# FCS-ATOMIC

# Final Presentation

**F**light **C**ontrol **S**ystem **A**ssessment **T**oolbox

for **O**ptimal **Mi**ssion **C**ost and Performance

Agenda

# FCS-ATOMIC Final Presentation

| | |
|---|---|
| 10:00 – 10:05 | Project Introduction |
| 10:05 – 10:15 | FCS-ATOMIC Framework |
| 10:15 – 10:30 | HERA FCS Assessment |
| 10.30 – 10:45 | G2G FCS Assessment |
| 10:45 – 11:00 | Q&A |

**FCS-ATOMIC FP**

# Project Introduction

# Project Context and Background

- **F**light **C**ontrol **S**ystem **A**ssessment **T**oolbox

  for **O**ptimal **Mi**ssion **C**ost and Performance - FCS-ATOMiC

JUICE Autonomous Navigation (GMV-ESP)

AIM System Studies

FEST (GMV-ESP)

FASTMOPS (GMV-POR)

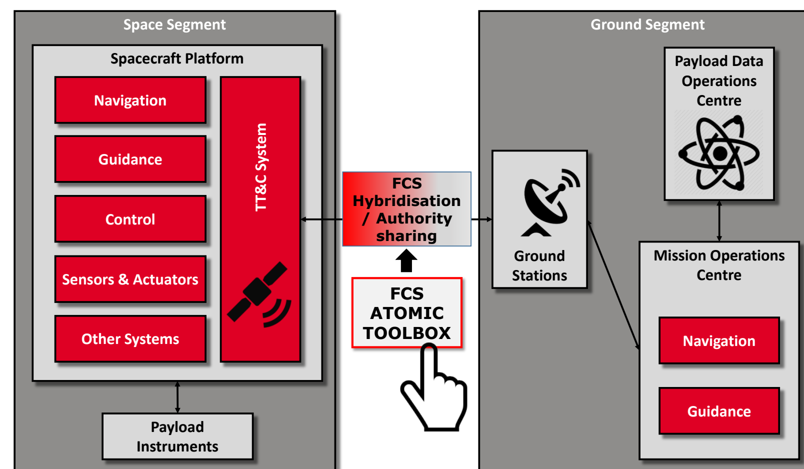
JUICE Autonomous Pointing (GMV-POR)

Phobos-SR GNC (GMV-POL)

G2G Mission Analysis (GMV-POL)

Operations (GMV-FDO)

FCS-ATOMIC



# Project Sequence

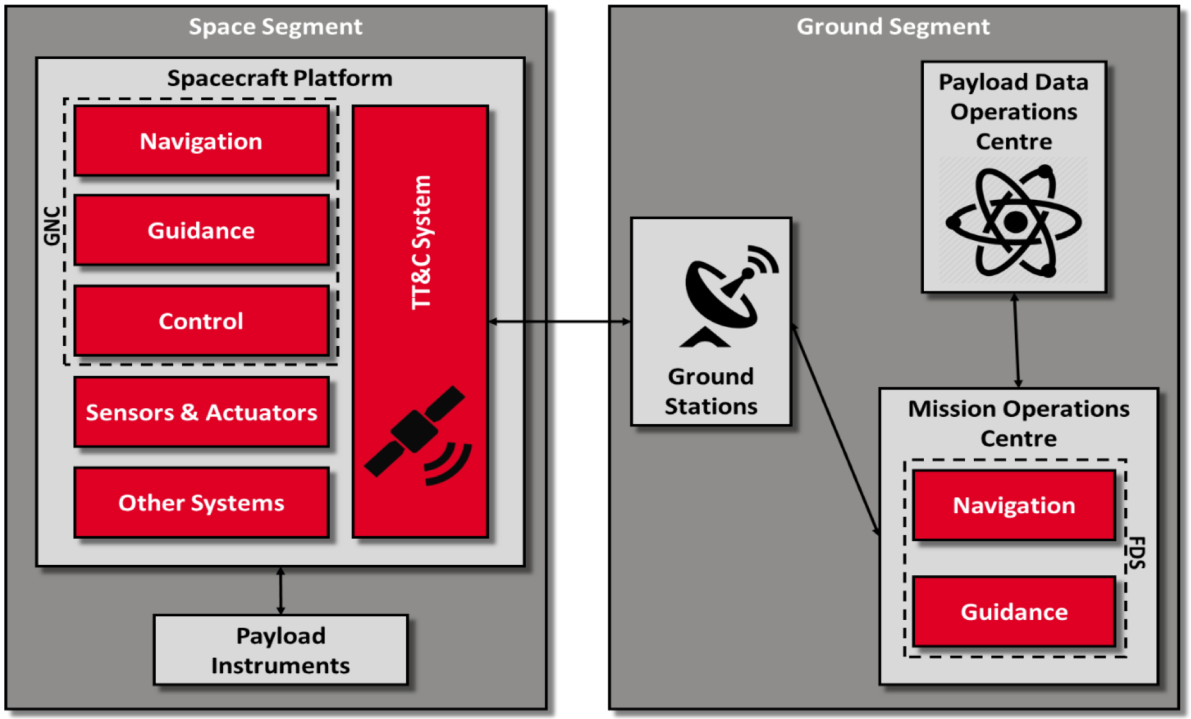
16-month Project
Mar 2017 – Jun 2018

FCS-ATOMIC

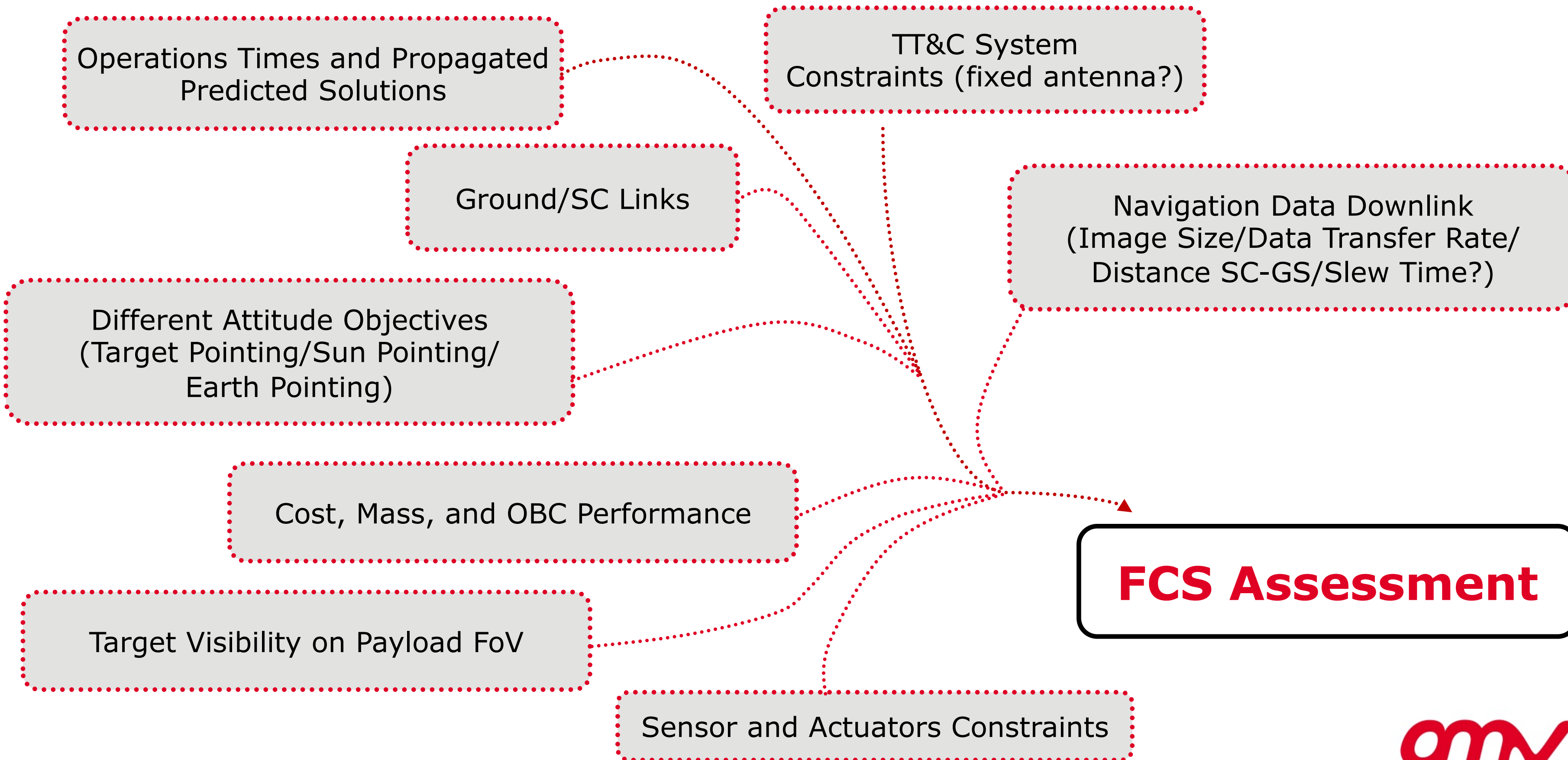
1. FCS Components Identification
2. FCS Models Formulation
3. Framework Development and Validation
4. Mission Scenarios FCS Assessment

# FCS-ATOMIC Framework

# FCS Components and Interfaces

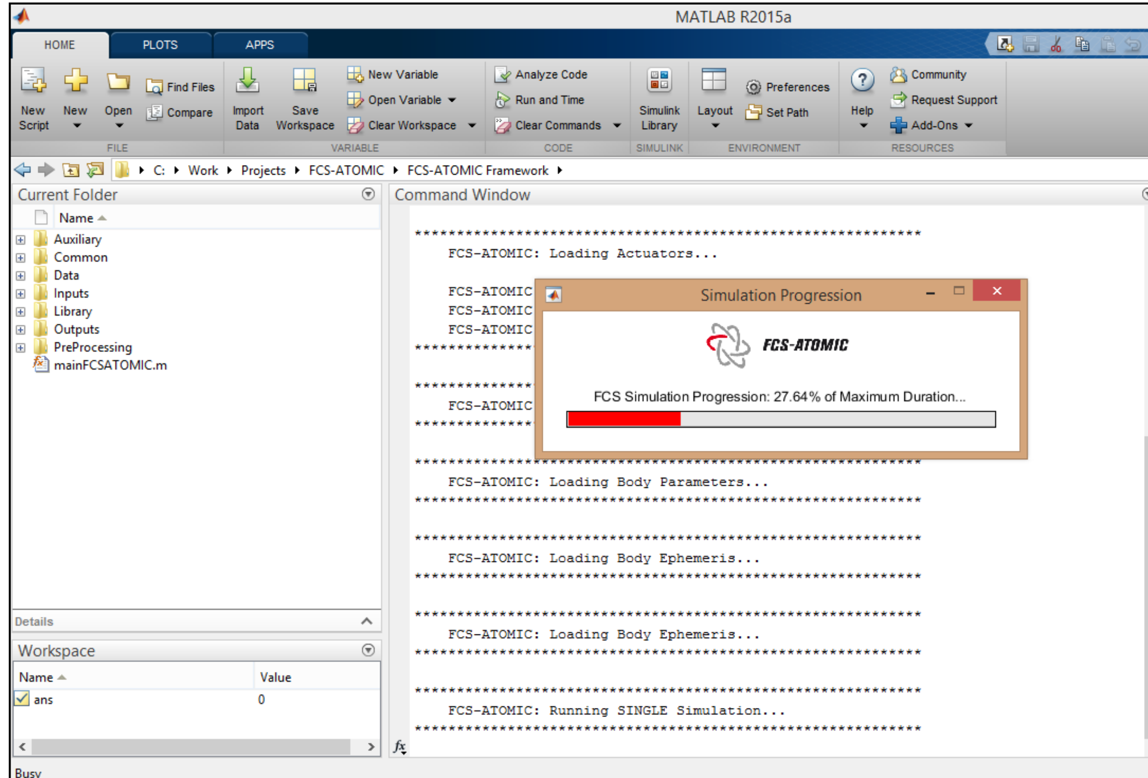


# FCS Constraints



# Framework Philosophy

- No installation required
- Scenario and Models configured by input files
- Modular: Each FCS Component defined by its input file
- No GUI



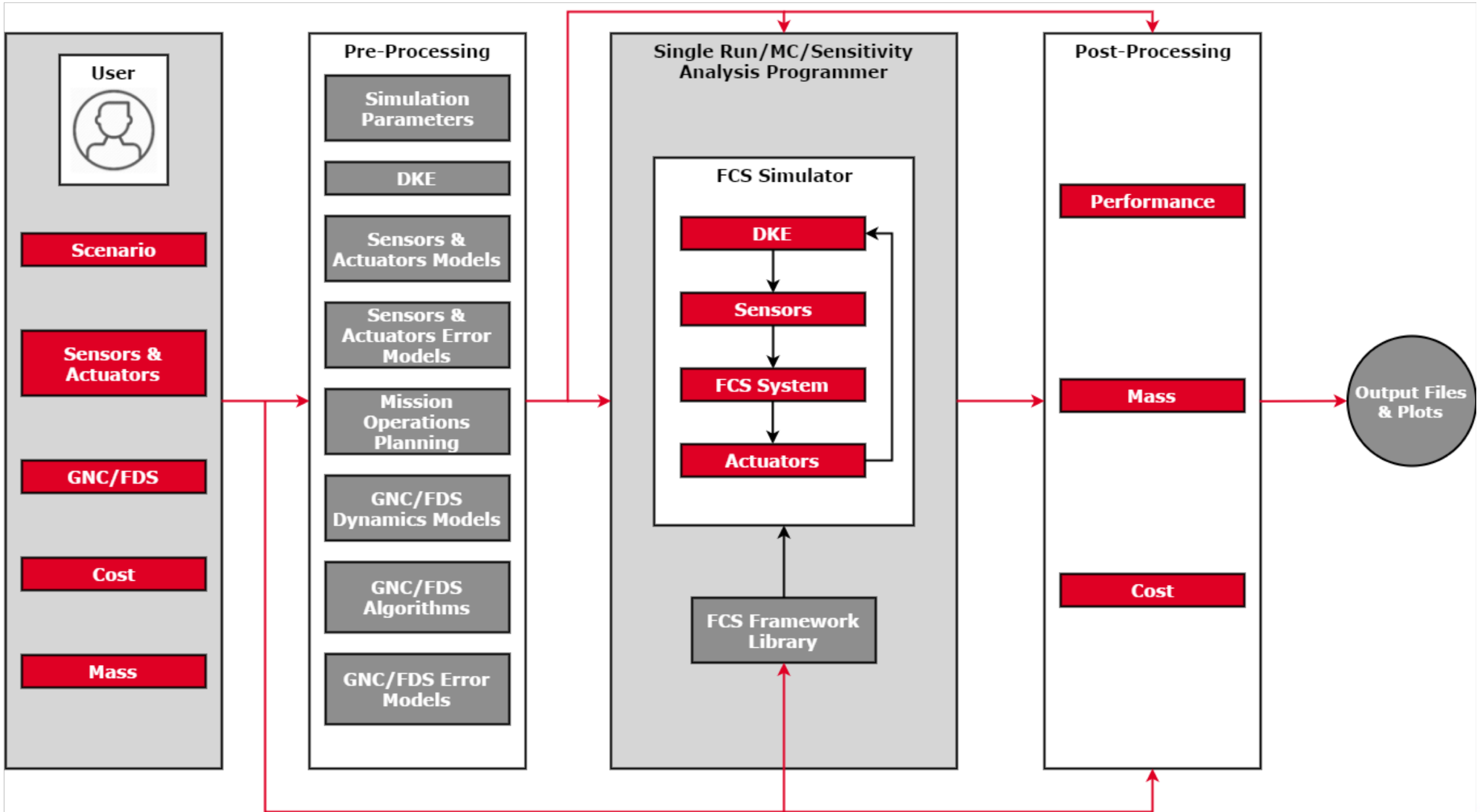

gmv

# Framework Language

- MATLAB selected for the flexibility and accesibility
- The user has the possibility to use MEX functions for increased speed

