1.2. THE FCS FRAMEWORK

The design of the FCS framework has been followed, at proposal level, by an identification (and subsequent analysis) of the top-level **user requirements** in order to support the FCS strategies evaluation.

The proposed FCS framework follows an architecture with the same philosophy of the FEST framework, previously developed by GMV for ESA, which has been identified in the Statement of Work. The proposed framework architecture is shown in the figure below:

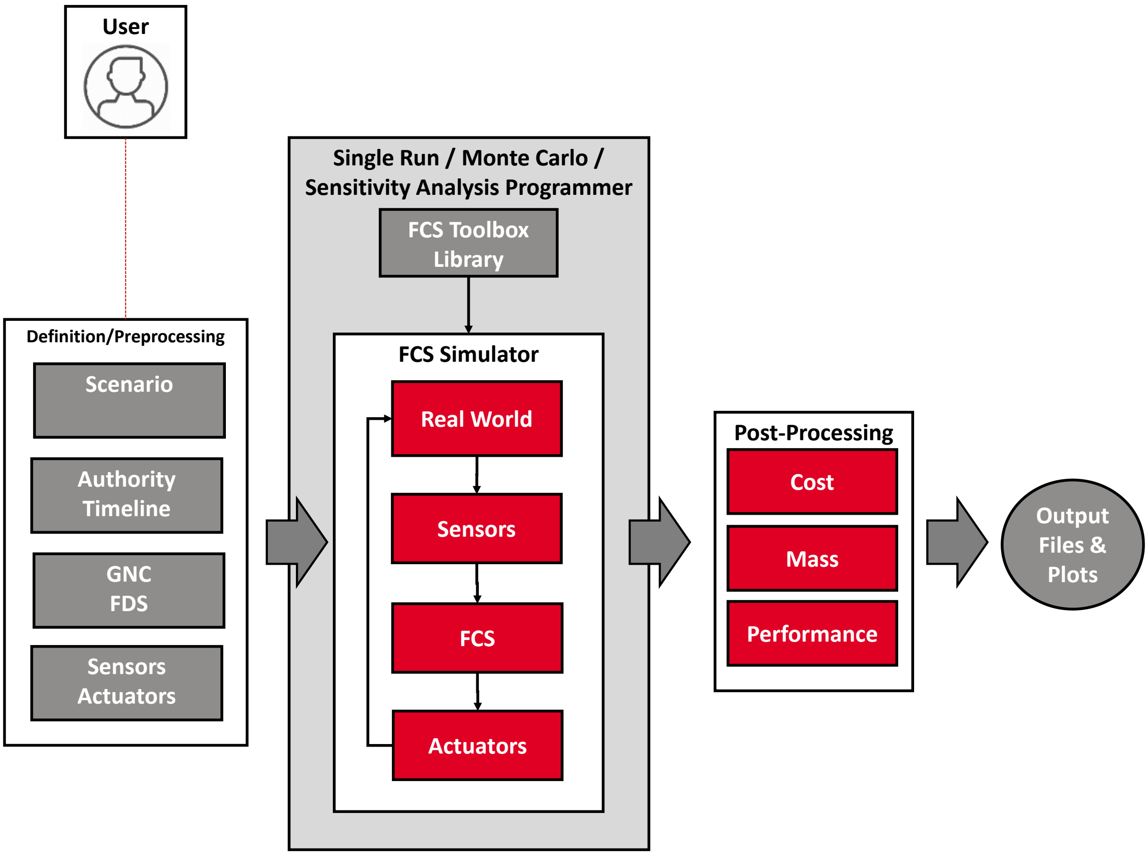


Figure 1-2: FCS Framework Proposed Architecture.

The proposed FCS framework allows the user to define the following inputs:

- **Scenario**: Definition of the simulation type (single run, sensitivity analysis, or Monte Carlo simulation), scenario dynamics and kinematics (DKE), trajectory and attitude profile, the authority timeline (between FDS and OB GNC), and the interfaces between the FDS and the OB GNC (the framework allows a hybrid use of the two systems, e.g.: use of OB GNC with ground state updates).
- **Sensors and actuators:** Definition of the sensors observation and error models as well as the actuators performance and error models. The cost per FDS component is provided here by the user, by a single value or a function with a cost model for each component, as well as a baseline cost of the remainder of the SC's systems that are not considered in this simulator. The latter is optional and helps the user to understand the total mission cost if he desires so. Moreover, the mass per FDS component is also provided here by the user as well as a baseline mass of the remainder of the SC's systems that are not considered in this simulator. Again, the latter is optional and helps the user to understand the total spacecraft mass if he desires so
- **GNC/FDS**: Selection of each navigation, guidance, and control algorithms for the FCS simulator and respective parameters.
- **Authority timeline**: selection of the FDS strategy of the sharing of tasks among on-board GNC and ground FDS

The FCS simulator then performs the simulation of the scenario according to the simulation type, the scenario definition and algorithm selection to compute the SC navigation performance as well as auxiliary performance parameters (e.g.: estimation of dynamical parameters or ephemerides). The FCS simulator makes use of the **FCS toolbox library** where validated algorithms, sensor, actuator, dynamics, and error models are stored as well as auxiliary functions. Again, GMV aims, when applicable, at re-using previously validated models and libraries from heritage activities.

The FCS simulation performance computed parameters are then be transmitted to the **post-processing** functions where the mass and cost of each used component in the FCS simulation is summed up to achieve an outcome for the mass and cost of the chosen strategy. Auxiliary performance relevant parameters are also computed according to the simulation type and a number of output flags defined by the user for each FDS component on the scenario input file.

The post-processing function then accordingly produces the **output files and plots** that allows the user to assess the scenario feasibility and/or the best mission strategy depending on the simulation type and the chosen dispersed parameters. A graphical example of how the plots help the user to assess different FCS strategies is shown in figure below. Figure 1-3 shows an example of parameter "X" (which could be the parameter of a sensor, like the field of view of a navigation camera) sensitivity analysis against the cost of different FDS/GNC hibridisation strategies.

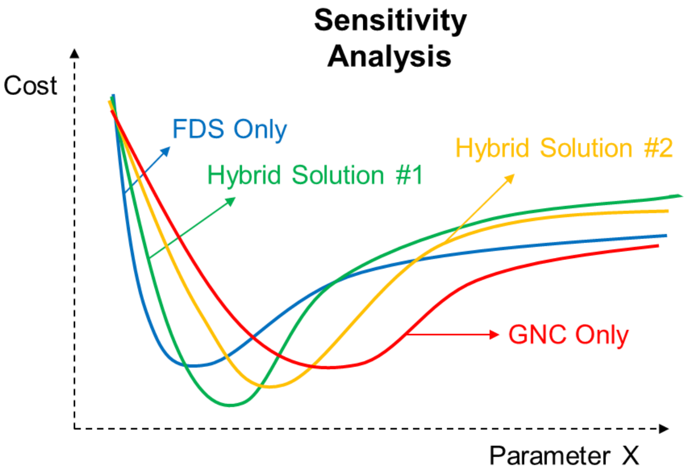


Figure 1-3: FCS framework output example: sensitivity analysis

The framework comes supplied with a great flexibility that allows the user to define a substantial number of parameters. Nonetheless, default values and parameters are included in case the user wishes to run a faster, more preliminary analysis. Furthermore, the run scripts of the analysed reference mission scenarios (Phobos-SR, AIM, and G2G) will be included on the SW delivery allowing a fast thorough analysis of those missions to the user.

Based on previous experience and heritage, Matlab was selected as the programming language and the development environment.

2. HERA FCS ASSESSMENT

The different assessed strategies and selected algorithms were previously accorded with ESA as reproduced in Table 2-1.

<table>
<tr><th>Parameter</th><th>Variations</th><th>Performance Goals/Constraints</th></tr>
<tr><td>Trajectory</td><td>The DCP trajectory from the AIM consolidation phase is taken as the reference trajectory to assess the high-fidelity model.</td><td rowspan="6">Velocity larger than sqrt(2)*V_{ESC} for spacecraft safety.
Target always in the camera’s FOV during target pointing mode
Dispersion in Position below 1 km (1σ)
Cost and Mass Optimisation.
Science Return (Target imaging resolution, closer is better)</td></tr>
<tr><td>Autonomy Level</td><td>The upper part of the 8-shaped hyperbolas will be analysed (7-days)
Two cases will be assessed:
- Pure ground based (no on-board navigation and pointing)
- On-board navigation (relative position) and pointing (ground defines delta-V and initial conditions</td></tr>
<tr><td>Measurements and Operational Strategy</td><td>This parameter will be tied with the autonomy where, besides dictating the measurement strategy with the required number of daily contact hours with ground, can defined interfaces between the FDS and GNC system (e.g.: autonomous GNC with ground periodic updates or ground checks). The reference case is 18h of camera measurement collection (minus time required for slews and other essential operations) and 6 hours of daily ground contact (aimed for data download).</td></tr>
<tr><td>Dynamical Uncertainties</td><td>The dynamical uncertainties may have an impact on propagation of the dispersion errors. Only a conservative set of values should be used based on the FASTMOPS activity results.</td></tr>
<tr><td>Manouevre Error</td><td>Manoeuvre execution magnitude errors will be varied between 0.1% and 10% (1σ).
Sensitivity analysis with more than 2 points</td></tr>
<tr><td>Initial Error</td><td>The initial error will impact on the overall performance and, as such, a set of conservative values will be used based on the FASTMOPS activity results.</td></tr>
</table>

Table 2-1: HERA FCS Analysis Scenarios.

