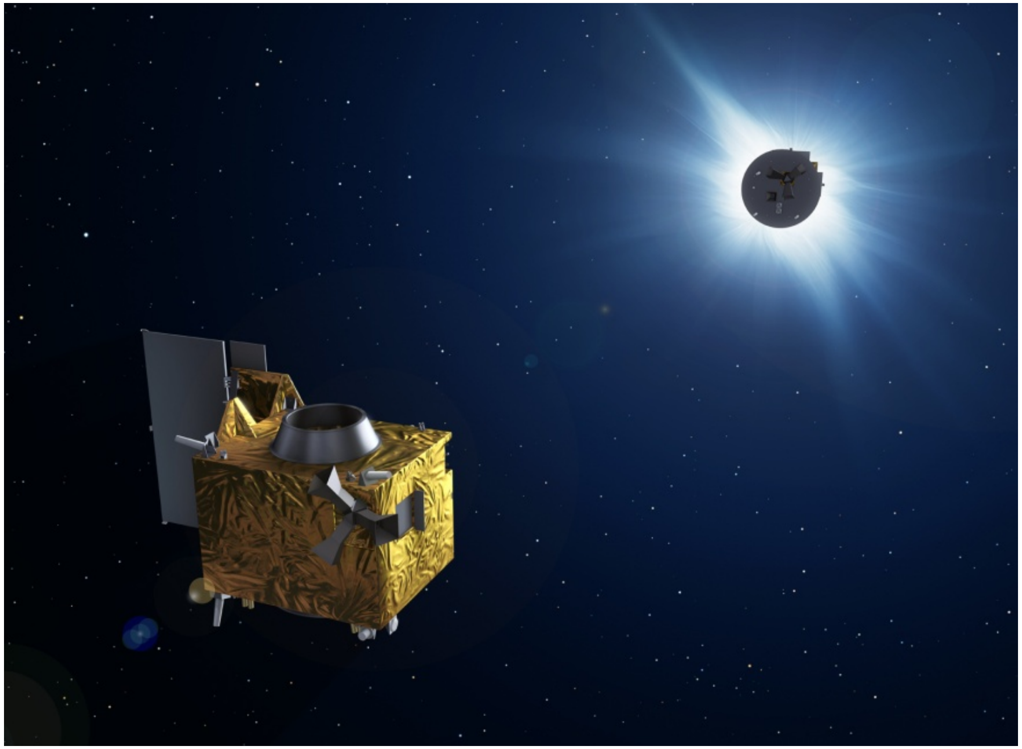
5th SFFMT Conference, 2013 May 30



PROBA-3 Formation Flying
High Precision Control

Aeroespacial

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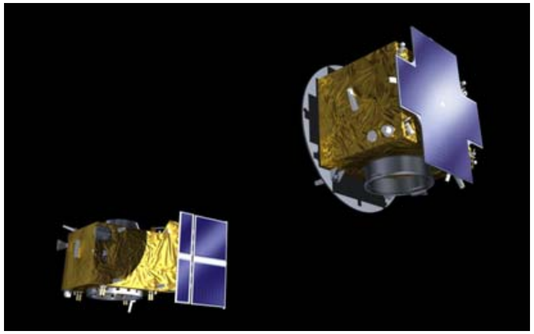
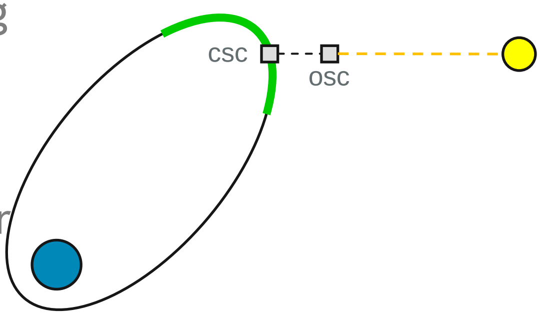
PROBA-3 Mission Overview

PRoject for On-Board Autonomy

- In orbit demonstration of precise Formation Flying (FF) techniques and technologies
- PROBA-3 consists of two spacecraft in a highly elliptic orbit:
  - Occulter Spacecraft (OSC): Master, active position controlled (during FF), blocks Sun to cast shadow on CSC
  - Coronagraph Spacecraft (CSC): Slave, carries payload, carries high precision metrology, free orbit drifting (during FF)
  - Flight-Formation (FF) near apogee during 6 hours
  - After apogee they break formation and is re-acquired after perigee pass
  - Required FF precision: 1mm from 25m to 250m inter satellite distance
  - Additional experiments: FF Manoeuvres, 6DoF thruster based control





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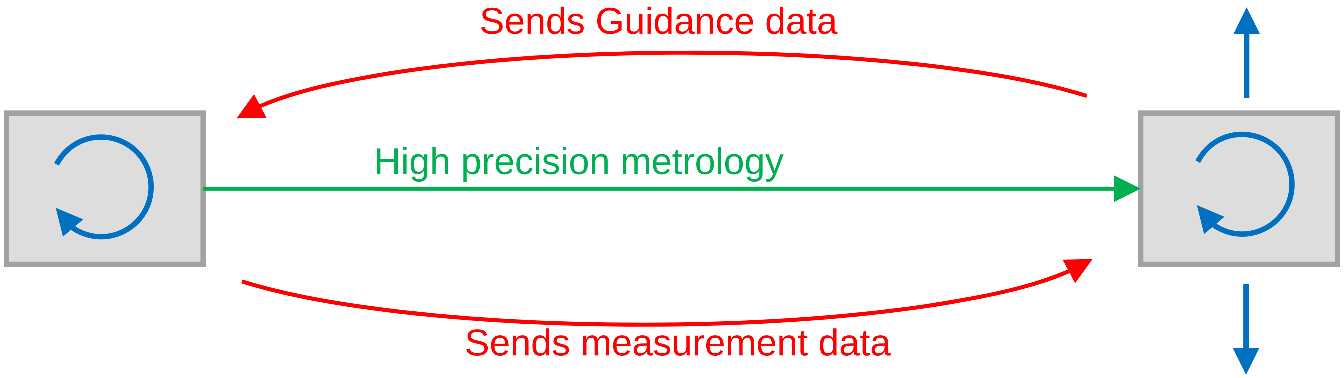
GNC Configuration