| Programming Language/Concept | Flexibility | Extensibility | Computational Speed | Accessibility |
|---|---|---|---|---|
| **MATLAB** | ★★★★★ | ★★★★★ | ★★ | ★★★★★ |
| **MATLAB with MEX functions** | ★★★★★ | ★★★★ | ★★★ | ★★★★ |
| **Simulink with S-functions** | ★★★★ | ★★★ | ★★★ | ★★★★ |
| **MATLAB/Simulink Hybrid** | ★★★ | ★★★ | ★★★ | ★★★★ |
| **FORTRAN** | ★ | ★★ | ★★★★★ | ★★ |

# High Level Architecture



# Framework Capabilities

Autonomy Levels easily defined for different components

On-Board and ground Estimation with automatised interfaces

SC State Estimation (translation + attitude)

Impulsive or Continuous Thrust Scenarios

Parameter Estimation

# Framework Capabilities

Easy to define probabilistic system failures

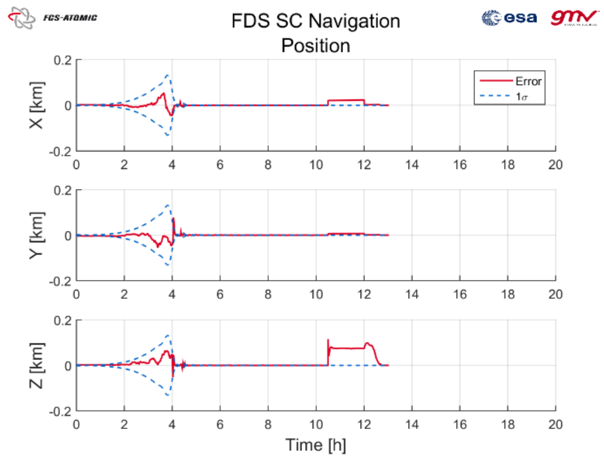
Different algorithms, frequencies, and error models for each system

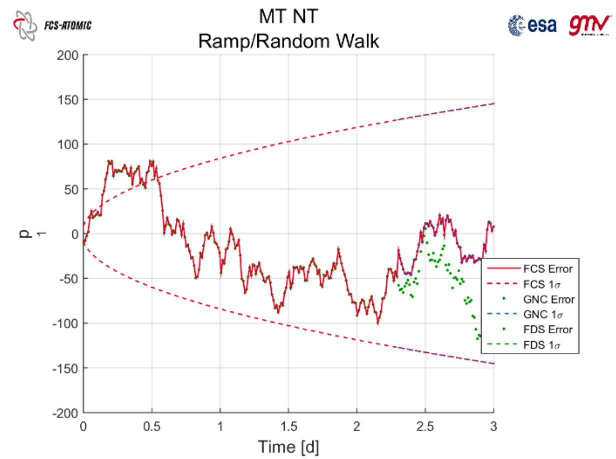
Flexible and easy to configure

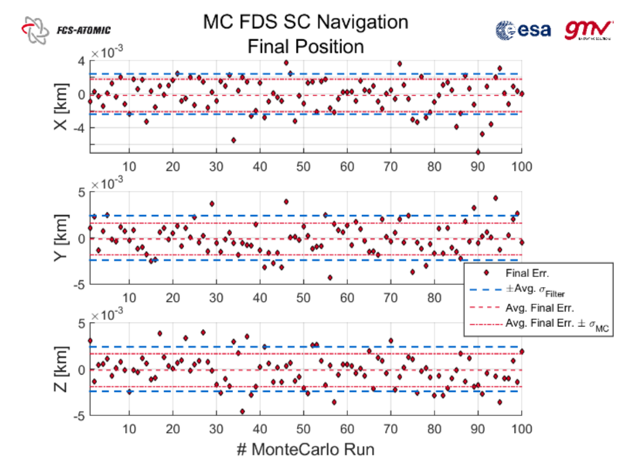
High-fidelity or performance models for the different components

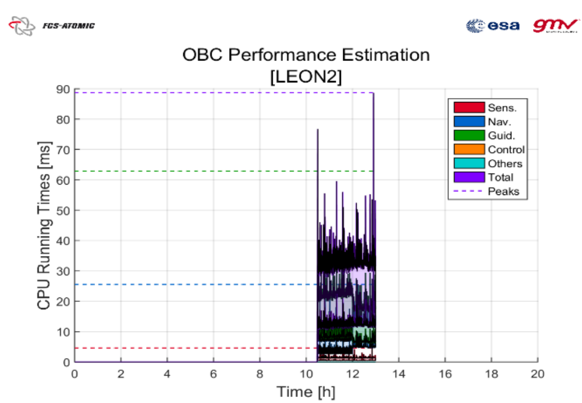
Single-Run, Sensitivity Analysis, or Monte Carlo Simulations.

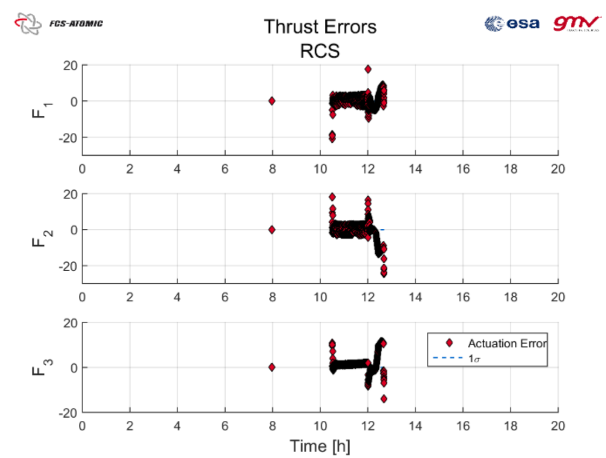
# Outputs


FCS-ATOMIC
esa
gmv
FDS SC Navigation
Position
X [km]
Y [km]
Z [km]
Error
1σ
Time [h]


FCS-ATOMIC
esa
gmv
MT NT
Ramp/Random Walk
p 1
FCS Error
FCS 1σ
GNC Error
GNC 1σ
FDS Error
FDS 1σ
Time [d]


FCS-ATOMIC
esa
gmv
MC FDS SC Navigation
Final Position
X [km]
Y [km]
Z [km]
Final Err.
±Avg. σ Filter
Avg. Final Err.
Avg. Final Err. ± σ MC
# MonteCarlo Run


FCS-ATOMIC
esa
gmv
OBC Performance Estimation
[LEON2]
CPU Running Times [ms]
Sens.
Nav.
Guid.
Control
Others
Total
Peaks
Time [h]


FCS-ATOMIC
esa
gmv
Thrust Errors
RCS
F 1
F 2
F 3
Actuation Error
1σ
Time [h]

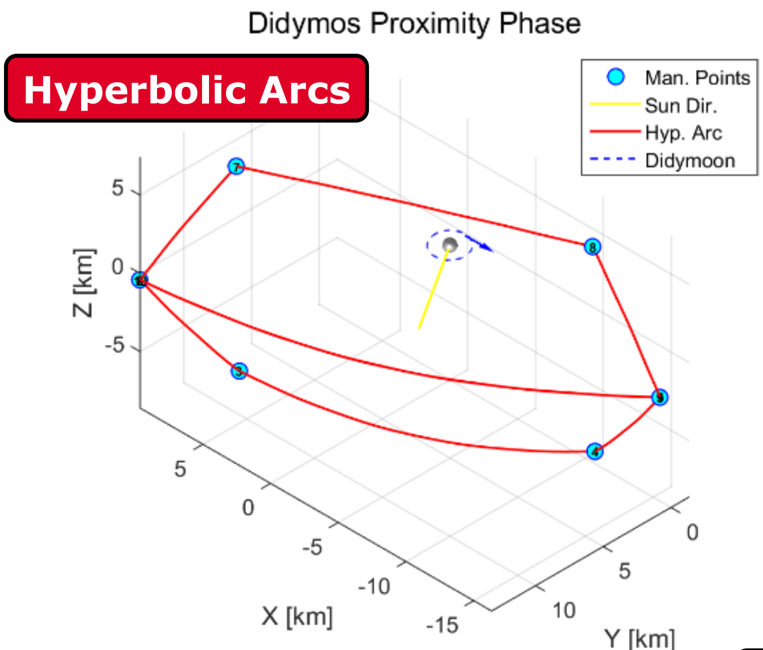
FCS-ATOMIC FP

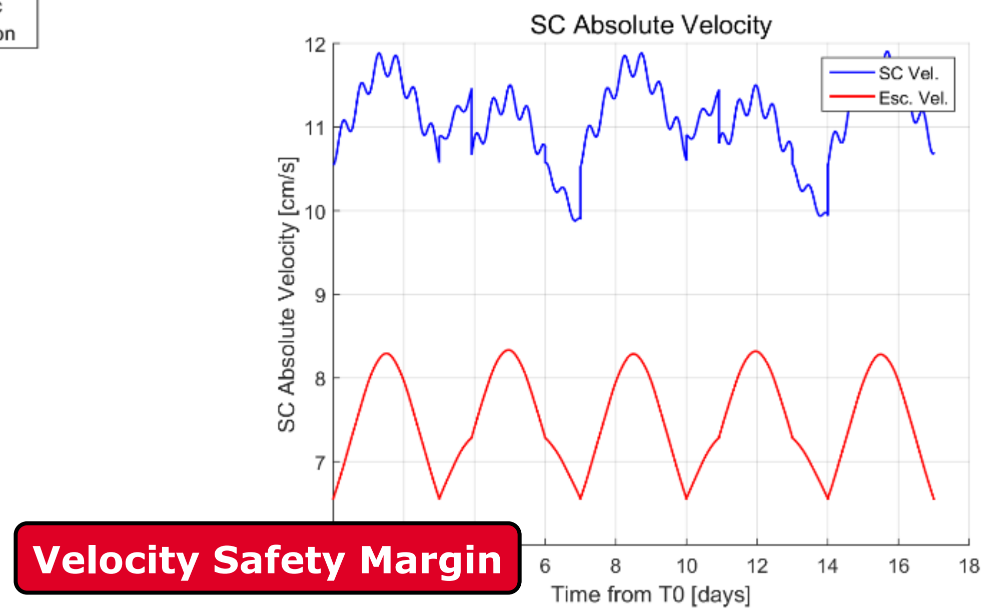
# HERA FCS ASSESSMENT

# HERA Mission


| Mission Phase | Key Events | Date / Duration |
|---|---|---|
| **Launch and Early Operations** | Launch | 22/10/2023 (LPO) - 12/11/2023 (LPC) |
| | Early Operations / Commissioning | 1-2 months (TBC) |
| **Cruise** | Deep Space Manoeuvre and Interplanetary transfer | ~3 years |
| | Arrival at Asteroid System | 02/09/2026 |
| **Asteroid System Rendezvous** | Insertion Manoeuvres | ~28 days |
| | Early Characterisation Phase (ECP) | ~6 weeks |
| **Proximity Operations** | **Detailed Characterisation Phase 1 (DCP1)** | ~6 weeks |
| | Payload Deployment Phase (PDP) | ~4 weeks |
| | Detailed Characterisation Phase 2 (DCP2) | ~6 weeks |
| | Detailed Characterisation Phase 3 (DCP3) | ~6 weeks |
| | End of Life Phase (ELP) | 12/07/2018 |
| | End of Life (EoL) | Jun 2027 |

# HERA DCP Scenario



# FCS Feasibility Study

- Close Proximity (~10-18 km) is a challenge given the large manoeuvre errors (from AIM SS)

- Ground Operational Turnaround Times have a negative impact on the navigation performance