2.1. HERA DETAILED CHARACTERISATION PHASE

One of the two scenarios to be analysed with the FCS-ATOMIC, and being reported in this section, is the DCP (Detailed Characterisation Phase) of the HERA mission. This phase was singled out as the most challenging navigation phase out of the mission’s proximity operations in the Didymos’ system.

The analysis performed follows the work performed for the cancelled AIM mission, which is used as the starting point for the HERA mission, and deals with the difficulties on navigating at close distance to the target bodies.

The turnaround times for the required operations to navigate the spacecraft from ground may result in the losing the target bodies from the camera’s FOV, thus, alternative strategies incorporating an autonomous pointing GNC system are analysed based on the main contributor to the pointing error – the spacecraft state navigation performance.

In section 2.4 the results for a ground only scenario and a scenario with an autonomous GNC systems computing the spacecraft’s navigation performance from optical measurements for attitude pointing purposes are presented. In the prior sections the whole set of assumptions to the design of the analysis are presented including the spacecraft platform, environment, and operations.

The analysis is then complemented with the derivation of a performance model for faster analyses and an analysis of one of the major navigation error contributors – the manoeuvre errors.

2.2. NAVIGATION ASSUMPTIONS AND ERROR MODELS

This section will deal with the assumptions and constraints that directly affect the modelling of the navigation systems. The environmental modelled system will be listed together with the error models for the navigation. This section will end with the description of the mission phase preceding the DCP, the ECP, from which the navigation assumptions were extracted.

2.2.1. ENVIRONMENT

The environmental and ejecta models for Didymos are taken from Didymos Reference Model document used in the AIM System Studies. For the unavailable data standard values coming from past experience are used.

The current used values for the dynamics are presented in Table 2-2. The used ephemerides were obtained with the SPICE kernel provided by ESA during the phase A/B1 system studies.

Parameter	Value
Solar Radiation Pressure [kPa]	4.65e-9
AU [km]	149597870.7
S/C Reflection Coefficient	1.5
S/C Cross Section [m^2]	5
S/C Mass [kg]	400
Didymos System Mass [kg]	5.278e11
Mass Ratio	0.0093
Sun's Gravitational Parameter [km^3/s^2]	132712440041.9394
Didymain's Radius (Sphere) [m]	780
Didymoon's Semi-Axes (Ellipsoid) [m]	103 x 79 x 66
Sun's Radius (Sphere) [km]	695990
Didymain's Rotation Period [h]	2.26
Didymoon's Rotation Period [h]	11.92
Didymain's Orbital Period [h]	11.92
Didymain's Orbital Elements (SMA,ECC,INC,RAAN,OMG,MEAN0,REF_EPOCH_J2000)	[1.18 km;0,0,0;0,0,0]
Didymain Pole Ecliptic Direction	λ=310 deg, β=-84 deg
Didymain's Harmonic Coefficients	*Computed from body's polygonal shape*
Didymoon's Harmonic Coefficients	*Derived from ellipsoid shape*

Table 2-2: AIM Environment Model.

2.2.2. NAVIGATION ERROR MODELS

The following navigational, measurement, and dynamical error models in Table 2-3 and Table 2-4 were elaborated from iterations with ESA and experience from past projects, GMV's past experience and iterated with ESA in the FASTMOPS-CCN activity and will be considered for this activity.

Measurement errors	**1-Sigma**
Range [m]	Noise: 3 Bias: 5
Range acquisition frequency	Every hour
Doppler [mm/s]	Noise: 0.1

Measurement errors	**1-Sigma**
	Bias: 0
Doppler acquisition frequency	Every 10 min
ΔDOR [m]	Noise: 0.1/0.2 (TBC)
ΔDOR frequency	Every 4 days
Ground station position [m]	Bias: 0.5
Ground Station considered	Cebreros, New Norcia, Malargüe

Table 2-3: Navigation and Measurement Error Models.

Dynamical Parameter assumptions	**1-Sigma**
Didymain ephemeris position error [m]	1000
Didymain ephemeris velocity error [m/s]	0.001
Didimain Centre-of-Mass/Centre-of-Gravity Offset [m]	[1,1,1]
Didymoon orbital elements error (SMA,ECC,INC,RAAN,OMG,TRUEAN0)	10m, 0.01, 0.1deg, 0.1deg, 0.1deg, 1deg.
Didymain gravity parameter error [%]	0.1
Didymoon gravity parameter error [%]	1
Solar radiation Pressure Constant	1%
Landmarks Position	1 pixel
Ground Station Location Error	1m in each coordinate
Didymain Scale Factor Error	0.1%
Non-gravitational accelerations [m/s^2]	$1x10^{-11}$ (1 day autocorrelation time)

Table 2-4: Dynamical Parameters Uncertainty Error Models.

Note that typical non gravitational accelerations considered in navigation analysis are in the order of 10^{-9} m/s, however, this would become one of the main forces in this scenario. Thus, in order to reduce this value to a more acceptable value for this scenario, it is advised to run an analysis on the typical perturbation that encompass this acceleration as the SC thermal radiation's model and outgassing.

Furthermore, the thruster may require specific calibration to the DCP manoeuvres and a bias initial error may be considered in the very first manoeuvres.

2.3. OVERVIEW OF THE FCS ALGORITHMS

A pre-selection of the FCS algorithms to be used in one of the next project phases – the development and implementation of mathematical models, which is based on GMV's experience on the scenario missions – is performed. These models are subject to iteration during the project.

Models	**HERA**
FDS Navigation	▪ Batch-sequential SRIF with optical landmark measurements and radiometry (range/Doppler/DDOR) ▪ Information segmented in batches – Batch size equal to frequency of Range measurements ▪ Augmented State Vector with three groups of parameters – Process-noise parameters (Non-Modelled Accelerations) – Dynamical parameters (SC State) ▪ Constant parameters (Didymain point mass gravity)
GNC Translation Navigation	▪ UKF with optical centroiding measurements with Augmented State Vector Considering Errors on: – SC State – Didymain point mass gravity

	– Didymoon point mass gravity – Didymain Ephemerides (wrt the Sun) – Didymoon Ephemerides (wrt Didymain) – Manoeuvre Errors (When a manoeuvre is performed) – Solar Radiation Pressure Constant – Non-Modelled Accelerations – Centroiding Bias from camera misalignment – Centroiding White Noise – Centroiding Centre-of-Brightness of set (ECRV) – Centre-of-Gravity / Centre-of-Geometry Offset
GNC Attitude Navigation	■ Not Simulated.
FDS Guidance	■ Classical Linear FTOA with two manoeuvres being computed at once.
GNC Guidance	■ None.
Translational Manoeuvre Control	■ Manoeuvre execution performance model ■ Open-loop Manoeuvres
Attitude Guidance	■ Triad-based profile with two modes: – Target Mode: Camera's z-direction pointing to the target (Didymain) x-direction along Sun's direction (thermal constraints) on the Camera's CCD plane. – Earth Mode: HGA's z-direction pointing to Earth. X-direction along sun's direction on the plane normal to the z-direction (thermal constraints). ■ Attitude Computed by FDS or GNC depending on the scenario case. Ths is one of the trade-offs of this analysis.
Attitude Control	■ Not Simulated.
Sensor Obs. Models	■ Camera: See IP ■ Range: Distance to Ground Station ■ Doppler: Velocity radial to the ground station ■ ΔDOR: bearing to Ground Station
Sensor Error Models	■ Camera: See IP ■ Range: Error directly added to the measurement ■ Doppler: Error directly added to the measurement ■ ΔDOR: Error directly added to the measurement
Actuator Models	■ RCS (translation): Thrust Direction and Magnitude
Actuator Error Models	■ RCS (translation): 10% 3-sigma on magnitude and 3deg 3-sigma on direction
FDS Image-Processing Models	■ Landmark Matching (LoS to target's LM + error [as pixels in the CCD]) ■ Bias in the camera misalignment error
GNC Image-Processing Models	■ Centroiding (LoS to target's CoM + error [as pixels in the CCD]) ■ Bias in the camera misalignment error ■ White Noise + ECRV on the Ce
Databases	■ Ground LM database, Ephemerides, Manoeuvre Tables, Shape model of Didymoon and Didymain

Table 2-5: Selection of the FCS algorithms to be used in HERA analysis.

2.4. FCS RESULTS

The analysis to the HERA FCS Performance will be separated into three phases:

- High-Fidelity Implementation

  The implementation of a SRIF and an UKF filters for the simulation of the ground and on-board systems is performed to study, through high-fidelity simulations of the two autonomy scenarios: no autonomy and autonomous pointing. Performance models are used for the Image Processing performance.

- Sensitivity Analyses

High-Fidelity sensitivity analyses to the identified major error source – manoeuvre errors. These are performed on both autonomy scenarios from which the covariance results are used for the third phase.

- Performance Model Derivation

  Based on the covariance results of the second phase, FCS performance models, that into account the manoeuvre errors, for both autonomy scenarios are derived.