CSC:

- Slave (From GNC SW point of view)
- No position control → free drifting
- Carries metrology system
- RW, STR for attitude control
- Attitude control as independent module (SC-GNC) → receives absolute pointing guidance profile
- SC-GNC sends attitude data to FF-NAV
- Stringent attitude requirements

OSC:

- Master (From GNC SW point of view)
- 10mN thruster for relative position control
- RW, STR for attitude control
- Attitude control as independent module (SC-GNC) → receives absolute pointing guidance profile
- SC-GNC sends attitude data to FF-NAV
- Stringent position requirements
- Relaxed attitude requirements

Inter satellite link (ISL) delay = 3 sec

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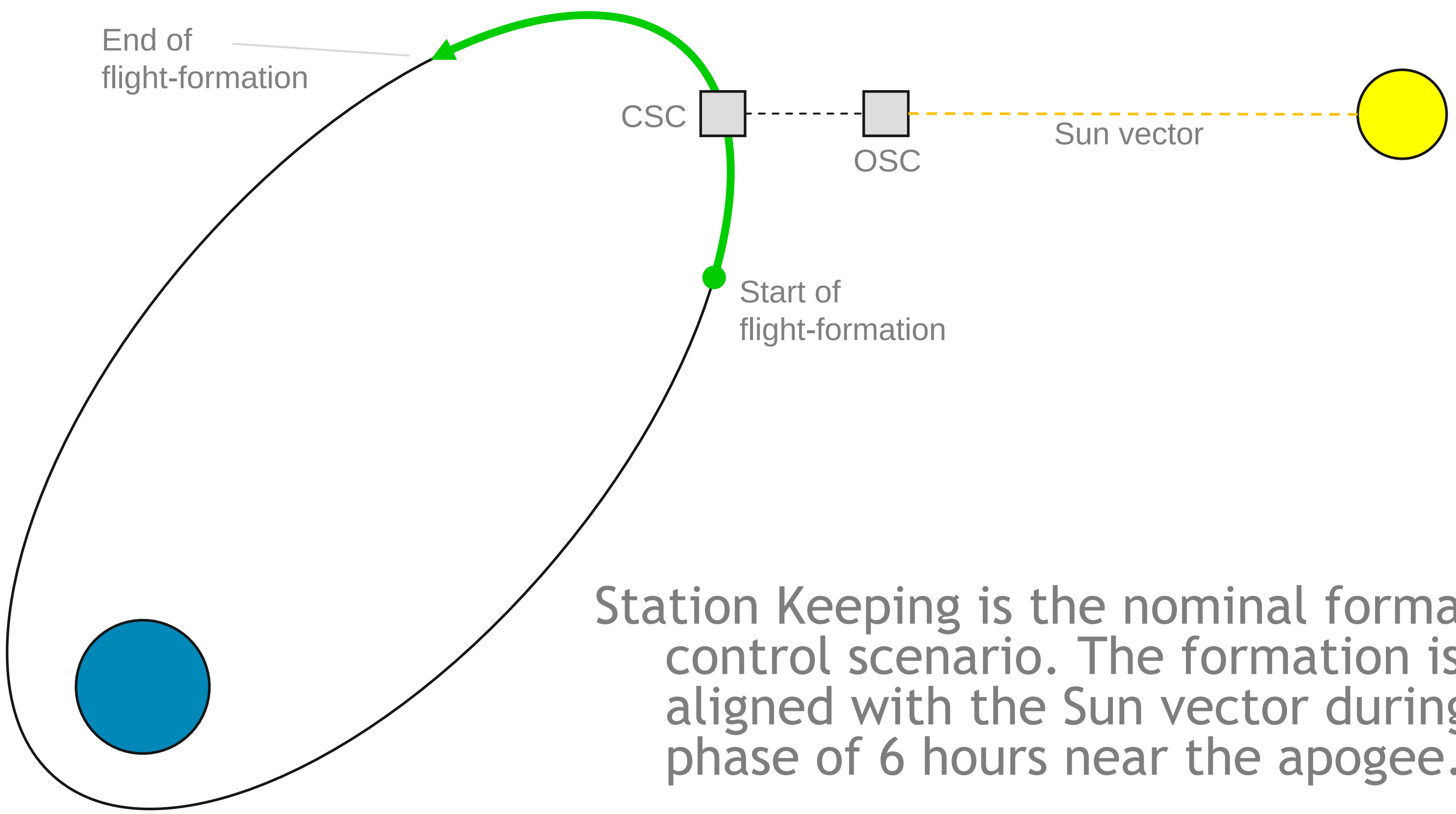
Control Objectives (High performance controller)

Station Keeping:



Station Keeping is the nominal formation control scenario. The formation is co-aligned with the Sun vector during a phase of 6 hours near the apogee.