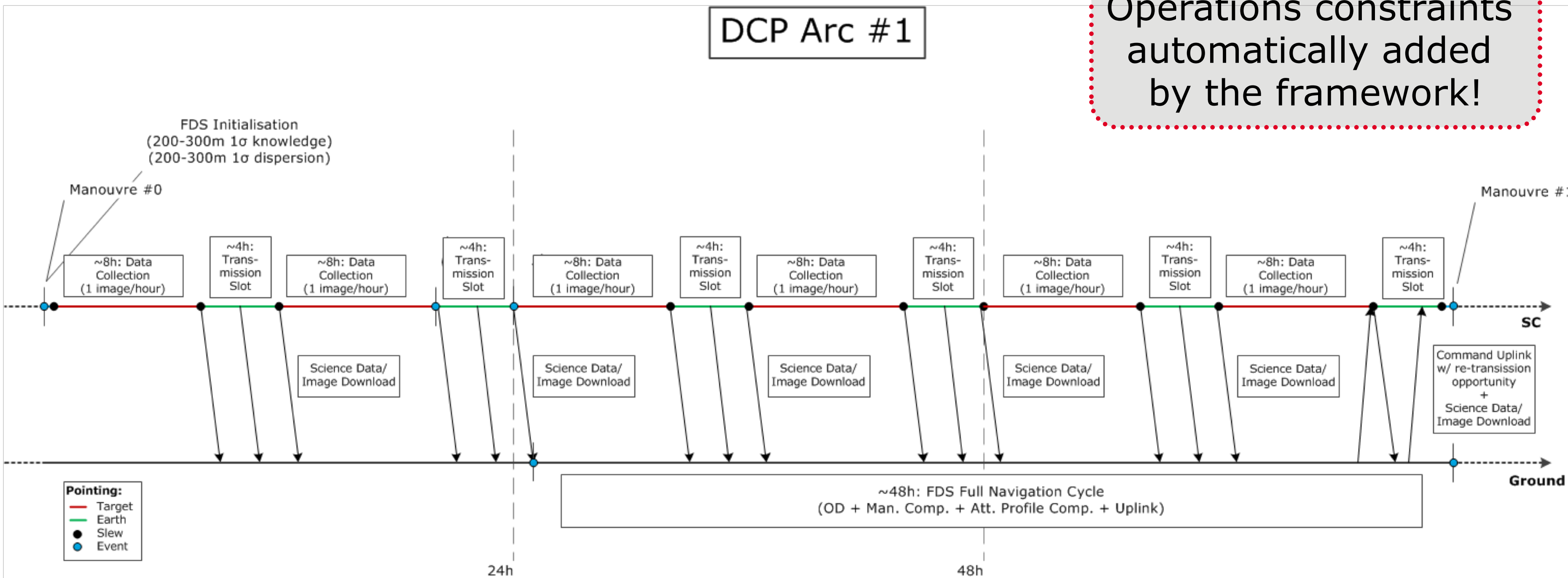
**<u>Question:</u>**

- **Can the spacecraft be safely controlled from ground?**
- **Does autonomy make the strategy feasible? And what autonomy level/strategy delivers the optimal performance/safety/cost?**

# No Autonomy

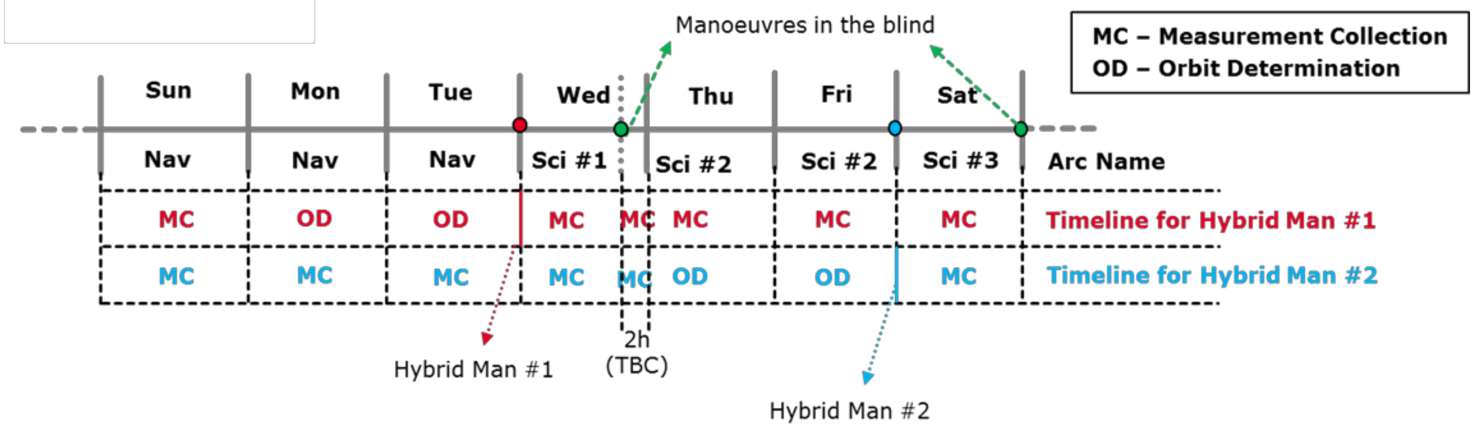
- 8h Earth communication slot / day with non-steerable HGA

Operations constraints automatically added by the framework!

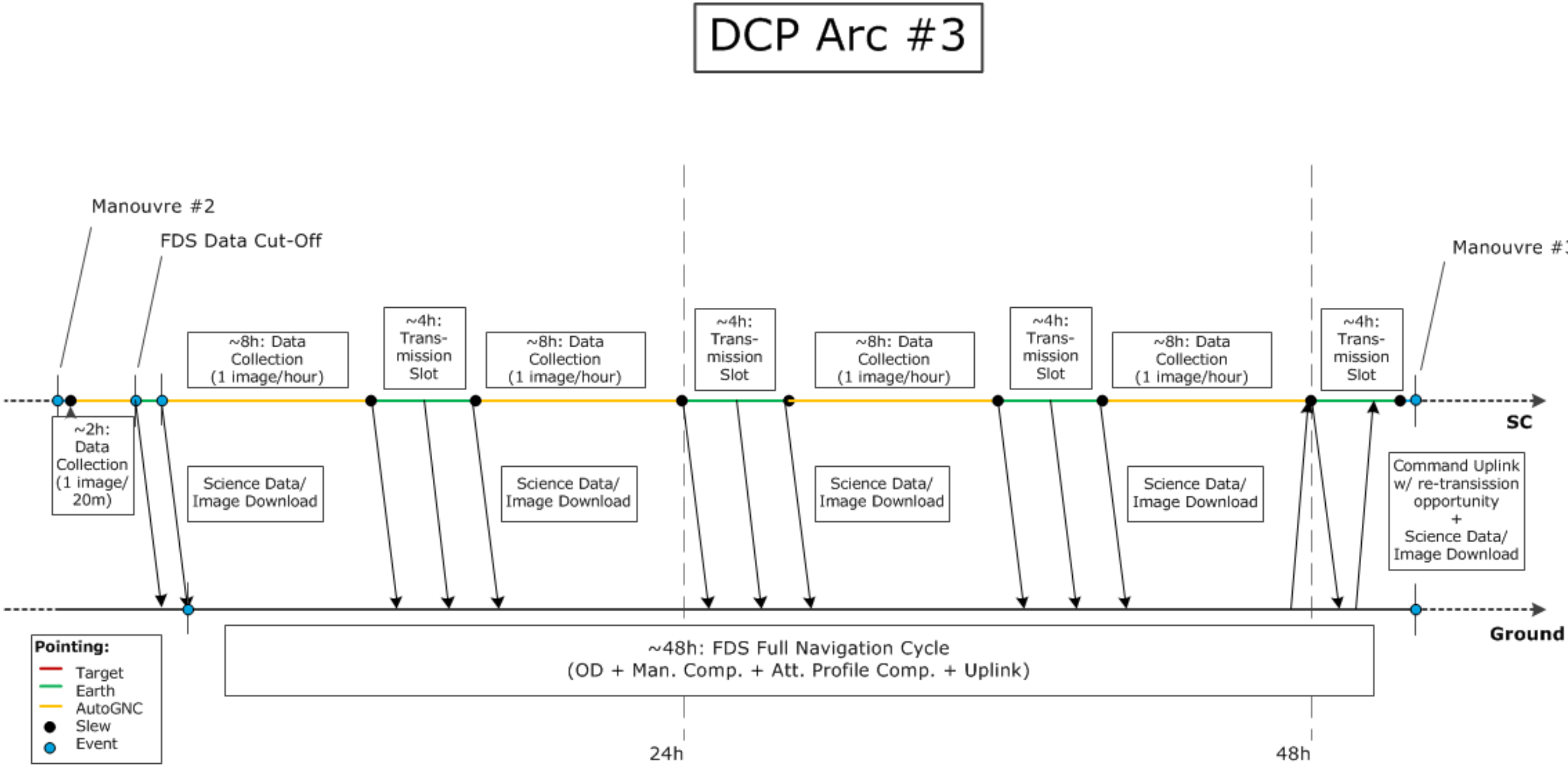


# No Autonomy

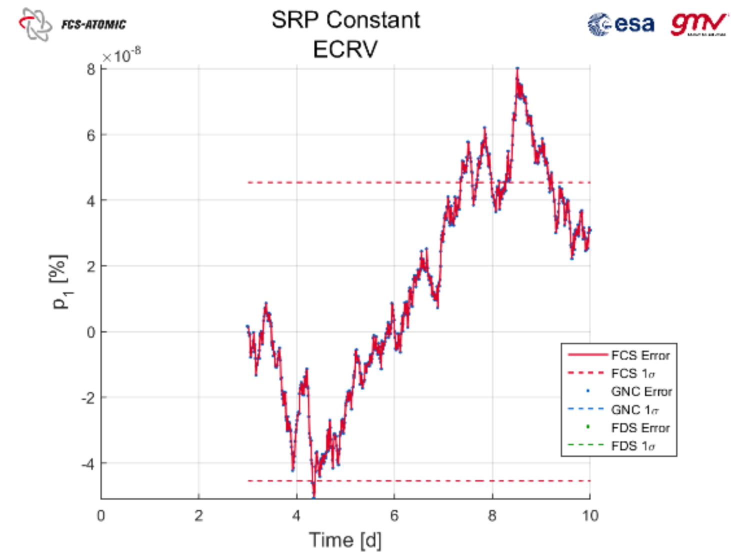
- No weekend or night shifts
- 48h turnaround time



# Medium Autonomy



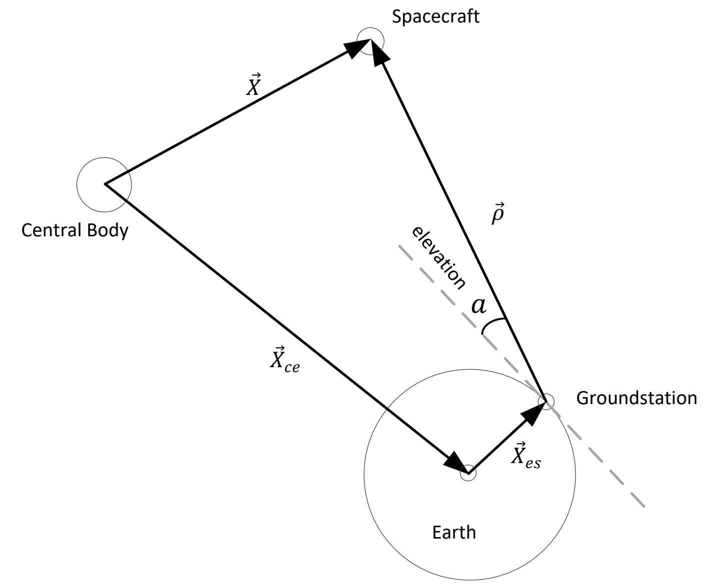
# Dynamical Uncertainties



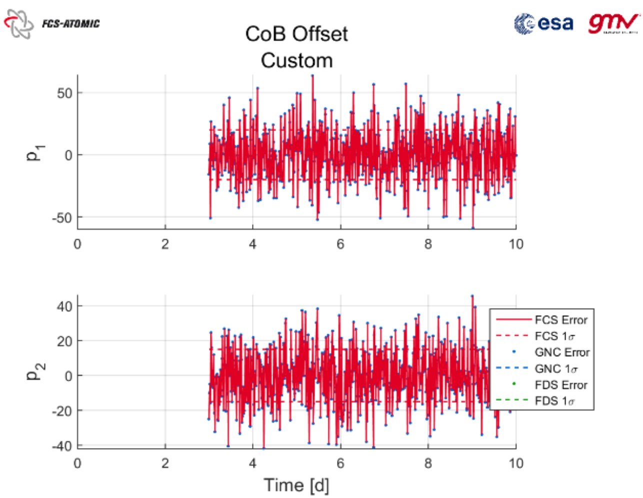

| Dynamical Parameter assumptions | 1-Sigma |
|---|---|
| Didymain ephemeris position error [m] | 1000 |
| Didymain ephemeris velocity error [m/s] | 0.001 |
| Didimain Centre-of-Mass/Centre-of-Gravity Offset [m] | [1,1,1] |
| Didymoon orbital elements error (SMA,ECC,INC,RAAN,OMG,TRUEAN0) | 10m, 0.01,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

# Radiometric Measurements

| Measurement errors | 1-Sigma |
|---|---|
| Range [m] | Noise: 3<br><br>Bias: 5 |
| Range acquisition frequency | Every hour |
| Doppler [mm/s] | Noise: 0.1<br><br>Bias: 0 |
| Doppler acquisition frequency | Every 10 min |
| Ground station position [m] | Bias: 1m |
| Ground Station considered | Cebreros, New Norcia, Malargüe |



# Optical Measurements




| Dynamical Parameter assumptions | 1-Sigma |
|---|---|
| Didimain Centre-of-Mass/Centre-of-Gravity Offset [m] | [1,1,3] |
| Landmarks Detection | 1 pixel |
| Didymain Scale Factor Error | 0.1% |
| Landmark Position [m] | 1 |
| Didymain Orientation [deg] | [1, 1, 1] |

**Centroiding:**

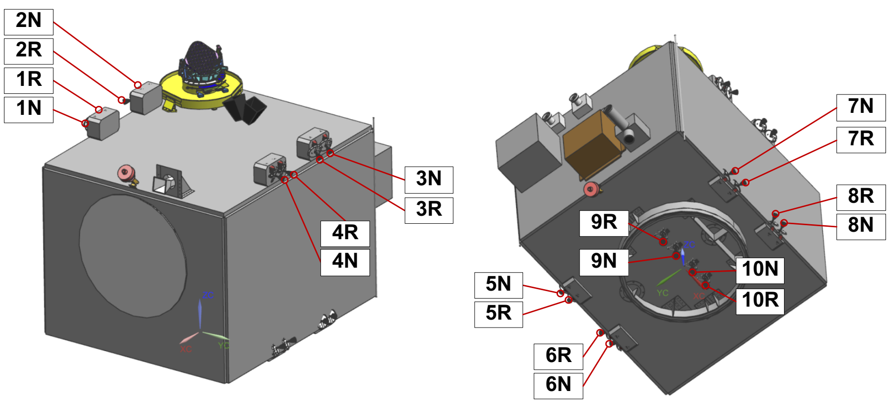
- **1pxl White Noise**
- **1pxl Bias (camera misalignment)**
- **CoB Offset**
- **CoM Offset**

**LMs Uncertainties:**

- **CoM Offset**
- **LM Detection Performance**
- **LM Position**
- **Body Scale Error**
- **Body Orientation**