2.4.1. AUTONOMOUS POINTING

In this HERA scenario, the on-board autonomous GNC System takes over control of the spacecraft attitude system to accurately point the camera to its target – Didymain.

The centroiding error is modelled with a simple white noise, a bias (from the misalignment of the camera due to thermal expansion effects), an offset on the centre-of-mass/centre-of-geometry, and an error on the estimation on the determination of the centre-of-brightness. Determination which is approximated in the observables function by

$$\bar{x}_{COB} = \frac{8R_{pxl}}{3\pi} \sin\left(\frac{\alpha}{2}\right) \bar{e}_{dun/Detector}$$

where R_{pxl} is the radius of the bodies in pixels in the camera's CCD, α is the Sun's phase angle, and $\bar{e}_{dun/Detector}$ is the Sun's direction projected in the camera detector's plane.

This approximation is accurate enough for quasi-spherical bodies. The error between the real CoB and the estimated is modelled with an ECRV as presented in Figure 2-1 following Jesus Gil's approach.

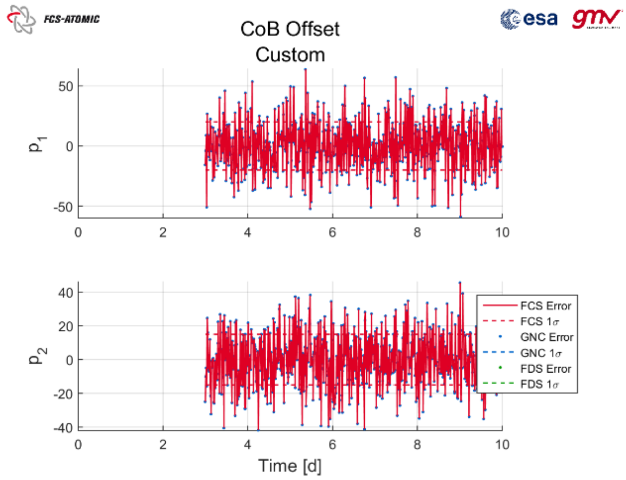
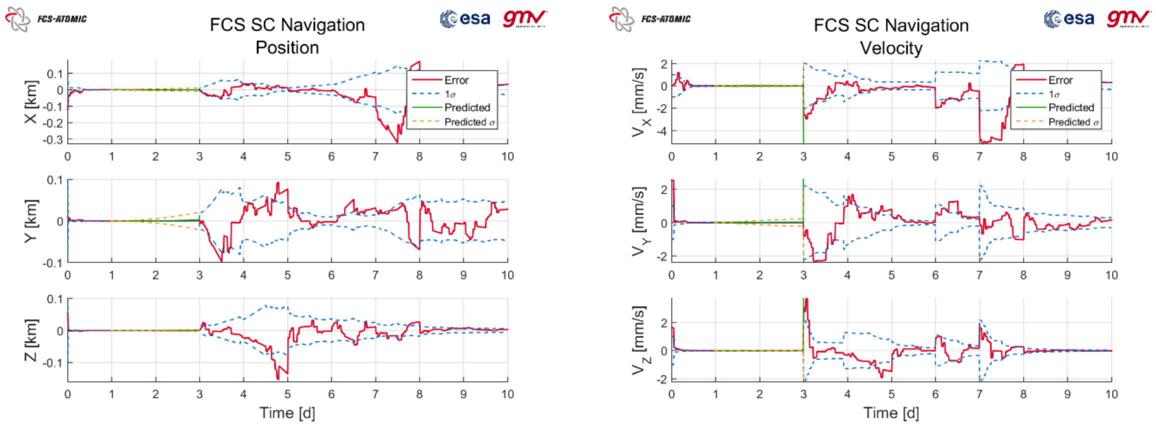


Figure 2-1: Measurement Errors

Single Run

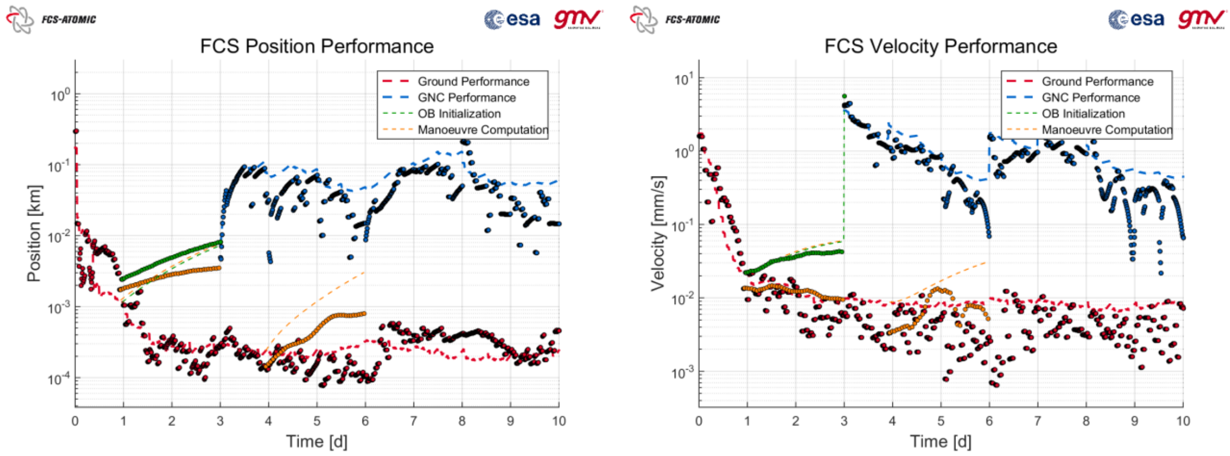
The single-run analysis presented here will allow us to analyse the filter covariance and filter behaviour (of 1 run) with respect to this covariance. A MonteCarlo campaign is latter run to confirm the coherence between filter behaviour and performance and its covariance computation.

In Figure 2-2, the FCS performance is plotted; the on-board autonomous pointing system manages to estimate the spacecraft state to a satisfying degree of accuracy and with a satisfactory behaviour nevertheless, the impact of the manoeuvres errors should be noted. This led to the identification of the manoeuvre errors as one of the most critical challenges (see section 2.4.2)The performance can be analysed in better detail in a logarithmic scale (Figure 2-3).



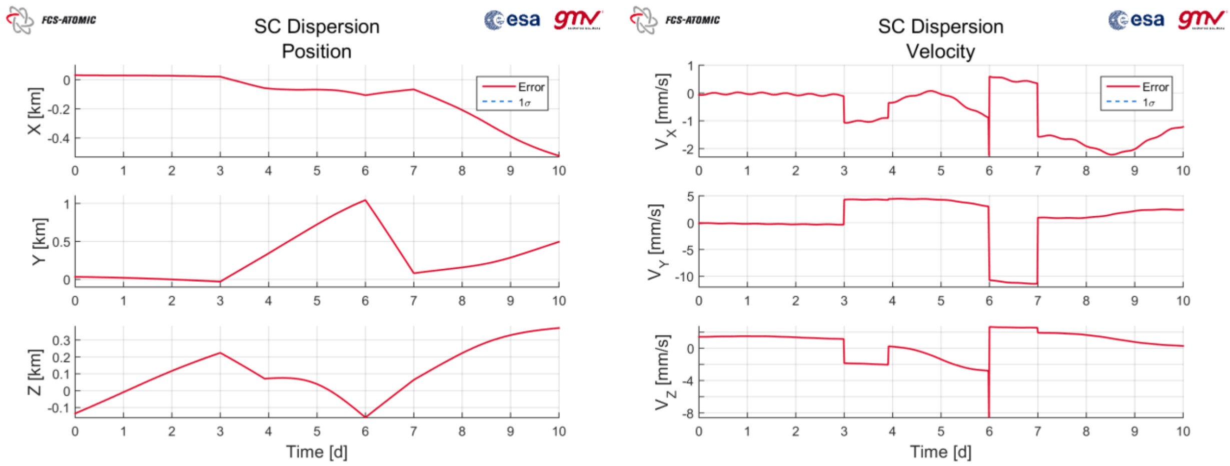
(a) Position **(b) Velocity**

Figure 2-2: Spacecraft FCS Navigation Performance



(a) Position **(b) Velocity**

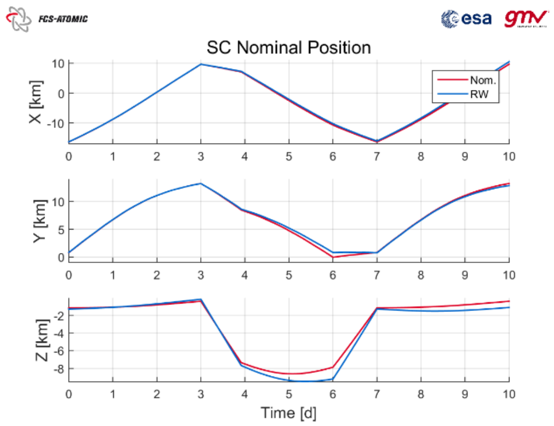
Figure 2-3: Spacecraft FCS Navigation Performance (logarithmic scale).