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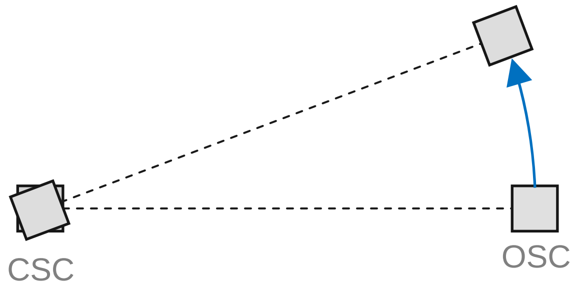
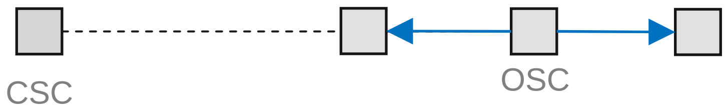
Control Objectives (High performance controller)

Apart from nominal Station Keeping, a set manoeuvres is to be performed as well as part of the experiments.

Retargeting Manoeuvre:



Resizing Manoeuvre:



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Performance Requirements

Error	PROBA-3 Positioning Requirements: During Station Keeping	PROBA-3 Positioning Requirements: During Manoeuvres	Remarks
RDE_X	**1.5 mm**	**2.5 mm**	1σ. Error along nominal formation direction (longitudinal error)
RDE_Y RDE_Z	**0.5 mm** (ISD up to 40m) **0.73 mm** (ISD up to 160m) **1.2 mm** (ISD up to 250m)	**2.5 mm**	1σ Lateral errors to nominal formation direction

S/C	Error	PROBA-3 Pointing Requirements	Remarks
CSC	AAE_X	300 arc-sec	1σ. Around LOS
	$AAE_{Y,Z}$	**2.8 arc-sec**	1σ. Across LOS
	$AAME_X$	30 arc-sec	1σ. Around LOS
	$AAME_{Y,Z}$	**1.25 arc-sec**	1σ. Across LOS
OSC	AAE_X	900 arc-sec	1σ. Around LOS
	$AAE_{Y,Z}$	30 arc-sec	1σ. Across LOS
	$AAME_X$	300 arc-sec	1σ. Around LOS
	$AAME_{Y,Z}$	5 arc-sec	1σ. Across LOS

Legend:

- RDE: Relative Displacement Error
- AAE: Absolute Attitude Error
- AAME: Absolute Attitude Measurement Error
- ISD: Inter-Satellite Distance
- LOS: Line of Sight

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Design Approach and Drivers

- H_∞ synthesis and μ-analysis to design and analyse the high performance FF controller
- Relative orbital dynamics used for plant modelling (based on Yamanaka-Ankersen equations for elliptic orbits)
- Main external perturbation sources: Gravity gradient and solar radiation pressure
- Combination of feedback and feedforward to improve responsiveness, especially during manoeuvres
- Actuators: Thrusters → Non-linear element → PWM
- Attitude controller is an independent module (SC-GNC SW) → controls absolute attitude with RW
- But attitude and relative position are not entirely decoupled and this is taken into account in control problem posing

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Coupling between Position and Attitude

- Attitude and Relative Position are coupled within the control problem, through both Dynamics (i.e. equations of motion) and Navigation
- Attitude controller is designed in parallel by another company → Not possible to have simultaneous 6DoF control synthesis
- Dynamic interaction between attitude and position is reduced by imposing design requirements, e.g.:
    1. Different controller bandwidths → attitude control bandwidth is higher than that of the position control
    2. Avoid too much thruster activity during position control → to reduce the average thruster based torque perturbations
    3. Quantify the low thruster torque perturbation due to the gravity gradient and specify as disturbance rejection requirement
- The attitude controller dynamics are to be included as a perturbation source within the H_∞ synthesis

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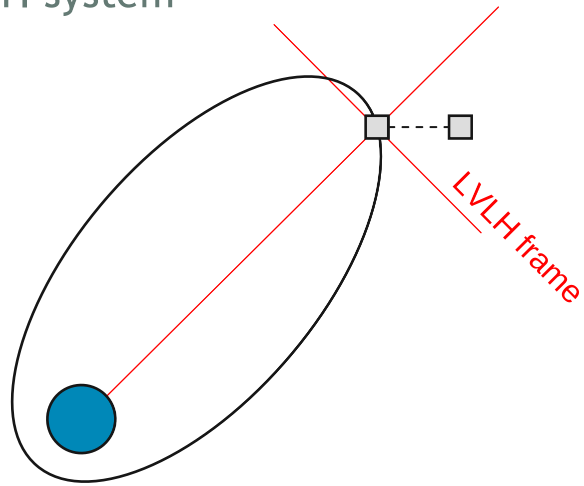
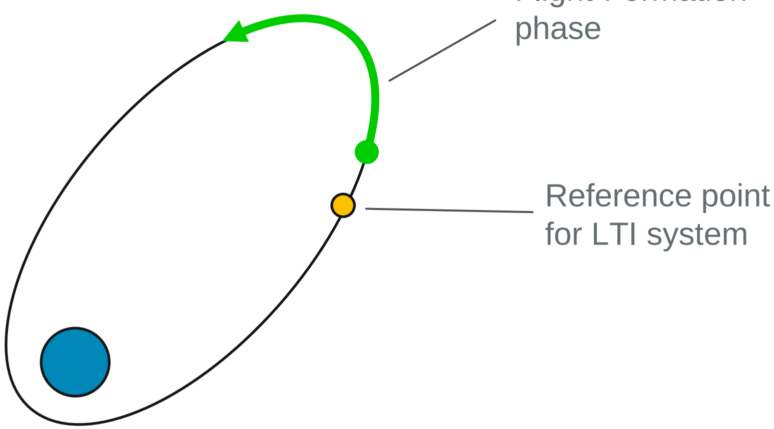
Plant modelling