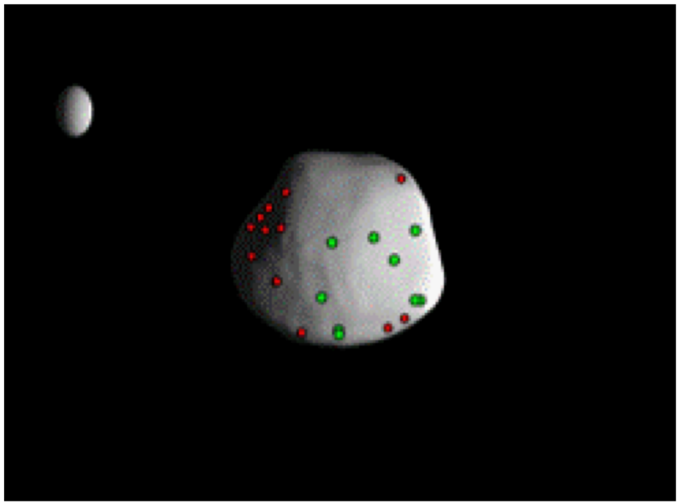
# Actuator Errors

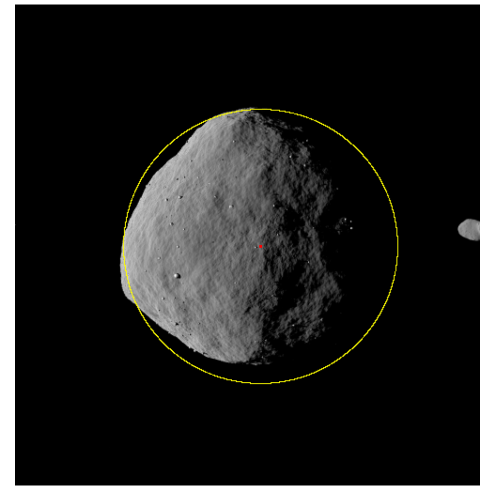
- RCS Use – 10N thrusters
- Sensitivity analysis on the manoeuvre error




| Scenario | 1σ Errors |
|---|---|
| Optimistic Case | ▪ Manoeuvre Magnitude Error: 0.3%<br>▪ Manoeuvre Direction Error: 0.5 deg |
| Baseline Case | ▪ Manoeuvre Magnitude Error: 1%<br>▪ Manoeuvre Direction Error: 1 deg |
| Pessimistic Case | ▪ Manoeuvre Magnitude Error: 3%<br>▪ Manoeuvre Direction Error: 1.5 deg |

# Image Processing Techniques

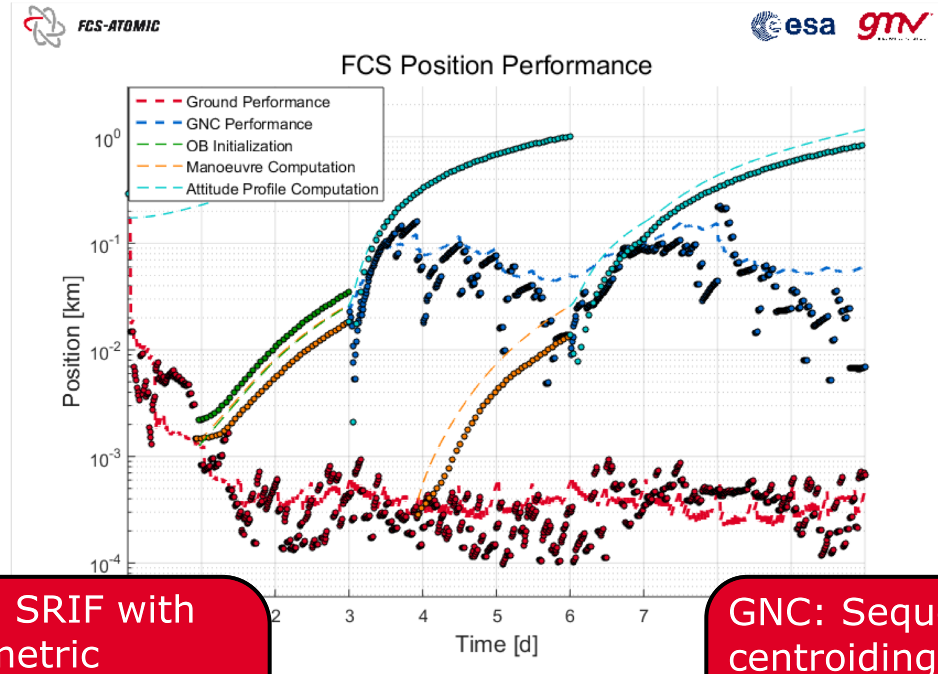




FDS: Landmarks-based Navigation

GNC: Centroiding-based Navigation

# Navigation Algorithms



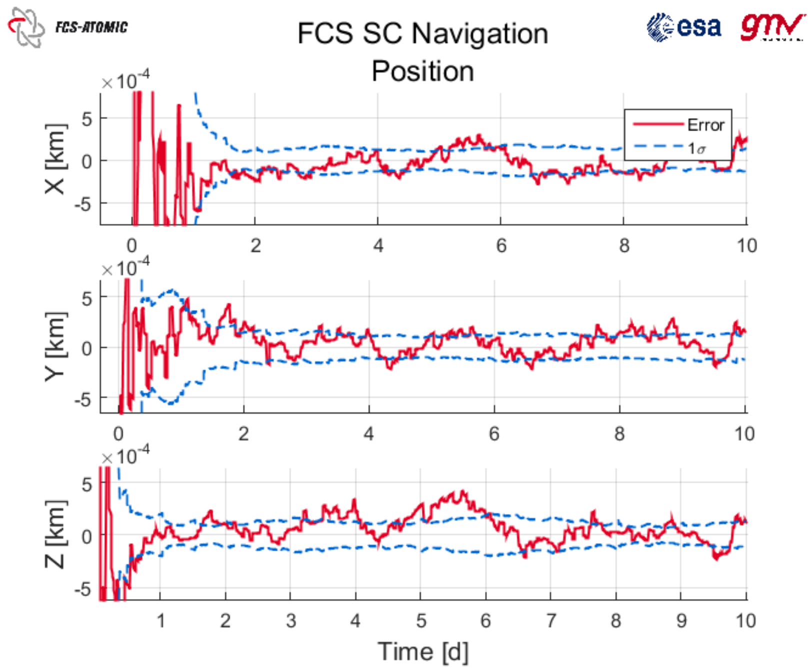

FDS: Sequential-Batch SRIF with Landmarks and Radiometric measurements:

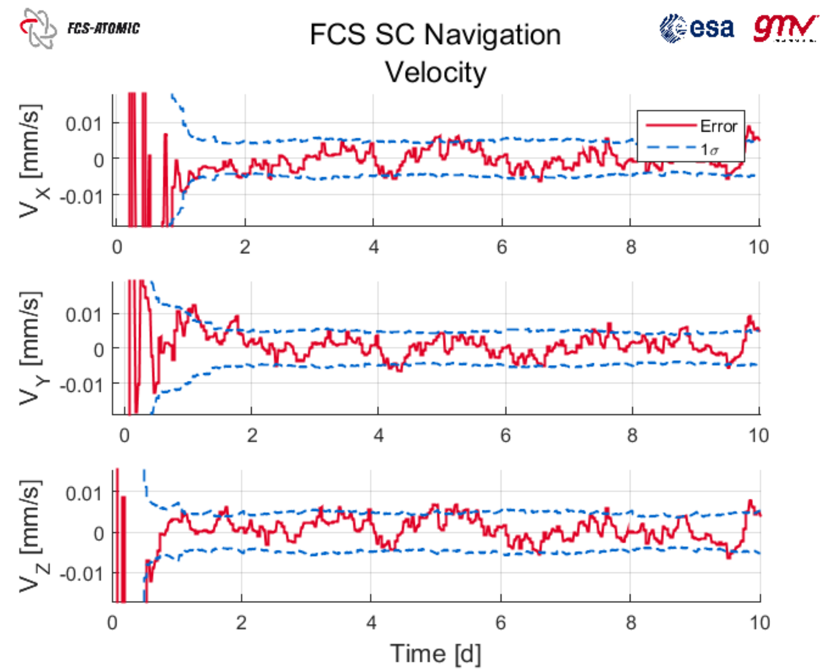
- SC State
- Process Noise
- Measurement Noise

GNC: Sequential UKF with centroiding measurements:

- SC State
- Process Noise
- Measurement Noise

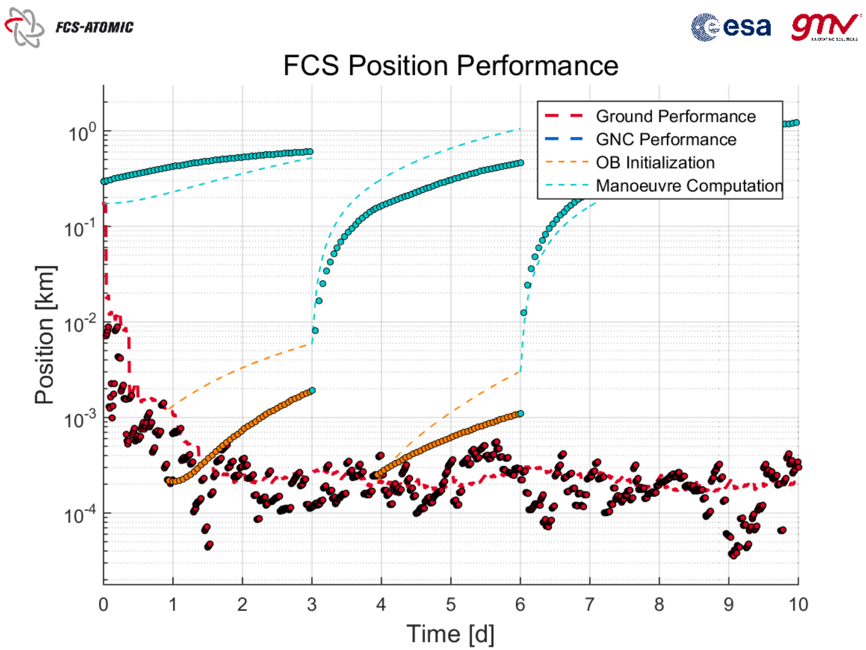
# Ground-only Reconstructed Performance

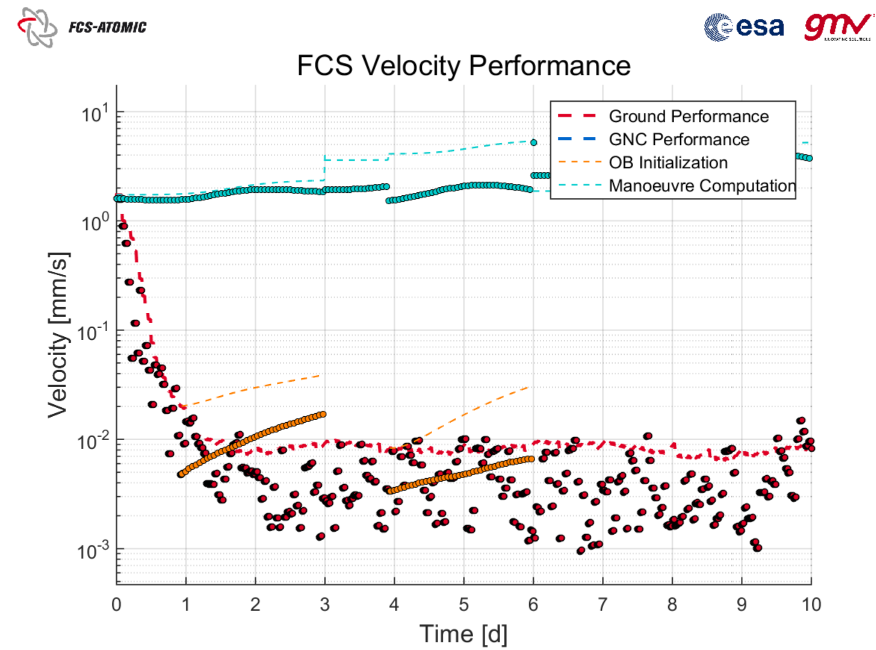


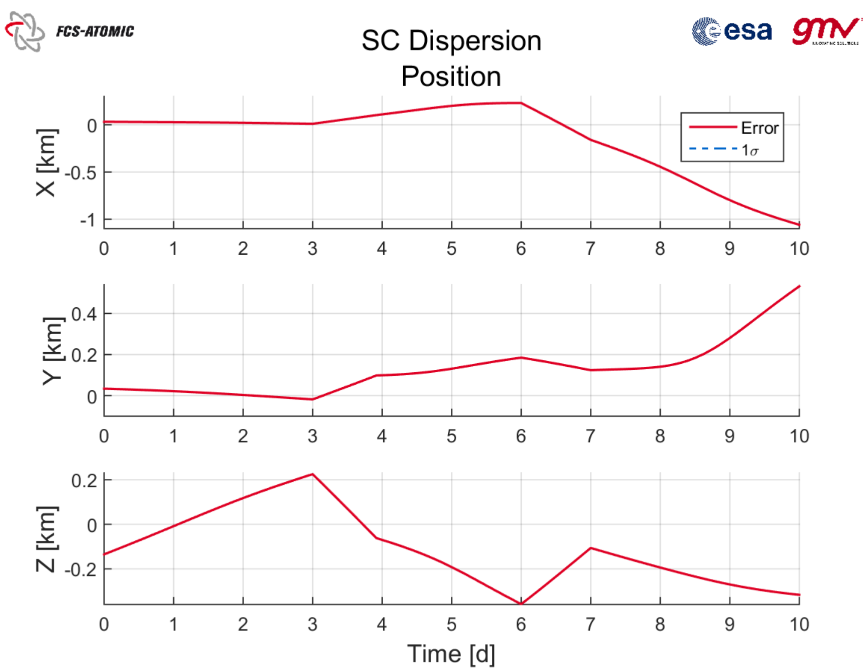
HERA

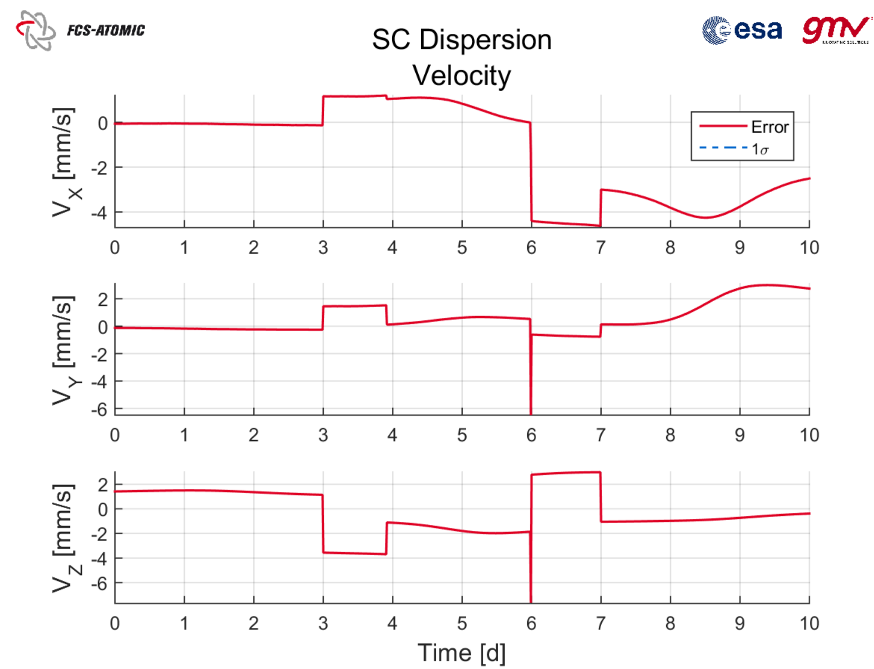
# Ground-only Predicted Performance



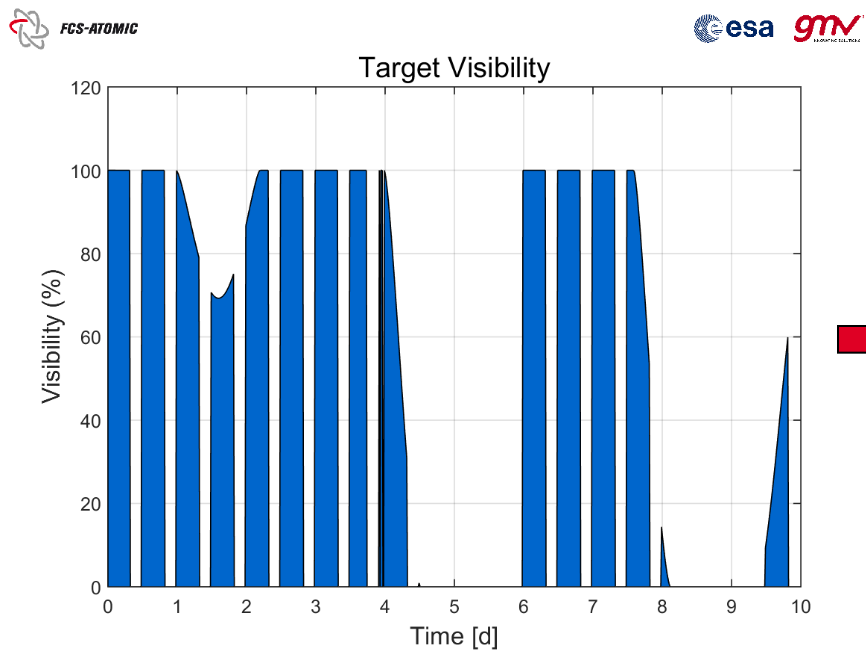



# Ground-only Dispersion Performance



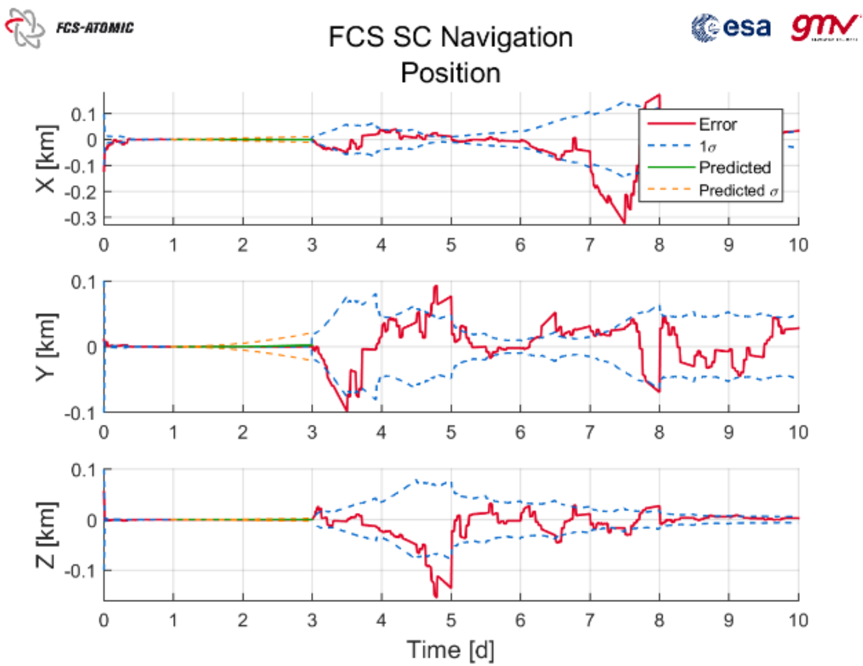



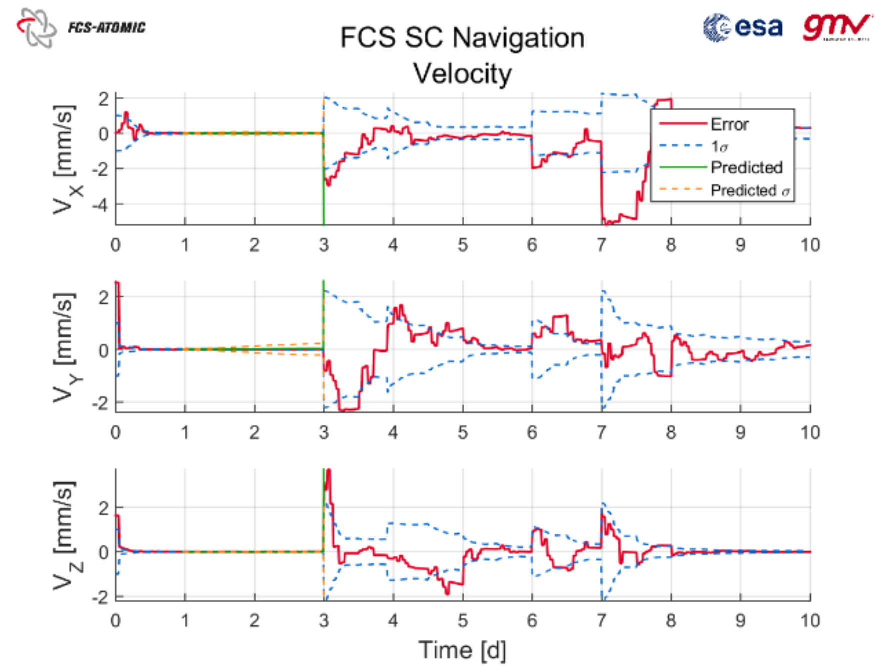
# Ground-only Pointing Performance




Target lost from camera's FOV

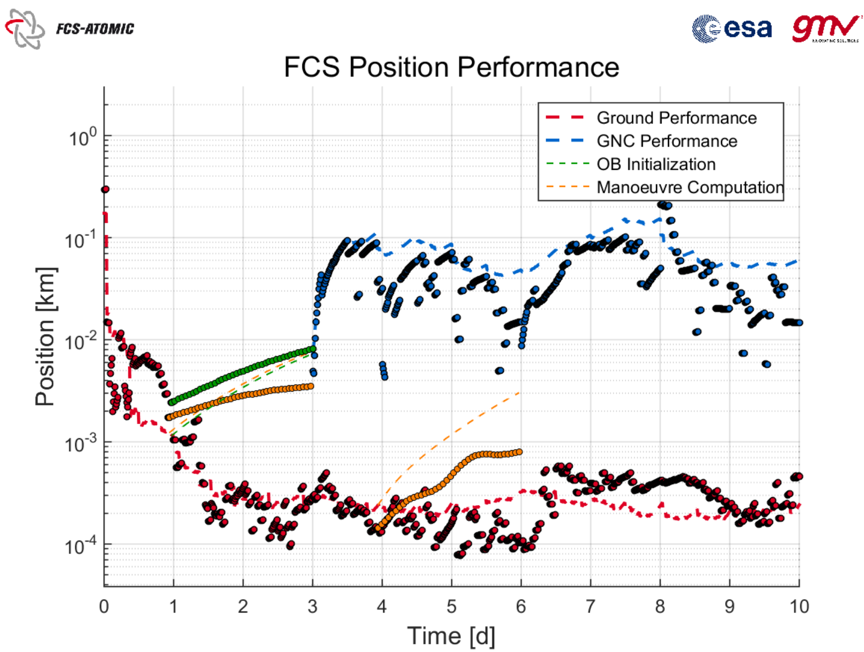
# Autonomous Pointing Navigation Performance