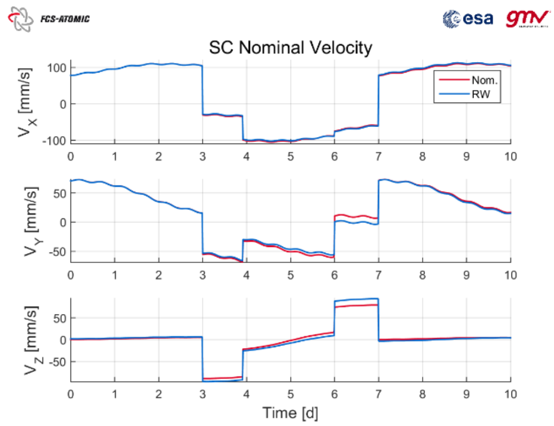
(a) Position **(b) Velocity**

Figure 2-4: HERA dispersion (single case)

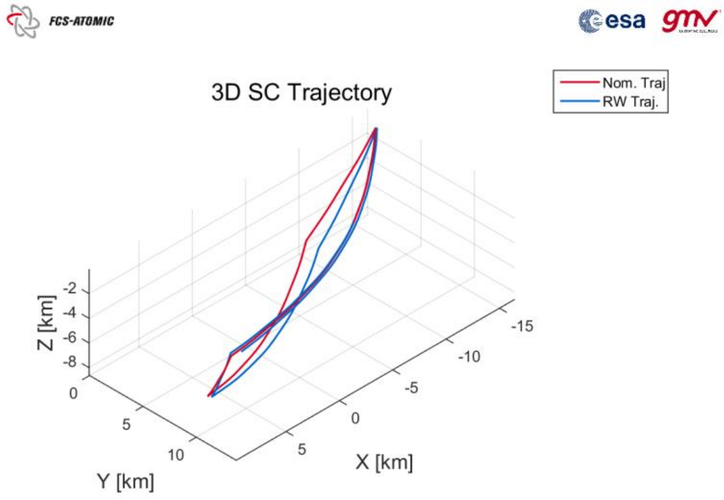
One of the challenges of navigating a spacecraft in such weak environments is the control of the spacecraft dispersion from the nominal trajectory. This single run results (Figure 2-4 and Figure 2-5) hint at such difficulties, but these are yet to be confirmed by the Monte Carlo Analysis.



(a) Position



(b) Velocity



(c) Trajectory

Figure 2-5: HERA nominal and real trajectory.

MonteCarlo Validation

A single run can not prove that a filter works in a robust fashion, capable of handling the multitude of error combination that arise from the provided defined destributions. Usually, a large number of MonteCarlo shots has to be run to validate the GNC algorithms, but this out of the scope of this project. Rather a middle ground is found to prove the feasibility concept: 20 MonteCarlo shots were run to see if the cases followed the computed covariance.

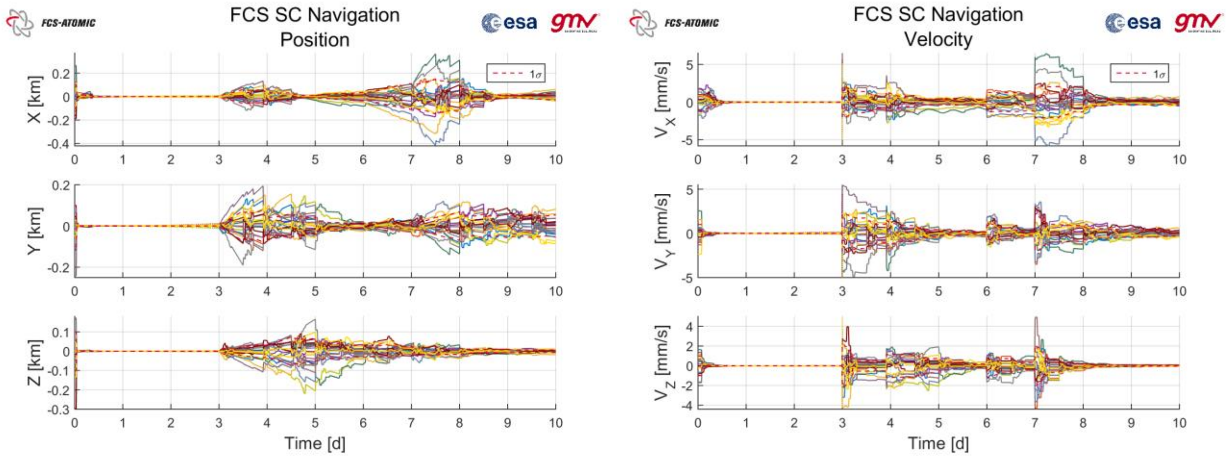
In Figure 2-6, the 20 MC shots suggest that the filter is quite well behaved, even taking only 1 image per hour, and having a blackout of 8h per day (due to communications with Earth). On the other hand, the dispersion is an issue as presented in Figure 2-7. If the manoeuvre error is a bit on the high side, the trajectory can easily diverge. The navigation filter, however, seems to recover well from the divergence introduced by the manoeuvre.

A manoeuvre error sigma of 1% in magnitude and 1 degree on direction was assumed for the open-loop manoeuvres. Although the first is optimistic if compared to AIM's latest RCS design the direction error was never analysed. Furthermore, the impact of the assumed two-manoeuvre strategy was never properly analysed.

This analysis leads us to suggest the following way forward:

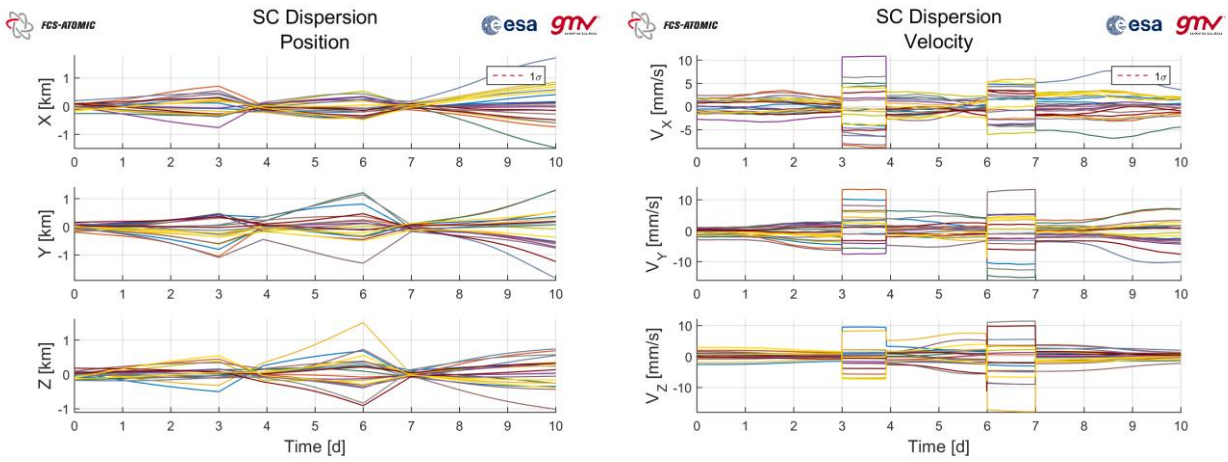
- Assess if the range of dispersions is compatible with the HERA safety requirements.
- RE-assess the RCS performance in terms of magnitude and direction.
- Assess the impact of a two-manoeuvre strategy.

- Prioritise the reduction of errors on the next iteration of the HERA RCS design.
- Assess the possibility of including autonomous corrections to the manoeuvres.
- Assess the possibility of closed-loop manoeuvres (with IMU) for the reduction of the manoeuvre magnitude error.



(a) Position **(b) Velocity**

Figure 2-6: Spacecraft FCS Navigation Performance – 20 MC shots.



(a) Position **(b) Velocity**

Figure 2-7: HERA dispersion (20 MC shots).

2.4.2. FCS PERFORMANCE SENSITIVITY TO MANOEUVRE ERRORS

Since the manoeuvre errors were identified as the main error challenging this strategy, a sensitivity analysis is performed on its error to help drive the HERA RCS design.

Three different error assumptions are considered:

Scenario	1σ Errors
Optimistic Case	■ Manoeuvre Magnitude Error: 0.3% ■ Manoeuvre Direction Error: 0.5 deg
Baseline Case	■ Manoeuvre Magnitude Error: 1% ■ Manoeuvre Direction Error: 1 deg
Pessimistic Case	■ Manoeuvre Magnitude Error: 3% ■ Manoeuvre Direction Error: 1.5 deg

Table 2-6: Three error scenarios analysed.

Note that these values will give a sensitivity analysis on the manoeuvre design but this does not exempt a FCS analysis with a detailed manoeuvre model during the HERA mission design that considers the two-manoeuvre strategy, continuous thrust, IMU performance, and RCS thrusters pointing and magnitude errors.

In Figure 2-9 and Figure 2-10 the results of the navigation performance and dispersion, respectively, of the three analysed scenarios are presented.

It is clear the large effect of the errors on the dispersion of the trajectory from the nominal trajectory. The filter performance, however, seems capable of handling the velocity "jumps" quite well. Note, however, that this assumes that the error distribution can be well quantified, i.e., the covariance added by the filter is representative of the error achieved by the RCS system. No analysis was performed on the mismodelling of the thruster errors (on the pessimistic or optimistic side) and on how the filter performance may be impacted by it but it might be opportune to do such an analysis in the near future.

In line of these results, it is suggested that either:

- RCS thruster error is reduced as much as possible during the propulsion system design
- Assess the possibility of autonomous correction to the ground commanded manoeuvres.