- The relative orbital dynamics are expressed in the Local Vertical Local Horizon (LVLH) reference frame → NAV, GUI & CTRL are expressed in the LVLH frame
- The relative orbital dynamics equations for an elliptic orbit (Yamanaka-Ankersen) are linearised wrt to the CSC (i.e. reference point on the orbit) → decoupled in-plane and out-of-plane motion
- The in-plane motion is a MIMO system and the out-of-plane motion is a SISO system
- The linearised equations are time varying as the orbital rate changes with time → A conservative reference point with stronger MIMO cross coupling is chosen to obtain an LTI system





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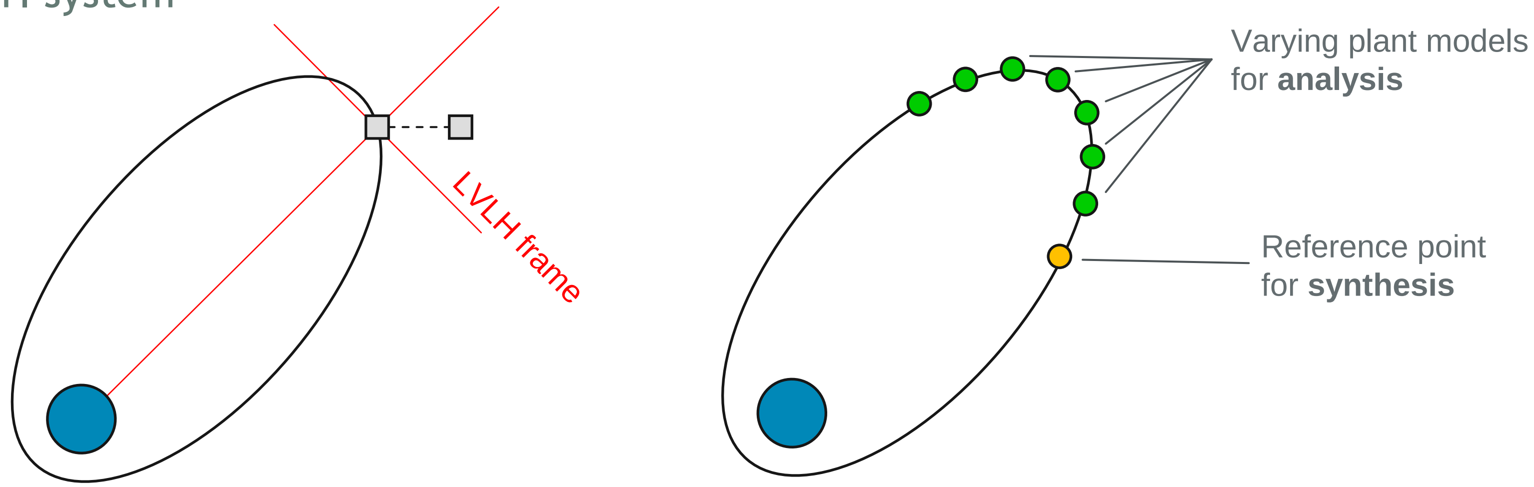

Feedforward control contribution

The controller will consist of a feedback and a feedforward term.

The Guidance module will provide the feedback contribution contains:

1. Acceleration profiles of the manoeuvres
2. Estimated gravity gradient acceleration
3. Estimated solar radiation pressure

NOTE: Even though the gravity gradient and solar radiation pressure are compensated through a feedforward term, the feedback control will be designed to be able to cope with them.

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Thruster Actuation

- Linear control commands are converted into a series of thrusters pulses through Pulse Width Modulation (PWM)
- HW specifications impose a limitation on total number of firings → PWM frequency is bounded
- The GNC runs at 1Hz and the PWM frequency is currently set at 0.05 Hz → PWM drives the upper limit of the controller bandwidth
- The controller frequency (1Hz) is faster than the PWM (0.05Hz) → The controller will observe the thruster pulse pattern → error signal smoothing is desired