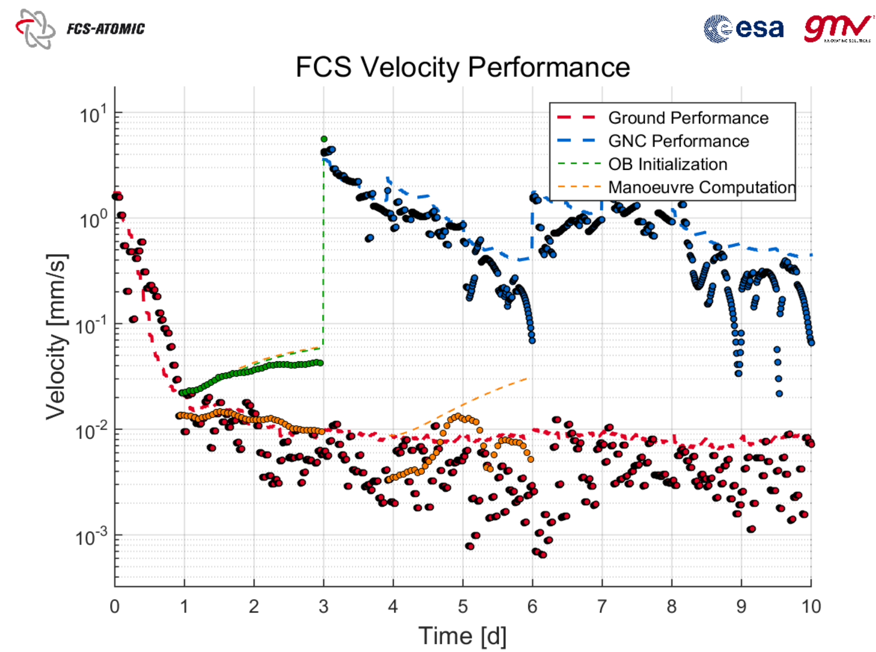



**Auto-GNC used only for payload pointing**

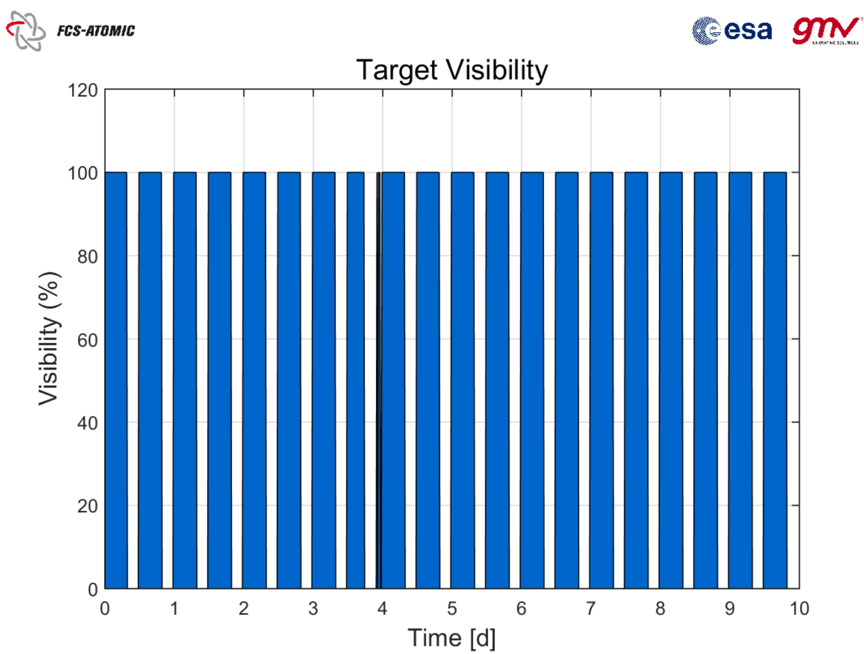
# Ground still computing manoeuvres



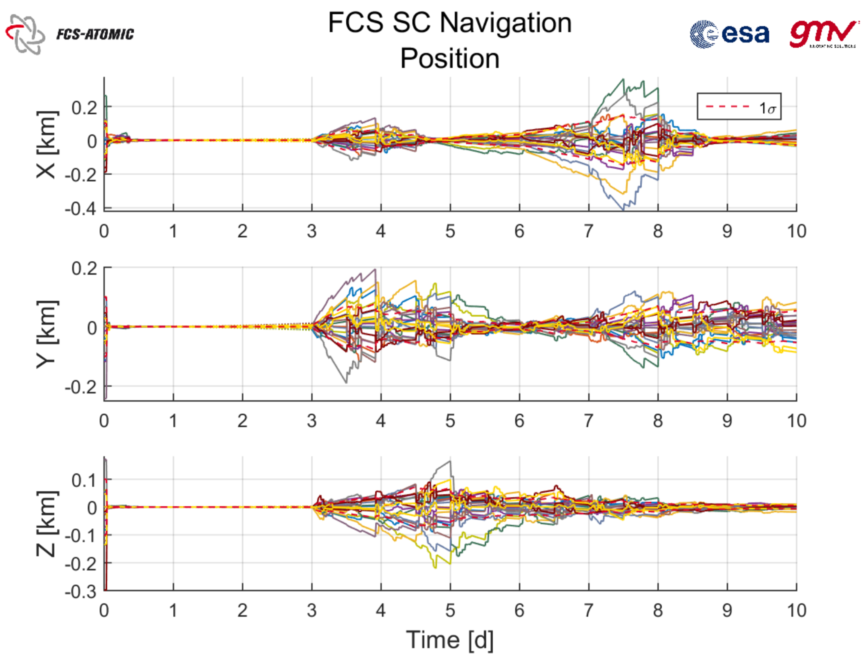

Dispersion remains unchanged

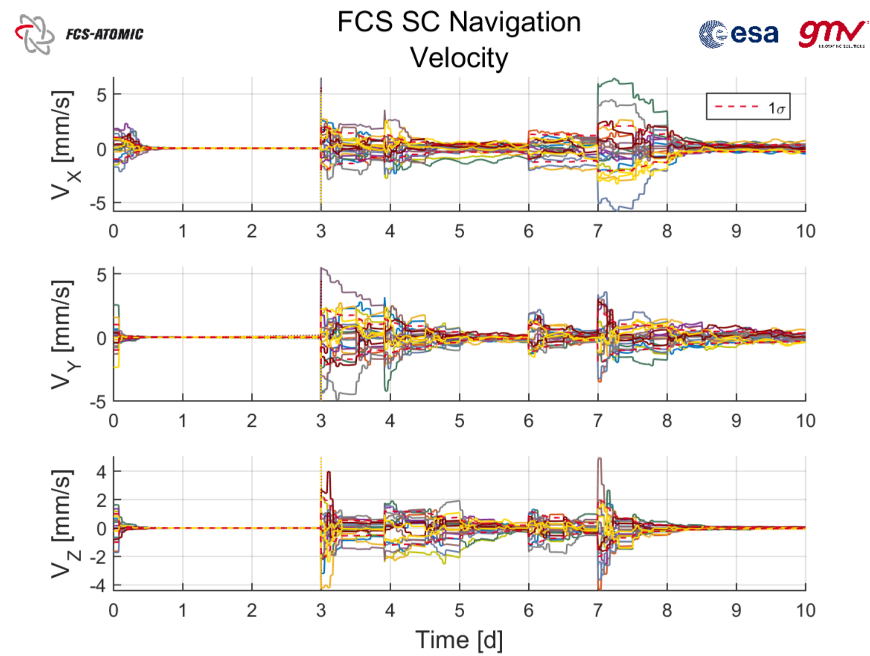
# Target is now permanently on the FOV



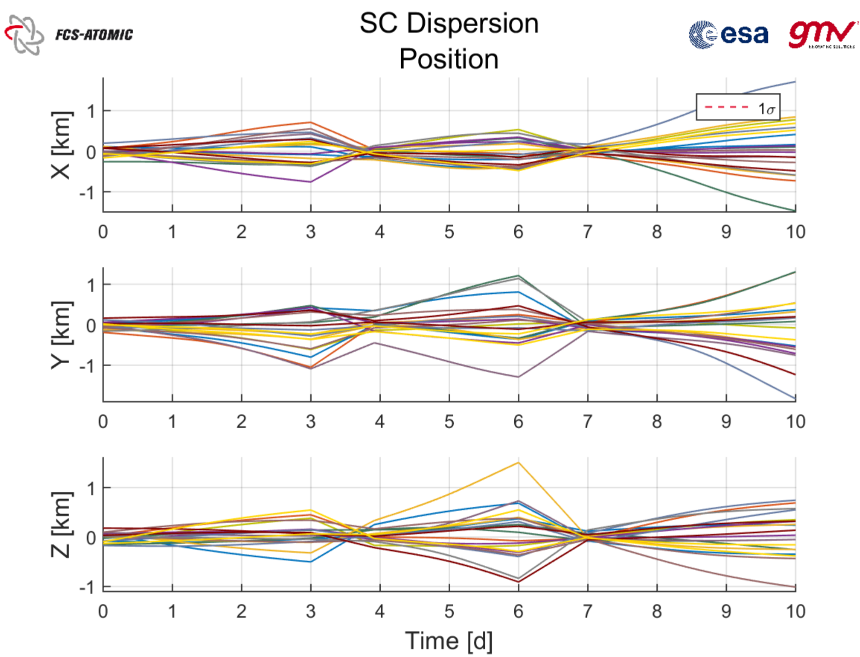

Target is kept in the camera's 5.5deg FOV

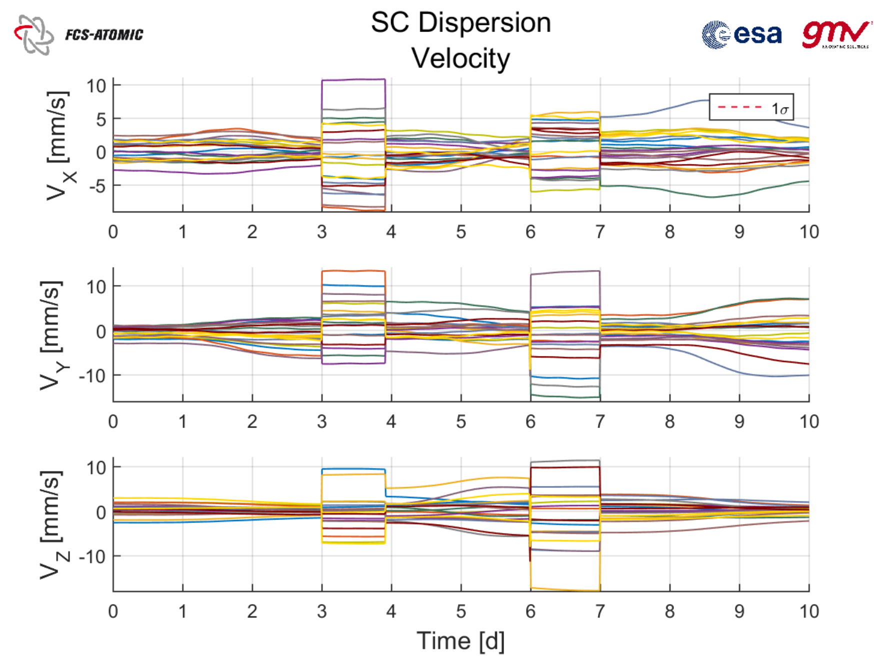
# A reduced MC run suggsts the covariance is indicative of the performance



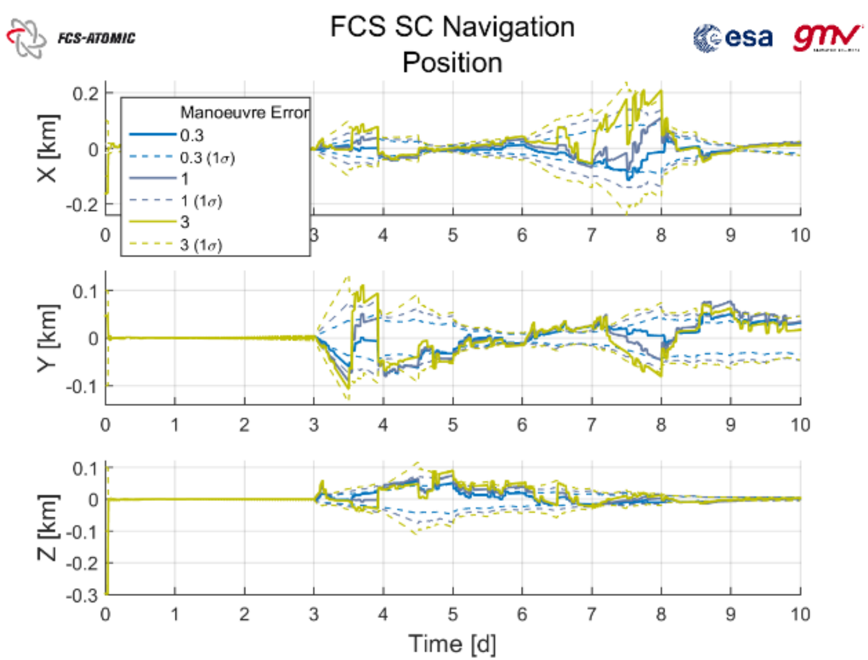



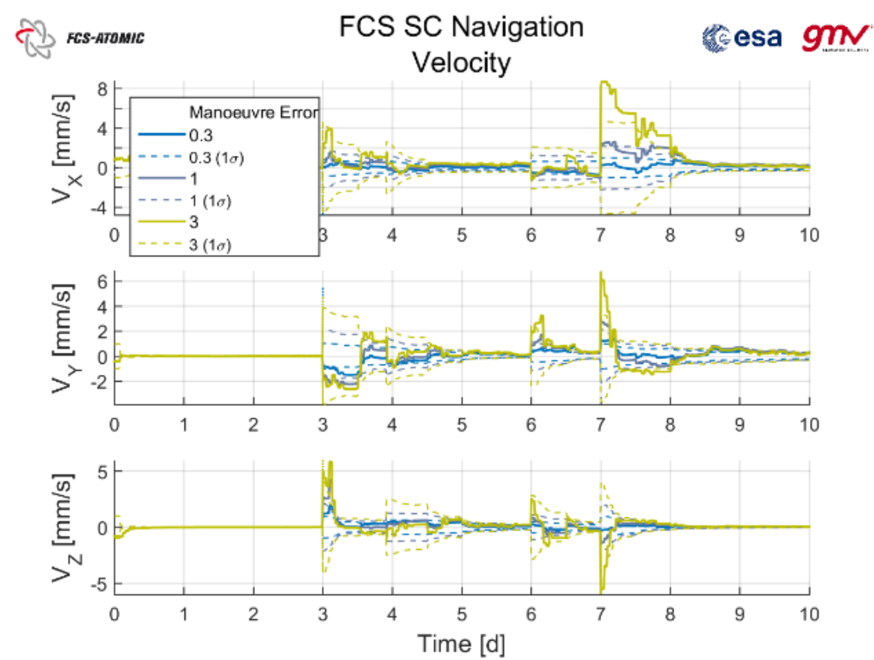
# MC Dispersion Results



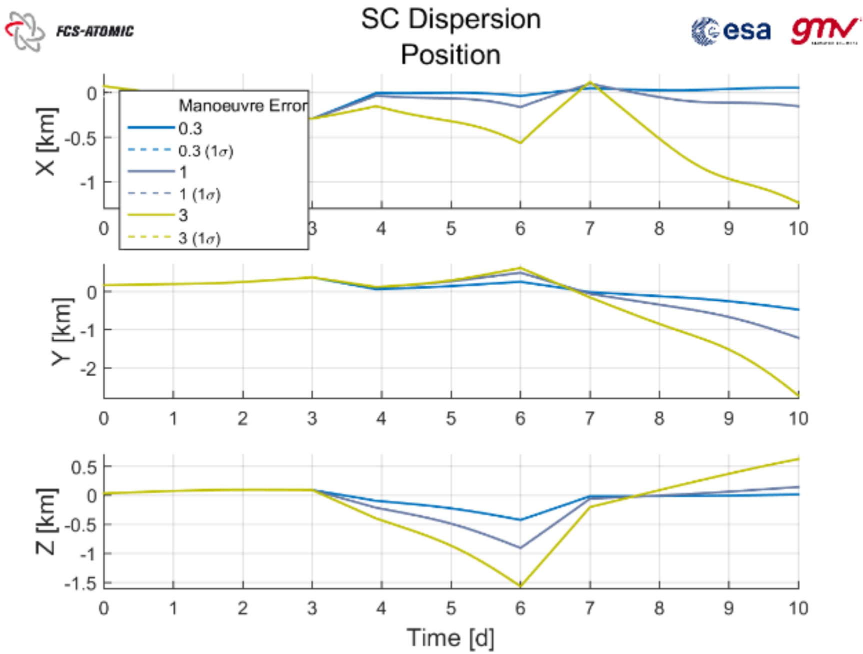



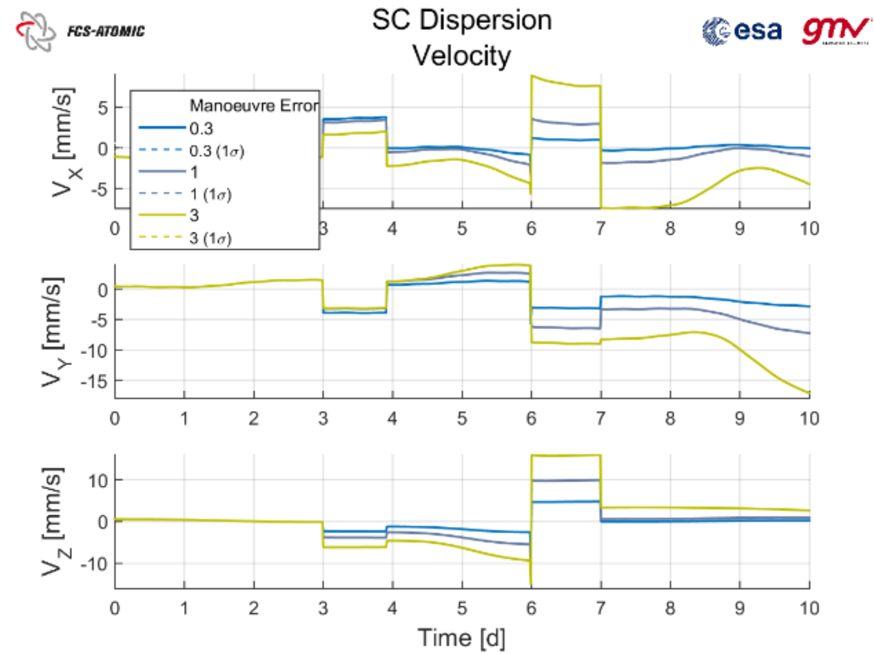
# Worst Case is used for a sensitivity analysis on the manoeuvre errors