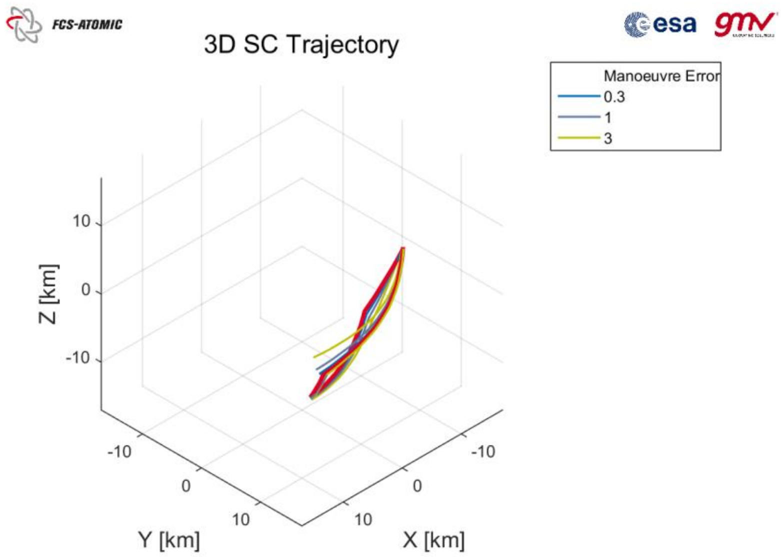
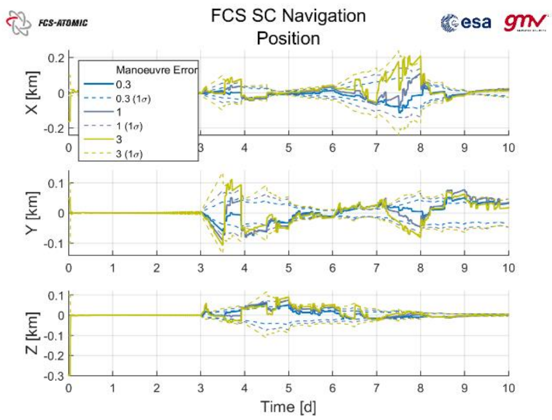
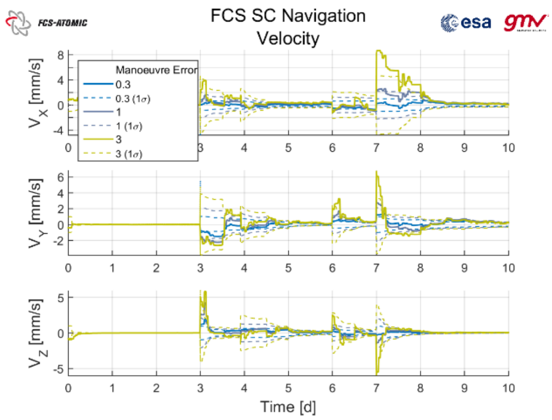


Figure 2-8: Dispersion on the trajectories of the sensitivity analysis.

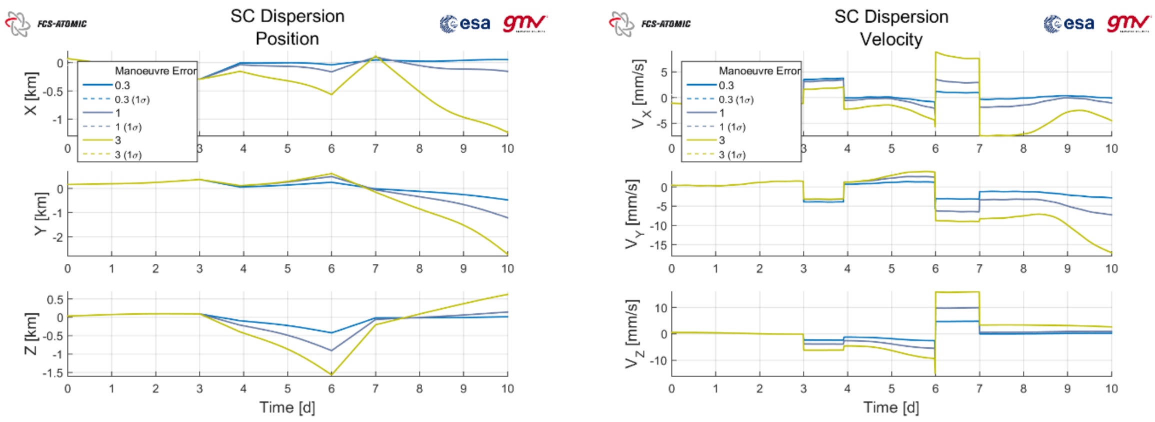


(a) Position



(b) Velocity

Figure 2-9: Spacecraft FCS Navigation Performance – Sensitivity Analysis.



(a) Position **(b) Velocity**

Figure 2-10: HERA dispersion – Sensitivity Analysis.

2.4.3. PERFORANCE MODEL DERIVATION

In this section, the process for the derivation of the filter performance model is reported. This is based on the results of the previous analysis obtained with the FCS-ATOMIC framework for the HERA mission.

2.4.3.1. SRIF FILTER

The derivation of the SRIF performance model is based on the results of the only-ground scenario. The filter has been observed to quickly converge to a steady state lead by the measurement noise once measurements are available.

The effect of non-modelled accelerations on the filter's sigma for position and velocity has been identified and implemented in the performance model.

$$\boldsymbol{P}_{t_k} = \boldsymbol{\Phi}\boldsymbol{P}_{t_{k-1}}\boldsymbol{\Phi}^T + \boldsymbol{\Gamma}\boldsymbol{Q}\boldsymbol{\Gamma}^{\mathrm{T}}$$

$$\boldsymbol{\Phi} = \begin{bmatrix} 1 & 0 & 0 & \delta t & 0 & 0 \\ 0 & 1 & 0 & 0 & \delta t & 0 \\ 0 & 0 & 1 & 0 & 0 & \delta t \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad \boldsymbol{\Gamma} = \begin{bmatrix} \frac{\delta t^2}{2} & 0 & 0 \\ 0 & \frac{\delta t^2}{2} & 0 \\ 0 & 0 & \frac{\delta t^2}{2} \\ \delta t & 0 & 0 \\ 0 & \delta t & 0 \\ 0 & 0 & \delta t \end{bmatrix}$$

$$\boldsymbol{Q} = \begin{bmatrix} \sigma_{NMA1}^2 & 0 & 0 \\ 0 & \sigma_{NMA1}^2 & 0 \\ 0 & 0 & \sigma_{NMA1}^2 \end{bmatrix}$$

Once the sigma of all states σ_k have been propagated, the filter updates looks for available measurements. If a measurement is found, the sigma σ_k is updated to σ_j so that it asymptotically converges to the steady value σ_0.

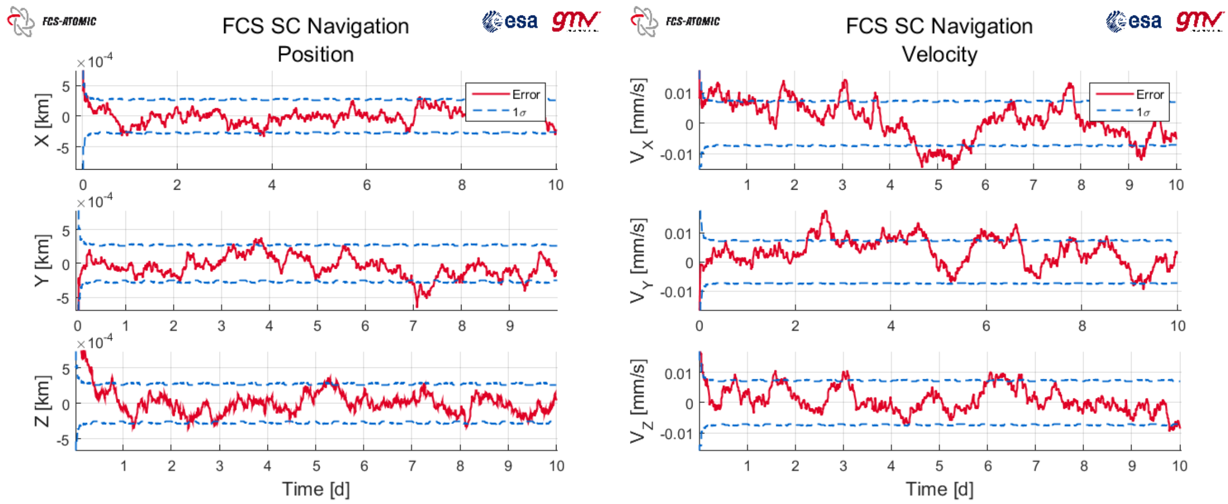
$$\sigma_j = \frac{2\sigma_k\sigma_0}{\sigma_k + \sigma_0}$$

Then an ECVR model is used to compute the estimation error, which is added to the RW value.

$$f = e^{-\frac{\Delta t}{\tau}}$$

$$\boldsymbol{\varepsilon}(t_k) = f\boldsymbol{\varepsilon}(t_{k-1}) + \sqrt{(1-f^2)}\boldsymbol{\vartheta}_{t_k}$$

$$\boldsymbol{\vartheta}_{t_k} \in N(0, \boldsymbol{\sigma}_{tk}^2)$$



(c) Position **(d) Velocity**

Figure 2-11: Spacecraft FDS Navigation Performance – Performance Model

2.4.3.2. UKF FILTER

This derivation is based on the results of the autonomous pointing scenario. The three obtained covariances for the different manoeuvre errors were combined (with a 2nd order polynomial) to obtain a covariance for the configured error of the current simulation.