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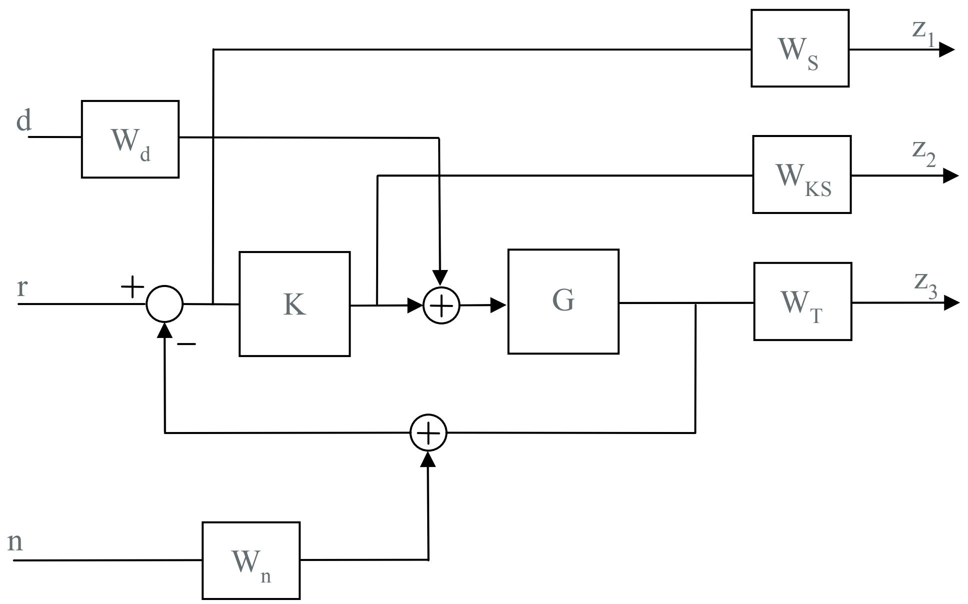
H_∞ Synthesis

A control synthesis tool has been created within the H_∞ framework



d: disturbance force
r: reference command
n: noise of Navigation
K: Controller
G: S/C plant model
$\mathbf{W_T}$: bounds T (upper limit of the bandwidth and also useful to include robustness properties).
$\mathbf{W_S}$: bounds S (to suppress low frequency external disturbance).
$\mathbf{W_{KS}}$: Imposes bounds on the control command, useful for adding noise smoothing filters.
$\mathbf{W_d}$: magnitude scaling and frequency range of the external disturbance.
$\mathbf{W_n}$: magnitude scaling and frequency range of the Navigation errors.

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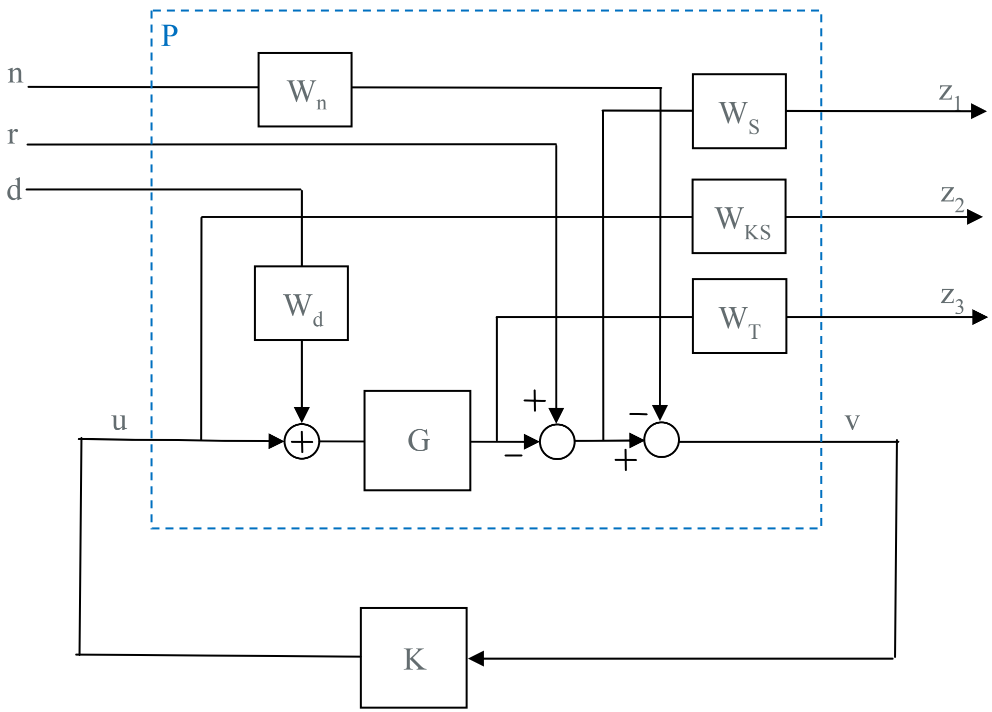
H_∞ Synthesis

- Augmented generalised plant P is obtained
- Analytical minimum realisation state-space representation is derived as a function of the individual G and W state-space matrices



$$\dot{\bar{x}} = \begin{bmatrix} A_d & 0 & 0 & 0 & 0 & 0 \\ B_G C_d & A_G & 0 & 0 & 0 & 0 \\ B_T D_G C_d & B_T C_G & A_T & 0 & 0 & 0 \\ B_S D_G C_d & B_S C_G & 0 & A_S & 0 & 0 \\ 0 & 0 & 0 & 0 & A_n & 0 \\ 0 & 0 & 0 & 0 & 0 & A_{KS} \end{bmatrix} \bar{x} + \begin{bmatrix} 0 & B_d & 0 & 0 \\ 0 & B_G D_d & 0 & B_G \\ 0 & B_T D_G D_d & 0 & B_T D_G \\ B_S & -B_S D_G D_d & 0 & -B_S D_G \\ 0 & 0 & B_n & 0 \\ 0 & 0 & 0 & B_{KS} \end{bmatrix} \begin{pmatrix} \bar{r} \\ \bar{d} \\ \bar{n} \\ \bar{u} \end{pmatrix}$$

$$\begin{pmatrix} \bar{z}_1 \\ \bar{z}_2 \\ \bar{z}_3 \\ \bar{v} \end{pmatrix} = \begin{bmatrix} D_S D_G C_d & D_S C_G & 0 & C_S & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{KS} \\ D_T D_G C_d & D_T C_G & C_T & 0 & 0 & 0 \\ D_G C_d & -C_G & 0 & 0 & -C_n & 0 \end{bmatrix} \bar{x} + \begin{bmatrix} D_S & D_S D_G D_d & 0 & -D_S D_G \\ 0 & 0 & 0 & D_{KS} \\ 0 & D_T D_G D_d & 0 & D_T D_G \\ I & -D_G D_d & -D_n & -D_G \end{bmatrix} \begin{pmatrix} \bar{r} \\ \bar{d} \\ \bar{n} \\ \bar{u} \end{pmatrix}$$