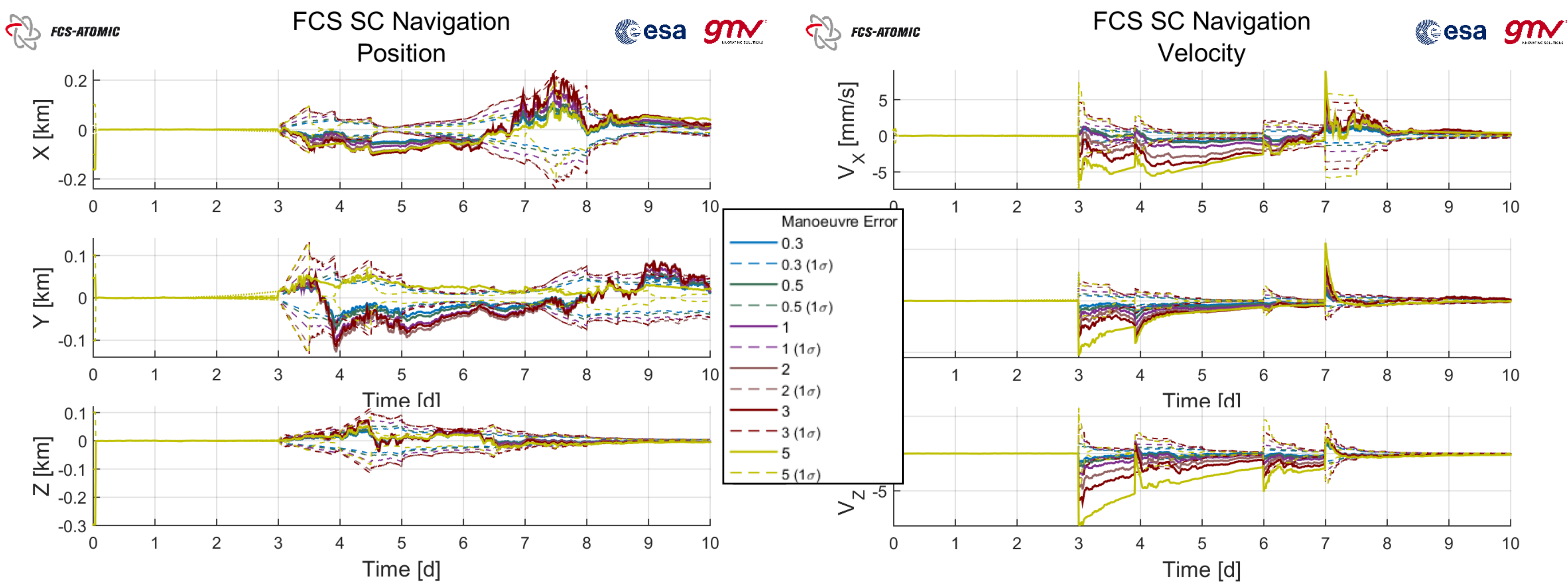
# Manoeuvre erros dominate the dispersion



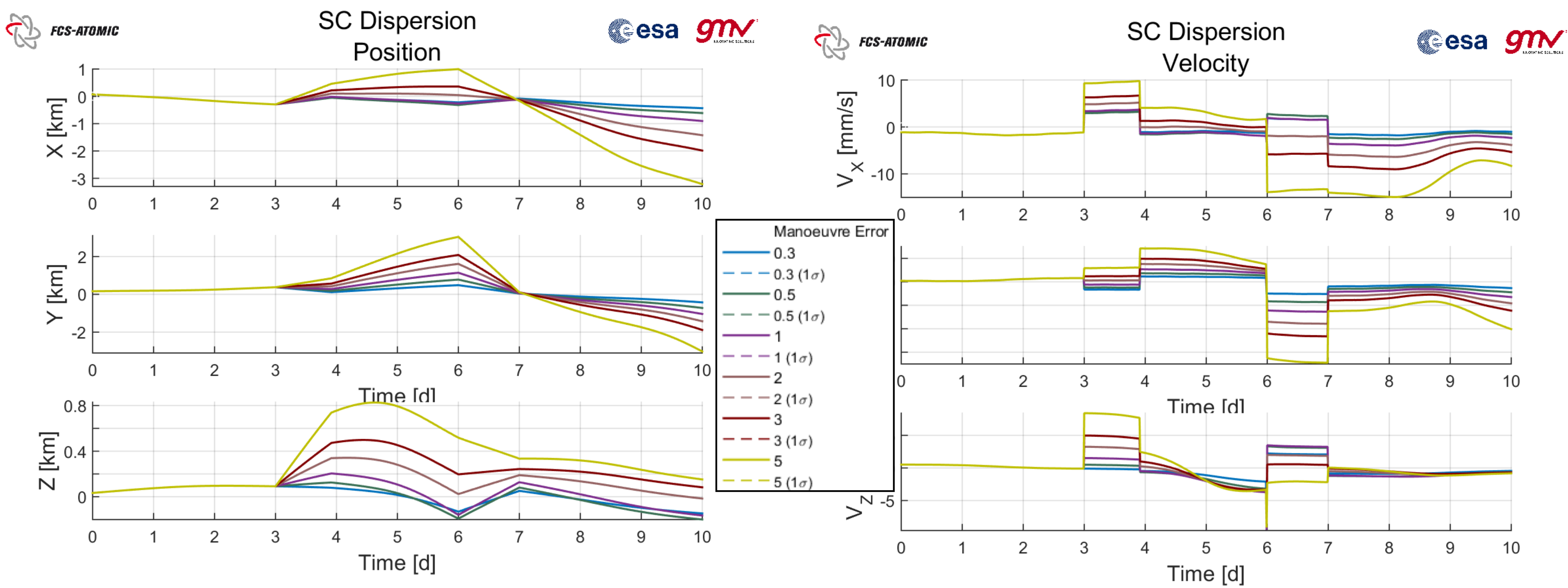




This FCS-ATOMIC feature is very helpful for the systems design!

# Performance Model Derivation for Simplified Analyses



# Dispersion Performance Model



# HERA Way Forward

- Develop a higher-fidelity manoeuvres model and assess the performance of IMU closed-looped manoeuvres

- Implement higher-fidelity on-board image processing algorithms

- Assess the possibility of having more precise RCS thrusters

- Assess the possibility of having autonomous correction to the ground-commanded $\Delta V$

# Conclusions

- The FCS Assessment with the FCS-ATOMIC Framework:

Allowed to design and validate the feasibility of the DCP strategy

Identified the minimum required autonomy level

Identified and analysed the system driving errors (RCS thrusters)

Derived and validated a performance model to the expected performance

FCS-ATOMIC FP

# G2G FCS ASSESSMENT

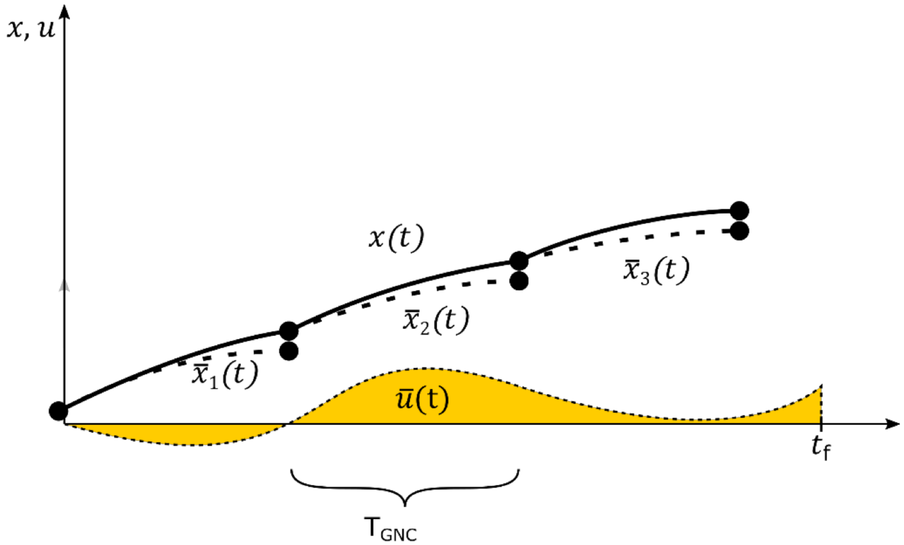
# G2G mission

- Electric propulsion orbit raising
- Assessment of the impact of the increased on-board autonomy

| Parameter | Variations |
|---|---|
| **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 12/07/2018 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.<br><br>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**. |
| **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** and **medium autonomy**.<br><br>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.<br><br>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 for sensitivity analysis: 80 and 480 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.<br><br>For the receiver performance, a nominal tracking threshold of **25 dBHz** will be assumed. A value of **30 dBHz** will also be analyzed to assess a degraded receiver performance.<br><br>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.<br><br>The analysis will be extended to initial values between **0.1 - 1.0 %** with a degradation between **1-10 %** per year. |
| **Time step** | **150s** |

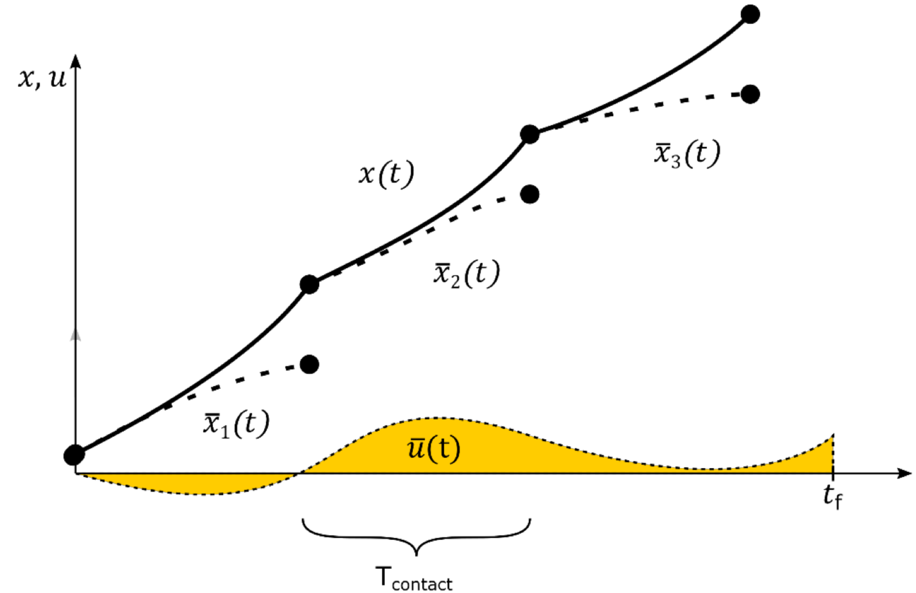
# Scenario 1: medium autonomy

- The guidance law is executed at every time step as it would be executed on-board.
- All relevant error models take into account the on-board knowledge of the process (i.e. can be worse than precise ground-based orbit determination).
- Periodic update of on-board parameters (like actual thrust level, mass) may also be incorporated.



# Scenario 2: No autonomy

- The same guidance law (as in scenario 1) is used to generate a reference trajectory using the ground based knowledge error models.
- The reference trajectory (thrust) is executed in open-loop until the next ground-update.
- At the next ground update, the trajectory is re-computed and the process iterates.



# Guidance law: Thrust direction control

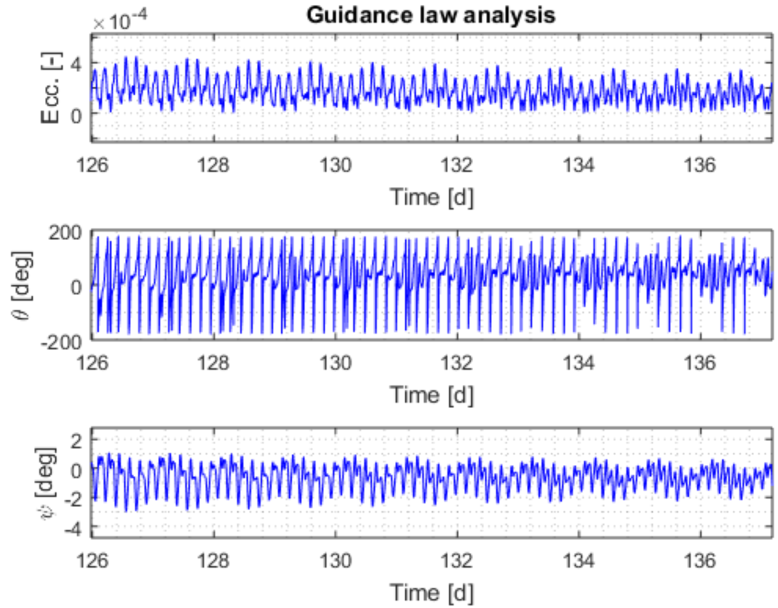
- Used as an alternative for the complex trajectory optimization strategies
- Guidance law expressed by:

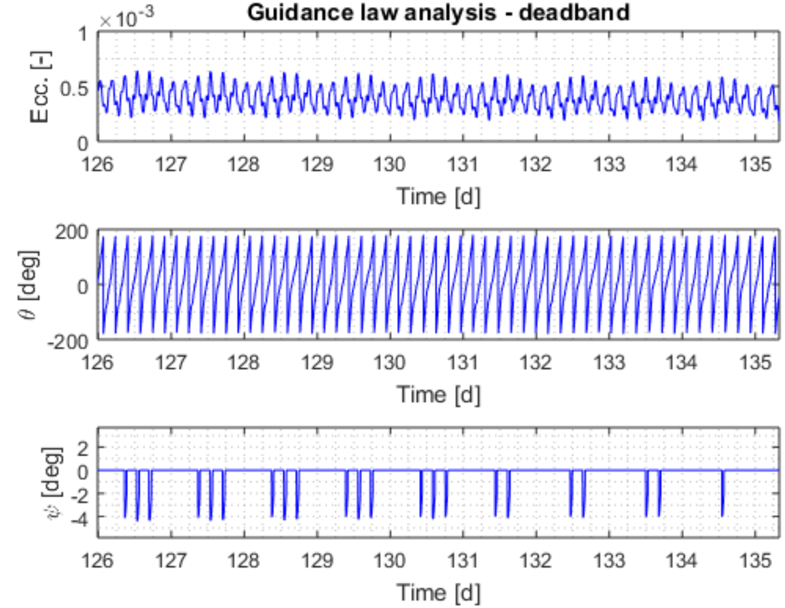
$$\psi = -k \sin(f)\, e$$

  - f: true anomaly
  - e: eccentricity
  - k: controller gain
  - $\psi$: thrust direction angle (in orbital plane) wrt along-path axis.
- Introduces stabilizing term into the eccentricity dynamical equation:

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

# Guidance law: jitter analysis




| Element | Nominal MA-1 case mean | Case with deadband |
|---|---|---|
| e [-] | 5,26E-04 | 5,47E-04 |
| i [deg] | 56,1935 | 56,1933 |
| RAAN [deg] | 40,4688 | 40,4959 |
| ΔV [m/s] | 2910,2741 | 2910,1672 |
| Time [days] | 333,7847 | 333,6857 |