This covariance is then used for computing the general error which is based on an ECRV-like model with

$$f = e^{-\frac{\Delta t}{\tau}}$$

$$\boldsymbol{\varepsilon}(t_k) = f\boldsymbol{\varepsilon}(t_{k-1}) + \sqrt{(1-f^2)}\boldsymbol{\vartheta}_{t_k}$$

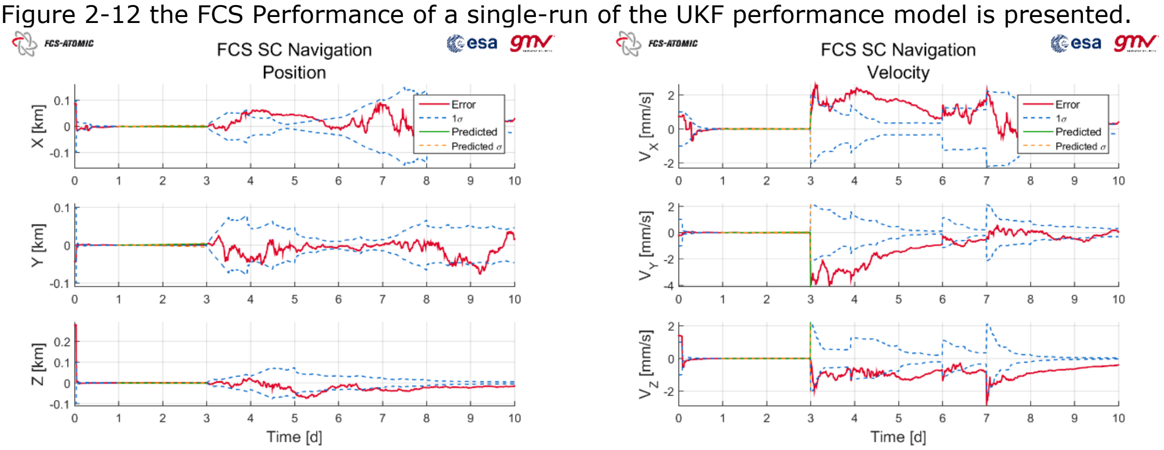
$$\boldsymbol{\vartheta}_{t_k} \in N(0, \boldsymbol{\sigma}_{tk}^2)$$

where σ_{tk}^2 is the modelled covariance for the current manoeuvre error. Note that added noise follows the same "randomness" between position and velocition, only varying between coordinates so as

$$\vartheta_i = {}^{\sigma_i}/_{\sigma_{vi}}\, \vartheta_{vi,} \qquad (i\ =\ x, y, z).$$

Furthermore, a bias is added in the velocity components during the manoeuvre that is then recovered over time. This has an impact on the performance in velocity and position.

In Figure 2-12 the FCS Performance of a single-run of the UKF performance model is presented.



(e) Position **(f) Velocity**

Figure 2-12: Spacecraft FCS Navigation Performance – Performance Model.

3. GALILEO 2ND GENERATION (G2G) ORBITAL RAISING

The different assessed strategies and selected algorithms were previously accorded with ESA as reproduced in.Table 3-1. This sections presents the assessment approach for the reference mission scenarios. The assessment is divided in 2 main groups:

- *Medium autonomy*
- *No autonomy*

Each of above autonomy levels will be assessed in terms of robustness with respect to GNSS receiver performance and thruster errors. The scenarios will be also checked with different nominal thrust values and initial semi-major axis.

Parameter	Variations	Performance Goals/Constraints
Trajectory Generation	The initial orbit would have an altitude of **3163 km** (SMA = 9541 km), and a **56 deg** inclination and will be circular. The remainder of the parameters are eccentricity, argument of perigee, RAAN and true anomaly, which are fixed with TBD values as those have no impact on the performance. The parameter that will be varied between the simulations is SMA with intervals of 100 km. The final orbit is a circular Medium Earth Orbit (MEO) at an altitude of **23222 km** (SMA = 29600 km) above the Earth and at an inclination of the orbital planes of **56 deg**. The remainder of the orbital parameters is eccentricity, argument of perigee, RAAN and true anomaly, which are fixed to the TBD values as those parameters have no impact on the performance.	• LEO-MEO transfer with accuracy: ○ SMA: +/- 5 m ○ RAAN: +/- 1 deg ○ Inclination: +/- 2 deg ○ Along track: +/- 2 deg • Transfer duration within 1 year • Power budget within eclipses (increase of transfer time) • Ground segment contacts and operation cost optimization
Autonomy Level	The autonomy covers the translation guidance function, which can be calculated on-ground or on-board. Thus, the autonomy level can be selected between no autonomy (worse performance) and medium autonomy (less operational costs). Autonomy level selection has impact on the cost of the mission and performance goals.	
Thrust to Mass Ratio	Electric propulsion system is the crucial element for the continuous thrust strategy and the selection of the thrust magnitude has a huge impact on the transfer time for the specific configuration of the spacecraft mass. The preliminarily selected values for the nominal G2G mission setting is of **180 mN** for the thrust (Isp=1,720s) and **1785 kg** and **1500 kg** for the wet and dry masses, respectively. In order to fulfill the performance goals, different thrust magnitudes are analysed in order to find the values that optimizes the performance/cost ration while fulfilling the required constraints. The **thrust values varied between 80 and 480 mN with an interval of 50 mN.**	
GNSS Receiver Performance	The transfer accuracy and transfer time is dependent on the whole translation navigation chain (from measurements up to navigation solution). Its performance varies with the GNSS receiver performance. For the receiver performance, a nominal tracking threshold of **25 dBHz** will be assumed. A value of **30 dBHz** will also be analised to assess a lesser receiver performance. These distinct receiver performances will translate to different navigation performances and GNSS outages (unavailabilities) by the formulated performance model.	
Thrust Error and Degradation	A nominal initial thrust error of **0.56%** is assumed with a degradation of **2% per year** following a linear degradation law.	

Parameter	Variations	Performance Goals/Constraints
	The analysis will be extended to initial values between **0.1 - 1.0 %** with a degradation between **1-10 %** per year.	

Table 3-1: G2G FCS Analysis Scenarios.

3.1. MISSION OVERVIEW

Part of the mission implemented within the FCS-ATOMIC is supposed to raise orbit of a G2G satellite from LEO (SMA = 9541 km) to MEO (SMA = 29600 km). The aim of the analysis is assessment and fair comparison between two guidance strategies for the G2G mission presented in Figure 3-1. The considered strategies are:

- Medium on-board autonomy guidance strategy.
    - The guidance is calculated on-board based on the guidance law.
    - The navigation (state) is estimated on-board using GNSS receiver.

- No on-board autonomy guidance strategy.
    - The guidance reference trajectory is calculated on-ground and periodically updated.
    - The reference thrust is executed on-board in an open-loop.

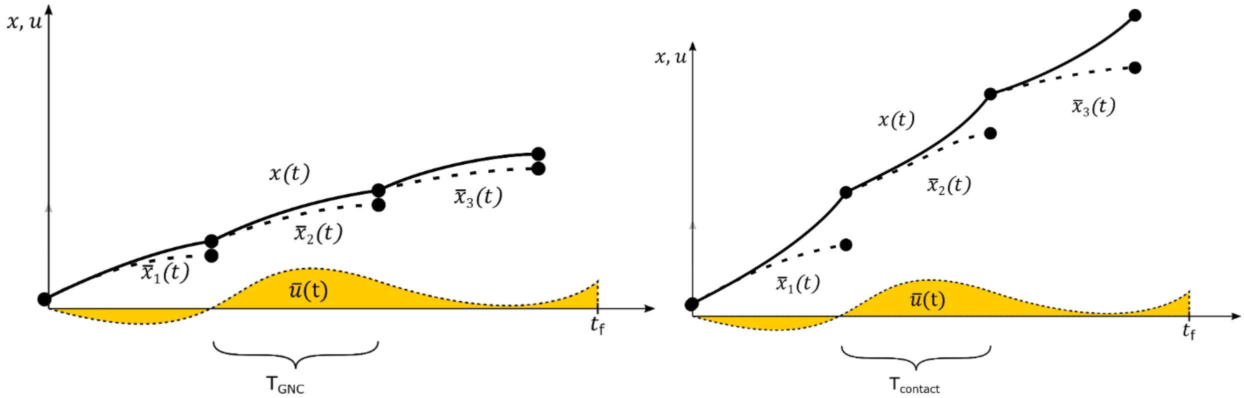


Figure 3-1. G2G guidance strategies: medium autonomy (left) and no autonomy (right).

For assessment of the strategies the following metrics are taken into account:

1. Frequency of operations (orbit determination + trajectory generation)
2. Total delta-v
3. Duration of transfer

Since we do not want to compare the trajectory-design itself both strategies should be compared under same assumptions regarding the trajectory. Circular to circular transfer is assumed. We also assume that control of RAAN is performed by letting the orbit drift for a pre-specified time when altitude of spacecraft is still low, and that the considered guidance is only responsible for controlling the semi-major axis and eccentricity.