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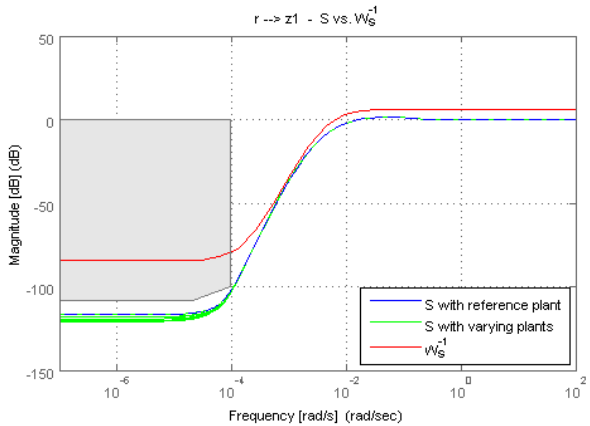
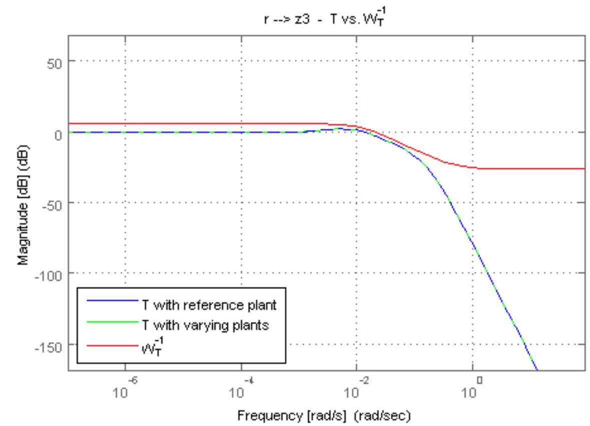
H_∞ Synthesis

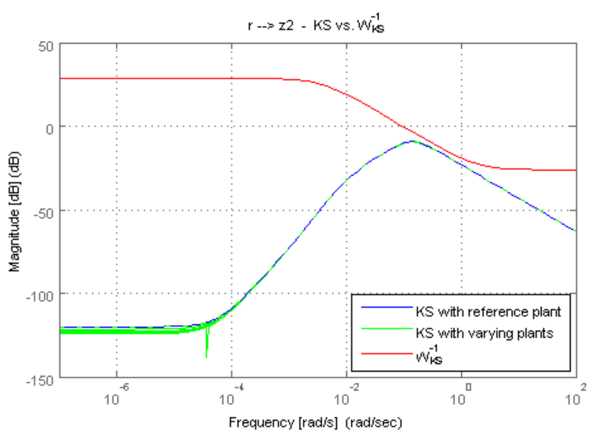
Weighting function design criteria:

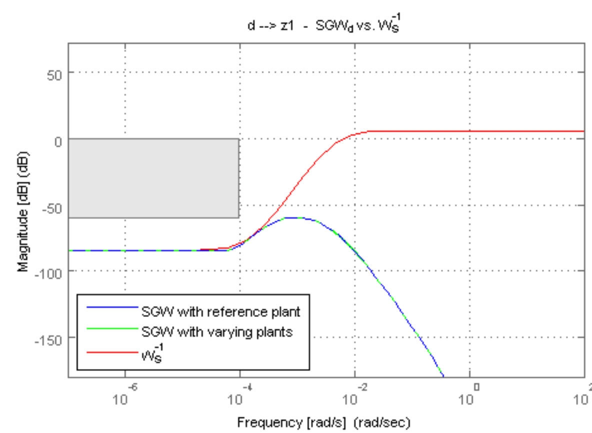
- $\mathbf{W_T}$ is used to set an upper limit of the bandwidth which is driven by the PWM frequency
- $\mathbf{W_S}$ is used to suppress the control error in the presence of:
  - Relative orbital dynamics (gravity gradient)
  - Manoeuvres (angular rotations of the formation)
  - Low frequency external perturbations (solar radiation pressure)
- $\mathbf{W_{KS}}$ is used to introduce poles (i.e. low pass filters) above the cross-over frequency in order to smoothen the error signal
- $\mathbf{W_d}$ serves to characterise the external perturbation (solar radiation pressure)
- $\mathbf{W_n}$ serves to characterise the navigation error properties