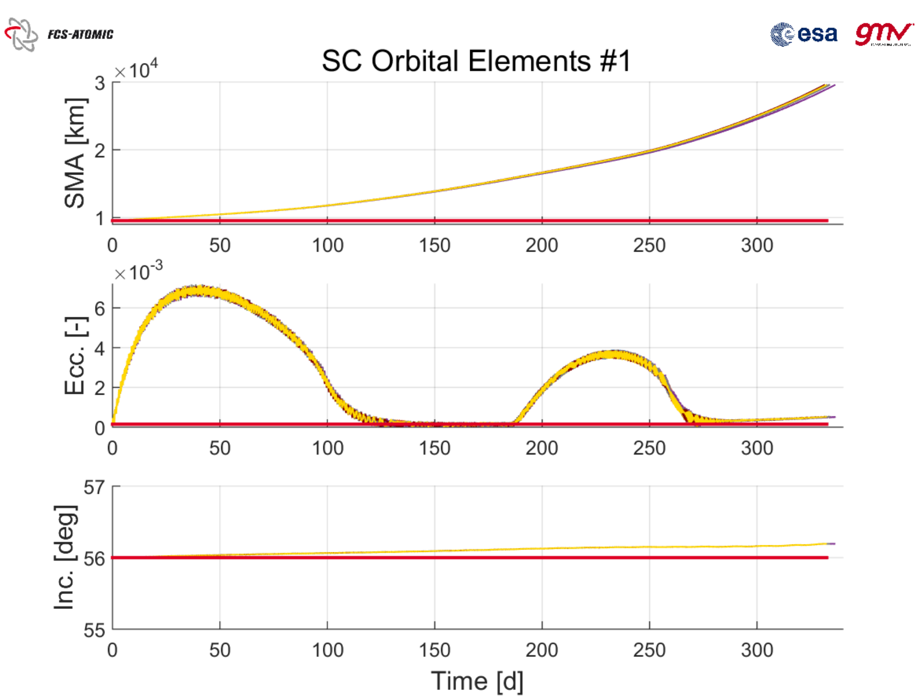
Conclusions:

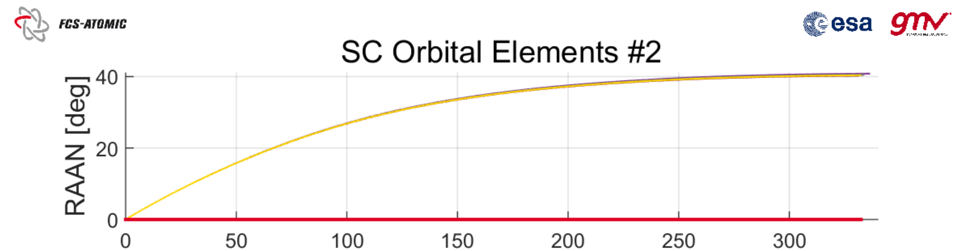
- Nominal control seems to act too sensitively in presence of near-circular orbit
- The deadband correctly neglects small eccentricity variations which are not necessary to be supressed
- No major impact on overall orbit raising performance

# Test plan – 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><br>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.<br>The results of the batch of runs will identify which combination of conditions (navigation and thruster errors) may produce worst cases. | 10 | Initial parameters:<br>• SMA – 9541 km<br>• Inclination - 56 deg<br>• Autonomy level – medium<br>• Nominal thrust – 180 mN<br>• GNSS receiver performance – 25 dBHz<br>• Initial thrust error – 0.56%<br>• Thrust degradation 2%/year | Performance model of GNSS-based Navigation + Measurements + Visibility (GNC)<br>Performance model of Error Dispersion + Thrust Performance |
| **Various Nominal Thrust Tests** | | | | |
| FCS-G2G-MA-2 | <u>Different nominal thrust</u><br>Assessment of impact of different nominal thrust on orbit raising time and performance. | 5 | Same as FCS-G2G-MA-1 but:<br>• Nominal thrust – 80 mN | Same as FCS-G2G-MA-1 |
| FCS-G2G-MA-3 | | 5 | Same as FCS-G2G-MA-1 but:<br>• Nominal thrust – 480 `mN | Same as FCS-G2G-MA-1 |
| **Various Initial SMA Tests** | | | | |
| FCS-G2G-MA-4 | <u>Different initial SMA</u><br>Assessment of impact of initial semi-major axis on orbit raising time and performance. | 5 | Same as FCS-G2G-MA-1 but:<br>• SMA – 9441 km | Same as FCS-G2G-MA-1 |
| FCS-G2G-MA-5 | | 5 | Same as FCS-G2G-MA-1 but:<br>• SMA – 9641 km | Same as FCS-G2G-MA-1 |
| **Robustness Testing – GNSS receiver performance** | | | | |
| FCS-G2G-MA-6 | <u>Sensitivity to GNSS receiver performance</u> | 5 | Same as FCS-G2G-MA-1 but:<br>• GNSS receiver performance – 30 dBHz | Same as FCS-G2G-MA-1 |
| **Robustness Testing – thruster errors** | | | | |
| FCS-G2G-MA-7 | <u>Sensitivity to thruster initial error</u> | 5 | Same as FCS-G2G-MA-1 but:<br>• Initial thrust error – 0.1% | Same as FCS-G2G-MA-1 |
| FCS-G2G-MA-8 | | 5 | Same as FCS-G2G-MA-1 but:<br>• Initial thrust error – 1% | Same as FCS-G2G-MA-1 |
| FCS-G2G-MA-9 | <u>Sensitivity to thruster degradation</u> | 5 | Same as FCS-G2G-MA-1 but:<br>• Thrust degradation 1%/year | Same as FCS-G2G-MA-1 |
| FCS-G2G-MA-10 | | 5 | Same as FCS-G2G-MA-1 but:<br>• Thrust degradation 10%/year | Same as FCS-G2G-MA-1 |

# Medium autonomy – nominal case




| 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 |

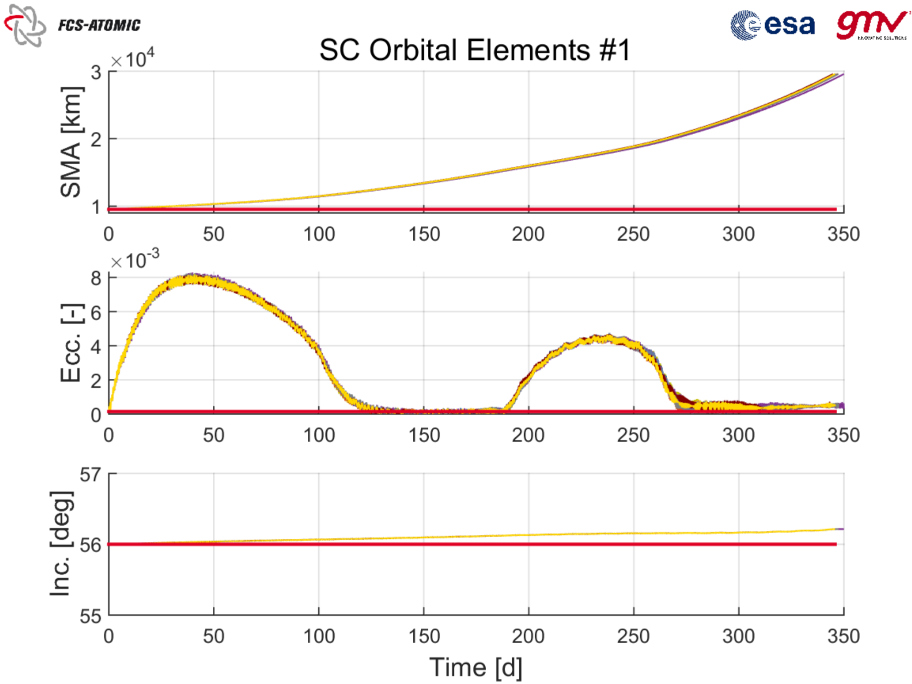
# Medium autonomy - sensitivity

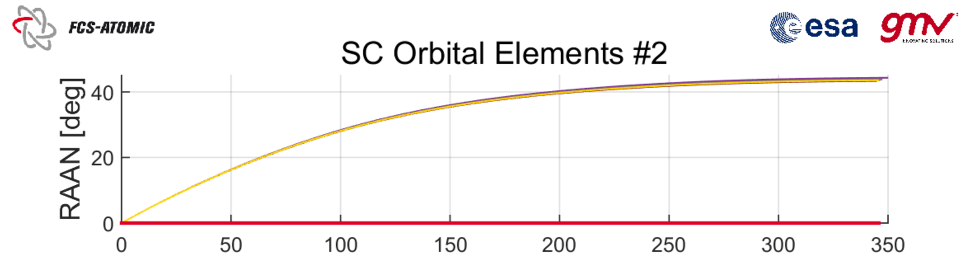
| Case | RAAN σ [deg] | Mean ΔV [m/s] | Mean Time [d] | Time σ [d] |
|---|---|---|---|---|
| MA-1 | 0,149 | 2910,274 | 333,78 | 1,318 |
| MA-2 | 0,187 | - | - | - |
| MA-3 | 0,073 | +1,77% | -205,14 | 0,563 |
| MA-4 | 0,177 | +1,37% | +5,21 | 1,491 |
| MA-5 | 0,162 | -1,35% | -3,99 | 1,486 |
| MA-6 | 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 |

# Test plan – no autonomy

| Test case | Test description | Batch size | Scenario configuration | Error sources |
|---|---|---|---|---|
| **Nominal No Autonomy Case** | | | | |
| FCS-G2G-NA-1 | Nominal case of no autonomy scenario.<br>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.<br>The results of the batch of runs will identify which combination of conditions (navigation and thruster errors) may produce worst cases. | 10 | Initial parameters:<br>• SMA – 9541 km<br>• Inclination - 56 deg<br>• No autonomy<br>• Nominal thrust – 180 mN<br>• GNSS receiver performance – 25 dBHz<br>• Initial thrust error – 0.56%<br>• Thrust degradation - 2%/year<br>• Ground update period – 7 days | Performance model of Ground GNSS-based OD (FDS)<br>Performance model of Error Dispersion + Thrust Performance |
| **Various Nominal Thrust Tests** | | | | |
| FCS-G2G-NA-2 | Different nominal thrust<br>Assessment of impact of different nominal thrust on orbit raising time and performance. | 5 | Same as FCS-G2G-NA-1 but:<br>• Nominal thrust – 80 mN | Same as FCS-G2G-NA-1 |
| FCS-G2G-NA-3 | | 5 | Same as FCS-G2G-NA-1 but:<br>• Nominal thrust – 480 mN | Same as FCS-G2G-NA-1 |
| **Various Initial SMA Tests** | | | | |
| FCS-G2G-NA-4 | Different initial SMA<br>Assessment of impact of initial semi-major axis on orbit raising time and performance. | 5 | Same as FCS-G2G-NA-1 but:<br>• SMA – 9441 km | Same as FCS-G2G-NA-1 |
| FCS-G2G-NA-5 | | 5 | Same as FCS-G2G-NA-1 but:<br>• SMA – 9641 km | Same as FCS-G2G-NA-1 |
| **Robustness Testing – GNSS receiver performance** | | | | |
| FCS-G2G-NA-6 | Sensitivity to GNSS receiver performance | 5 | Same as FCS-G2G-NA-1 but:<br>• GNSS receiver performance – 30 dBHz | Same as FCS-G2G-NA-1 |
| **Robustness Testing – thruster errors** | | | | |
| FCS-G2G-NA-7 | Sensitivity to thruster initial error | 5 | Same as FCS-G2G-NA-1 but:<br>• Initial thrust error – 0.1% | Same as FCS-G2G-NA-1 |
| FCS-G2G-NA-8 | | 5 | Same as FCS-G2G-NA-1 but:<br>• Initial thrust error – 1% | Same as FCS-G2G-NA-1 |
| FCS-G2G-NA-9 | Sensitivity to thruster degradation | 5 | Same as FCS-G2G-NA-1 but:<br>• Thrust degradation 1%/year | Same as FCS-G2G-NA-1 |
| FCS-G2G-NA-10 | | 5 | Same as FCS-G2G-NA-1 but:<br>• Thrust degradation 10%/year | Same as FCS-G2G-NA-1 |
| **Various ground update periods** | | | | |
| FCS-G2G-NA-11 | Sensitivity to ground updates frequency | 5 | Same as FCS-G2G-NA-1 but:<br>• Ground update period – 3 days | Same as FCS-G2G-NA-1 |
| FCS-G2G-NA-12 | | 5 | Same as FCS-G2G-NA-1 but:<br>• Ground update period – 5 days | Same as FCS-G2G-NA-1 |

# No Autonomy – nominal case




| 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 |

# No autonomy - sensitivity

| 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 |

# Medium vs no autonomy

- In general the medium autonomy approach outperforms the no autonomy scenarios both in deltaV and in orbit raising duration

| Case | RAAN σ [deg] | | Mean ΔV [m/s] | | Mean Time [d] | | Time σ [d] | |
|---|---|---|---|---|---|---|---|---|
| | MA-x | NA-x | MA-x | NA-x | MA-x | NA-x | MA-x | NA-x |
| MA-1/NA-1 | 0,149 | +69,62% | 2910,274 | +2,88% | 333,78 | +4,00% | 1,318 | 7,45% |
| MA-2/NA-2* | 0,187 | +65,84% | - | - | - | - | - | - |
| MA-3/NA-3 | 0,073 | -74,65% | 2961,713 | +9,56% | 128,65 | +11,52% | 0,563 | -72,40% |
| MA-4/NA-4 | 0,177 | +67,22% | 2950,250 | +3,05% | 338,99 | +4,25% | 1,491 | 7,51% |
| MA-5/NA-5 | 0,162 | +46,37% | 2871,033 | +2,72% | 329,79 | +3,84% | 1,486 | 0,34% |
| MA-6/NA-6 | 0,170 | +61,83% | 2910,391 | +2,87% | 334,41 | +4,00% | 1,460 | 6,17% |
| MA-7/NA-7 | 0,030 | +75,36% | 2910,476 | +2,86% | 333,40 | +3,98% | 0,263 | -2,20% |
| MA-8/NA-8 | 0,288 | +75,72% | 2909,993 | +2,87% | 335,28 | +4,03% | 2,579 | 8,33% |
| MA-9/NA-9 | 0,165 | +70,89% | 2910,385 | +2,96% | 332,85 | +4,09% | 1,465 | 1,81% |
| MA-10/NA-10 | 0,177 | +103,83% | 2909,782 | +2,21% | 347,67 | +3,41% | 1,608 | 26,68% |
| MA-1/NA-11 | 0,149 | +24,27% | 2910,274 | +2,00% | 333,78 | +3,27% | 1,318 | 16,59% |
| MA-1/NA-12 | 0,149 | +61,45% | 2910,274 | +1,97% | 333,78 | +3,09% | 1,318 | 21,12% |

# Conclusions and Recommendations

- FCS-ATOMIC tool allowed analysis of a challenging scenario
  - Long duration of scenarios
  - Effective error modelling
  - Easy generation of new scenarios based on the nominal one
- Advantages of medium autonomy approach demonstrated
- Further improvements:
  - Guidance law to incorporate deadband
  - Guidance law with gain changes depending on altitude
  - Increased fidelity of ground processes
  - Increased fidelity of guidance algorithms

www.gmv.com

# THANK YOU

BLOG