Chosen guidance law controls thrust direction in orbital plane to ensure low eccentricity through the entire orbit raising.

This guidance law is

$$\psi = -k \sin(f)\, e \,,$$

where f and e are respectively true anomaly and eccentricity, and k is controller gain. Angle ψ describes a thrust direction in orbital plane with respect to the along-path axis. Such law injected into the eccentricity dynamical equation

$$\dot{e} = \frac{1}{h}\left(p \sin f \sin\psi F + \left((p+r)\cos f + re\right)\cos\psi F\right),$$

introduces an eccentricity-stabilizing term that limits its drift.

3.2. SCENARIO ASSUMPTIONS

3.2.1. ENVIRONMENT

The environmental parameters that have to be preserved during the FCS-ATOMIC project for the G2G scenarios are as follows:

- Gravity Field considers 12x12 model
- Third Body perturbation caused by the Sun and Moon
- Solar Radiation Pressure

3.2.2. SPACECRAFT

The satellite configuration for the defined scenarios is as follows:

- **Dry mass:** 1500 kg
- **Wet mass:** 1785 kg
- **SC cross section:** 35 m^2 (with solar panels)
- **Reflection coefficient:** 1.3
- **AOCS:**
    - Star tracker
    - Coarse sun sensors (3 per spacecraft panel)
    - 4 x Reaction wheels (pyramid configuration)
    - 3-axis Gyroscope
    - 2 x Magnetotorquers
    - Cold gas thrusters system
    - GNSS receiver
    - Electric Propulsion system
    - Retroreflectors

3.2.3. UNCERTAINTIES

For the G2G mission, in particular its transfer phase, EP system quality together with the AOCS plays great role in case of performance. Uncertainties of those system are crucial for the mission definition of the FCS-ATOMIC project. Main sources of the uncertainties of those systems are listed below (see Table 3-2 for parameters values):

Parameter name	Value	Unit	Description
Sensors Errors			
GPS receiver			
Along track position	20.4	m	Along track position error, RMS.
Along track position bias	20.0	m	Along track position bias.
Cross track position	31.0	m	Cross track position error, RMS.
Cross track position bias	24.0	m	Cross track position bias.
Radial position	87.5	m	Radial position error, RMS.
Radial position bias	-3.0	m	Radial position bias.
Along track velocity	0.11	m/s	Along track velocity error, RMS.
Along track velocity bias	0.0	m/s	Along track velocity bias.

Parameter name	Value	Unit	Description
Cross track velocity	0.11	m/s	Cross track velocity error, RMS.
Cross track velocity bias	0.0	m/s	Cross track velocity bias.
Radial velocity	0.84	m/s	Radial position velocity, RMS.
Radial velocity bias	0.0	m/s	Radial velocity bias.
Measurements availability	75%	-	Measurements availability in percentage. For the final orbit it gives around 9h of GNSS measurements
On-ground POD using Retroreflectors			
Along track position	56 (TBC)	cm	Along track position error.
Cross track position	19 (TBC)	cm	Cross track position error.
Radial position	12 (TBC)	cm	Radial position error.
On-ground Trajectory Planning			
Reference Trajectory Generation Error	TBD	-	Optimization process errors.
GNC Errors			
APE	[0.5; 0.5; 0.5]	deg	Absolute Pointing Error of the SC attitude, pictured as Roll, Pitch and Yaw angles respectively. Half cone about nominal x-axis direction (3-sigma). This error can be described as difference between commanded attitude and true attitude of the spacecraft.
AKE	[0.1; 0.1; 0.1]	deg	Absolute Knowledge error of the SC attitude, pictured as Roll, Pitch and Yaw angles respectively. It refers to one fifth of the APE.
Thrust magnitude knowledge	2 %	-	Variation of the thrust magnitude knowledge. Derived by the on-ground estimation using data from GNSS receiver.
Reference Trajectory Generation Error	TBD	-	Optimization process errors.
Actuators Errors			
Thruster			
Thrust magnitude	2 %	-	Variation of the actual thrust magnitude. Driven by the thruster design.
Thrust direction misalignment	0.15	deg	Thrust vector error with regard to SC x-axis due to thrust pointing mechanism angular resolution (3-sigma error).

Table 3-2: Errors of the Sensors, GNC and Actuators

3.3. FCS RESULTS

3.3.1. MEDIUM AUTONOMY

Test case	Test description	Batch size	Scenario configuration	Error sources
Nominal Medium Autonomy Case				
FCS-G2G-MA-1	<u>Nominal case of medium autonomy scenario.</u> The performance of the G2G medium autonomy case (GNC) is assessed in presence of all the expected error sources, in the nominal envelope of conditions. The results of the batch of runs will identify which combination of conditions (navigation and thruster errors) may produce worst cases.	10	Initial parameters: • SMA – 9541 km • Inclination - 56 deg • Autonomy level – medium • Nominal thrust – 180 mN • GNSS receiver performance – 25 dBHz • Initial thrust error – 0.56% • Thrust degradation 2%/year	Performance model of GNSS-based Navigation + Measurements + Visibility (GNC) Performance model of Error Dispersion + Thrust Performance

The results below show orbit transition of 10 MC cases. The required SMA is achieved within approximate range of 331 – 337 days. The guidance law effectively keeps eccentricity small. The peak value of eccentricity can be adjusted with the guidance law gain. However, high gain will use more propellant to keep the orbit circular in the periods with eclipses occurrence, so the gain value should be a result of a further trade-off. The guidance law fulfils also requirements to keep RAAN and inclination within small dispersion, respectively +/- 1 deg, +/- 2 deg. Table 3-3 summarizes final dispersion of eccentricity, inclination and RAAN and ΔV.

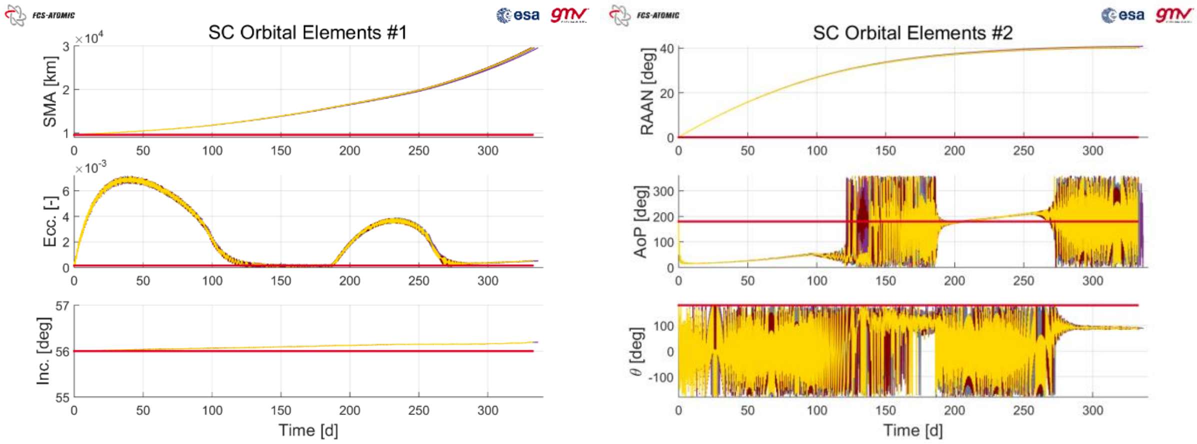


Figure 3-2. Orbital elements and ΔV in FCS-G2G-MA-1 test.

Table 3-3. Results of FCS-G2G-MA-1 test

Element	Max	Min	Mean	σ
e [-]	5,50E-04	4,98E-04	5,26E-04	1,67E-05
i [deg]	56,1938	56,1930	56,1935	2,22E-04
RAAN [deg]	40,8031	40,2583	40,4688	1,49E-01
ΔV [m/s]	2910,8276	2909,8696	2910,2741	3,22E-01
Time [days]	336,8056	331,9444	333,7847	1,318

3.3.2. NO AUTONOMY

Test case	Test description	Batch size	Scenario configuration	Error sources
Nominal No Autonomy Case				
FCS-G2G-NA-1	<u>Nominal case of no autonomy scenario.</u> The performance of the G2G no autonomy case (FDS) is assessed in presence of all the expected error sources, in the nominal envelope of conditions. The results of the batch of runs will identify which combination of conditions (navigation and thruster errors) may produce worst cases.	10	Initial parameters: • SMA – 9541 km • Inclination - 56 deg • No autonomy • Nominal thrust – 180 mN • GNSS receiver performance – 25 dBHz • Initial thrust error – 0.56% • Thrust degradation - 2%/year • Ground update period – 7 days	Performance model of Ground GNSS-based OD (FDS) Performance model of Error Dispersion + Thrust Performance

The results below show orbit transition of 10 MC cases. Ground updates interval has been set to 7 days. The required SMA is achieved approximately in range of 345 – 351 days. The guidance law effectively keeps eccentricity small. The peak value of eccentricity can be adjusted with the guidance law gain. The guidance law fulfils also requirements to keep RAAN and inclination within small dispersion, respectively +/- 1 deg, +/- 2 deg. The required delta V is roughly 3% larger in comparison to medium-autonomy guidance law.