H_∞ Synthesis Results









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Simulation Results

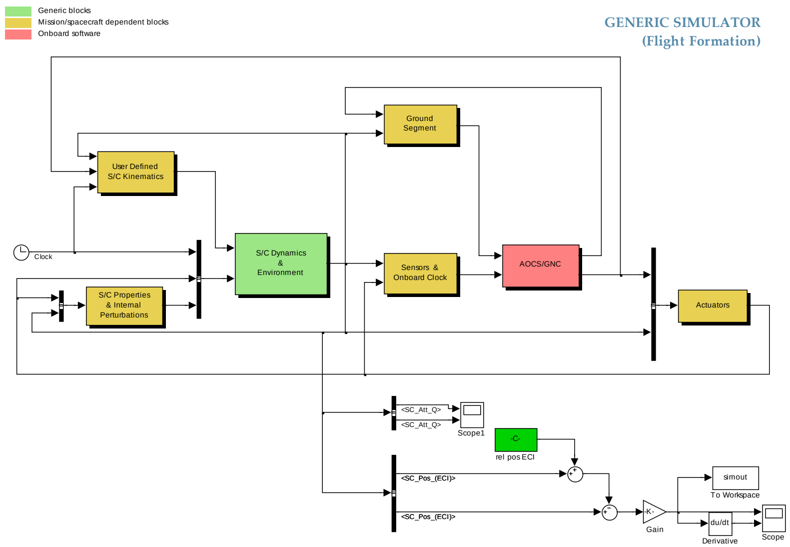
Preliminary simulations have been performed in *SENERIC*, an internal in-house developed 6DoF simulation tool.

The objective is to validate control design in the presence of:

- Representative relative orbital dynamics (Inter satellite distance = 150 m)
- Non-linear effects of the thruster PWM (*MIB = 50 msec, PWM period = 20 sec*)
- Inter satellite link delay (3 sec) in the loop

Simplifications:

- Simplified Navigation & Guidance (*attitude dependence is included*)
- Simplified yet functional attitude controller
- PWM applied to force commands
- No thruster torque perturbations
- COM to COM control

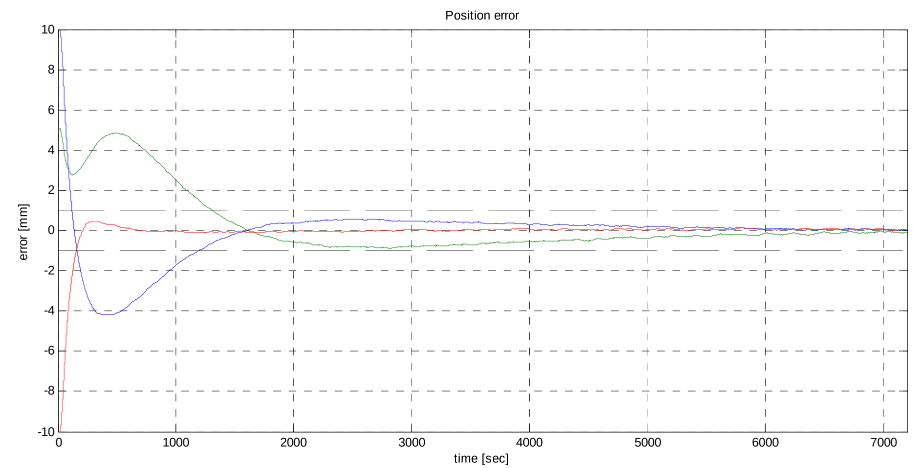


NOTE: Attitude controller and Rel. Pos. Navigation Kalman filter are developed by different companies → Not available for this internal simulation test

Simulation Results (2 hour simulation run)

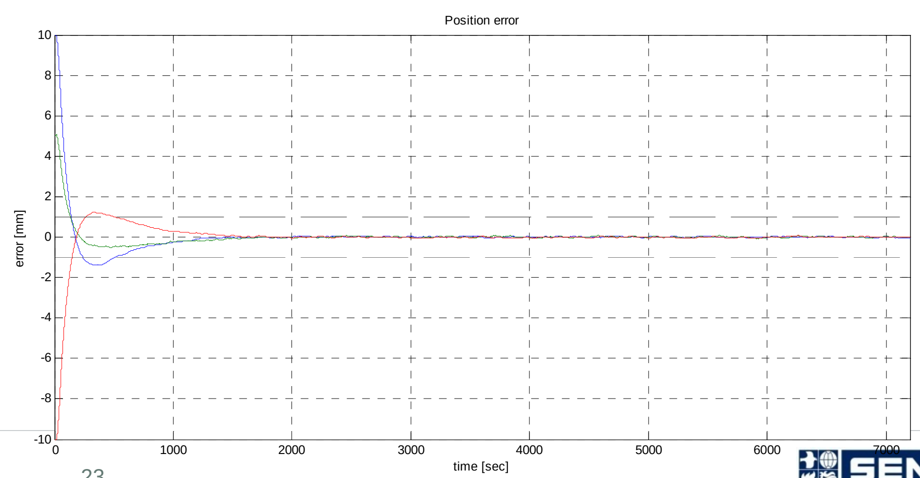
Case 1:

- No feedforward control term
- No attitude measurement errors
- Initial position error: 1 cm



Case 2:

- With feedforward control term
- No attitude measurement errors
- Initial position error: 1 cm