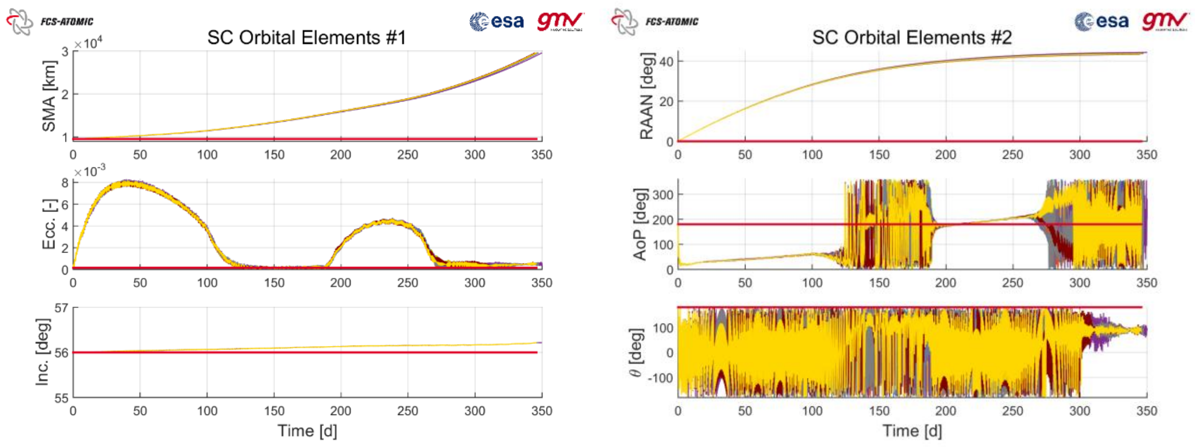


Figure 3-3. Orbital elements and ΔV in FCS-G2G-NA-1 test.

Table 3-4. Results of FCS-G2G-NA-1 test

Element	Max	Min	Mean	σ
e [-]	6,85E-04	4,65E-04	6,03E-04	6,33E-05
i [deg]	56,2148	56,2132	56,2144	4,78E-04
RAAN [deg]	44,2904	43,3604	43,7200	2,53E-01
ΔV [m/s]	2994,9624	2992,4219	2993,9816	7,26E-01
Time [d]	350,3472	345,1389	347,1354	1,416

3.3.3. RESULTS SUMMARY – MEDIUM AUTONOMY

Results of all medium autonomy scenarios are presented in Table 3-5. It contains a set of selected parameters:

- RAAN dispersion
- Mean Total required ΔV
- Mean Orbit raising time
- Orbit raising time dispersion

Values of mean ΔV and orbit raising time are shown as change with reference to nominal case MA-1.

Table 3-5. Results of medium autonomy scenarios

Case	RAAN σ [deg]	Mean ΔV [m/s]	Mean Time [d]	Time σ [d]
MA-1	0,149	2910,274	333,78	1,318
MA-2	0,187	-	-	-
MA-3	0,073	+1,77%	-205,14	0,563
MA-4	0,177	+1,37%	+5,21	1,491
MA-5	0,162	-1,35%	-3,99	1,486
MA-6	0,170	+0,00%	+0,63	1,460
MA-7	0,030	+0,01%	-0,38	0,263
MA-8	0,288	-0,01%	+1,49	2,579
MA-9	0,165	+0,00%	-0,94	1,465

MA-10	0,177	-0,02%	+13,89	1,608

3.3.4. RESULTS SUMMARY – NO AUTONOMY

Results of all no autonomy scenarios are presented in Table 3-6. It contains a set of selected parameters:

- RAAN dispersion
- Mean Total required ΔV
- Mean Orbit raising time
- Orbit raising time dispersion

Values of mean ΔV and orbit raising time are shown as change with reference to nominal case NA-1.

Table 3-6. Results of medium autonomy scenarios

Case	RAAN σ [deg]	Mean ΔV [m/s]	Mean Time [d]	Time σ [d]
NA-1	0,253	2993,982	347,14	1,416
NA-2	0,310	-	-	-
NA-3	0,018	+8,38%	-203,66	0,155
NA-4	0,296	+1,54%	+6,27	1,603
NA-5	0,237	-1,50%	-4,67	1,491
NA-6	0,275	+0,00%	+0,64	1,550
NA-7	0,053	-0,01%	-0,47	0,258
NA-8	0,506	-0,01%	+1,65	2,794
NA-9	0,282	+0,09%	-0,68	1,491
NA-10	0,360	-0,66%	+12,38	2,037
NA-11	0,185	-0,85%	-2,45	1,536
NA-12	0,241	-0,88%	-3,04	1,596

4. CONCLUSIONS AND RECOMMENDATIONS

The conclusion of the FCS assessment analyses and recommendations for the way forward are listed here for both scenarios.

4.1. HERA

The FCS assessment with the FCS-ATOMIC framework provided quite the insight on these scenarios and, specifically for HERA, allowed us to reach some conclusions:

- Ground FCS (FDS) Performance

  The FDS can achieve very accurate reconstructed performance using landmarks to navigate, however, the predicted performances are quite limited due to the large manoeuvre errors. This is the leading factr more than any measurement noise or dynamics uncertainty.

- Ground Payload Pointing

  Ground is not capable to safely point the 5.5 degree FOV camera to Didymain due to the large predicted FCS navigation errors.

- Autonomous FCS Performance

  The autonomous GNC system is capable of achieving quite an acceptable, and robust, performance. Even with low measurement frequencies (1 image per hour) and long measurement blackouts (8h per day).

- Autonomous Pointing.

  The good GNC performance allows the spacecraft to safely point its payloads to the target body without any danger of losing it.

- Trajectory Dispersion

  Depending on the platform's RCS translational manoeuvre errors, the dispersion can be quite high.

Some questions, however, remain to be answered and are here listed as some of the points to be tackled on the next stages of this analysis:

- Landmark database

  It is unclear, at this stage, if in this scenario the landmarks identified and estimated during ECP (~20-30 km) could be used at DCP (~10-18 km).

- Manouvre Error

  More detailed models should be used to account for the use of the RCS system once the HERA phase B1 starts off. Moreover, the impact of the two-manoeuvre strategy to change between hyperbolic arcs should also be assessed.

- Manoeuvre Error Reduction

  Strategies to reduce the manoeuvre errors should be considered. For now the manoeuvre errors were considered open-loop as, according to ESOC experts, in Rosetta, a manoeuvre magnitude of 10 cm/s is where the performance would balance between an open-loop and closed-loop schemes. However, this analysis should be translated into the HERA scenario with the designed IMU, RCS thrusters, and mass properties of the HERA platform.

- High-Fidelity IP Models

  In order to validate this strategy, higher fidelity models of the image processing on-board component should be used to validate the on-board performance.

- Non-Gravitational Accelerations

  A value of 10^{-9} m/s^2 is often considered for navigation analyses but this would dominate the dynamics in this scenario. Thus, the thermal radiation and outgassing should be analyses, as well as any other non-considered forces, to be able to assume a lower value for this perturbation.

4.2. G2G

The comparison of G2G scenarios with different autonomy level revealed significant differences in achieved performance. The medium-autonomy guidance law keeps the spacecraft state within smaller range than no-autonomy ground updates. On-board guidance is also noticeably more efficient in matter of required delta V. Even though the on-board state knowledge is less accurate than ground orbit determination, the continuous compensation of disturbances and thrusting errors results in more robust guidance law.

The sensitivity tests showed that 180mN is a reasonable choice of thrust to achieve final orbit in one year including time margin. 80mN thruster is incapable of the transfer within given duration, while 480mN thruster allows to reduce manoeuvre time to less than 130 days.

Accuracy of orbit raising strongly depends on the actuator performance. Only good knowledge of initial thrust and its degradation rate will allow for precise prediction of final state. Initial thrust variation of 1% may result in RAAN uncertainty close to required or even worse in case of no-autonomy guidance, thus at least such thrust magnitude estimation is necessary for successful orbit raising under given assumptions.

The worst influence of thrust errors is on the along-track position. Even smallest variation in initial thrust accumulates after thousands of orbits making the final along-track position hard to estimate. Additional phasing manoeuvre is therefore recommended. The repositioning manoeuvre has been discussed in G2G mission analysis as a separate mission stage. The phase change has been analysed assuming both chemical and electrical propulsion. For those two cases the estimated transfer duration was similar, while use of electrical propulsion results in higher required ΔV. **Table 4-1** presents result of the transfer analysis in case of electrical propulsion. XS and M are two types of satellite, the XS assumes thrust of 180 mN, ISP of 1730 s and mass of 1380 kg while M parameters are: thrust of 269 mN, ISP of 1867 s, mass of 2010 kg. The XS satellite values are very similar to those assumed in FCS Atomic G2G simulations.

Table 4-1 : G2G MEO repositioning manoeuvre with electrical

Change in True Anomaly [deg]	Delta-V [m/s]		Transfer Duration [days]	
	XS	M	XS	M
+22.5°	23.93	23.72	4.8	4.8
+67.5°	41.45	41.03	8.3	8.3
+112.5°	54.44	53.03	10.6	10.7
+157.5°	62.88	63.12	12.7	12.6