Simulation Results

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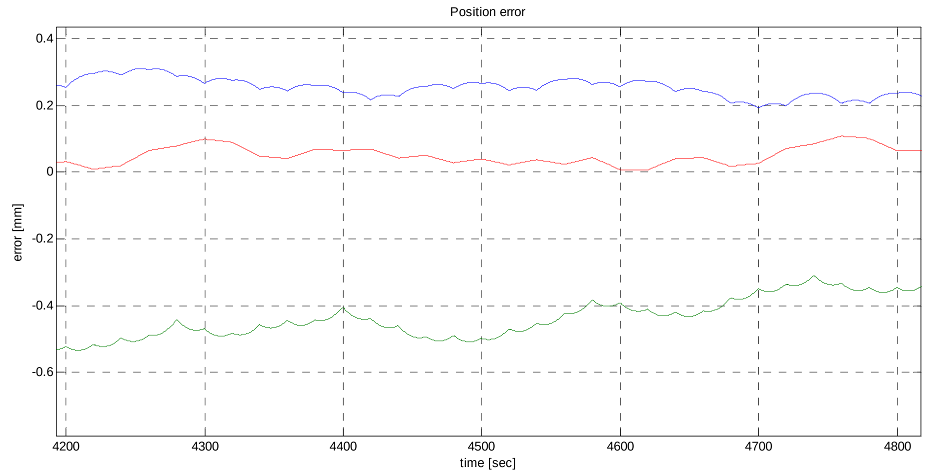
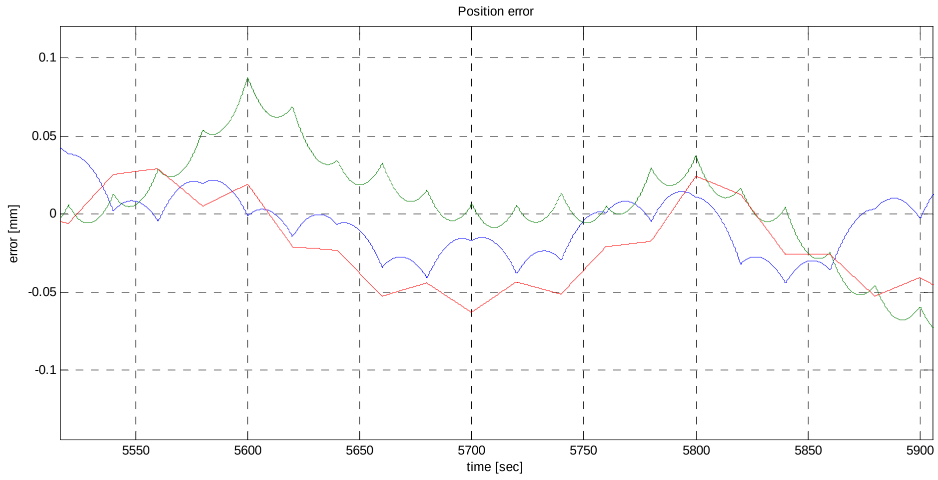


Case 2:

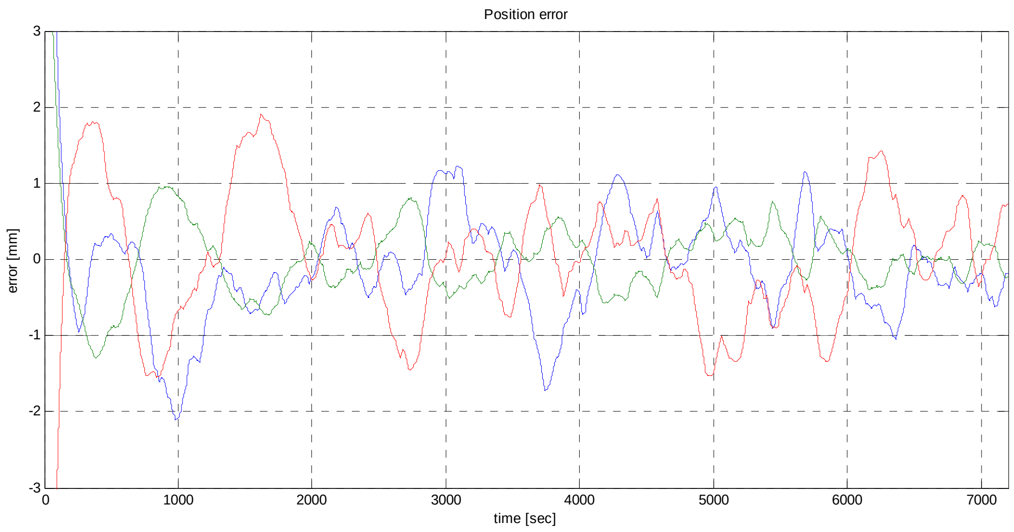
- With feedforward control term
- No attitude measurement errors
- Initial position error: 1 cm



Simulation Results

Case 3:

- With feedforward control term
- With attitude measurement errors
- Initial position error: 1 cm



Attitude knowledge error = 0.82 arcsec (1σ) → 0.6 mm (1σ) @ 150m

Gaussian noise assumed → Conservative as a Kalman filter is to be implemented

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Conclusions

- A MIMO control design tool within the H_∞ framework has been developed
- The plant model includes the relative orbital dynamics for elliptical orbits based on a LVLH formulation using the Yamanaka-Ankersen equations
- A high performance flight-formation controller has been designed meeting the GNC design criteria in the frequency domain
- Non-linear time-domain simulations in *SENERIC* (6DoF design simulator) have been performed for stand-alone validation purposes → results are very good → requirements for Nominal Performance are met

Next Steps

- Further analysis of the thruster PWM frequency (0.05Hz) vs. control frequency (1Hz) for possible revision for improved performance
- μ-analysis
- Include attitude aspects (e.g. couplings, uncertainty) within the H_∞ synthesis approach
- Robust Performance and Robust Stability → requires further consolidation of the Mission, GNC configuration, HW properties, etc.

Thank you for your attention

Any questions?

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