Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Formation Flying Guidance Navigation and Control design for science missions

A. Villien*, C. Cavel*, J. Morand*, J. Borde*

**EADS ASTRIUM Satellites, 31 Rue des Cosmonautes, F-31402 Toulouse Cedex 4,*

Abstract: This paper presents the recent activities performed by Astrium to design Guidance Navigation Control systems for European Formation Flying missions: PROBA 3, SIMBOL-X, Darwin and Pégase. These missions cover a wide range of formation flying needs from medium accuracy mission (astronomy) up to high accuracy (interferometry). For each class of mission the paper gives an overview of the major system requirements, the trade-off for the GNC architecture definition, the proposed GNC design and the assessment of the performances.

1. INTRODUCTION

Formation Flying (FF) is an emerging domain of space activities on which Astrium is very active for more than 10 years. EADS ASTRIUM Satellites is leading numerous studies on FF for system aspects, GNC (Guidance Navigation and Control) design, payload concepts, or technological development.

Control requirements for the target Formation Flying mission's operational phases are very challenging with arcsecond accuracy level for attitude and centimetre down to sub-millimetre accuracy for position. This paper highlights the recent activities performed to design GNC to meet these stringent requirements for four European missions: PROBA 3 (sun observation and FF demonstration), SIMBOL-X (large focal X-ray telescope), Darwin and Pégase (space born interferometers).

These missions cover a wide range of formation flying needs from medium accuracy mission (astronomy) up to high accuracy (interferometry). They give an overview of GNC architectures adapted to each class of mission and allowing managing different constellation sizes from 2 up to 5 spacecraft.

For each mission, the paper presents the major system requirements, the trade-off for the GNC architecture definition, the selected GNC design and the assessment of the expected performance.

2. PROBA 3

PROBA 3 is a future ESA FF mission dedicated to both science and demonstration of FF techniques and technologies in flight. PROBA 3 payload is a solar coronagraph (ASPIICS).

The formation is composed of 2 spacecraft: one spacecraft acts as occulter facing the Sun and the other one is the Coronagraph satellite in the shadow of the Occulter.

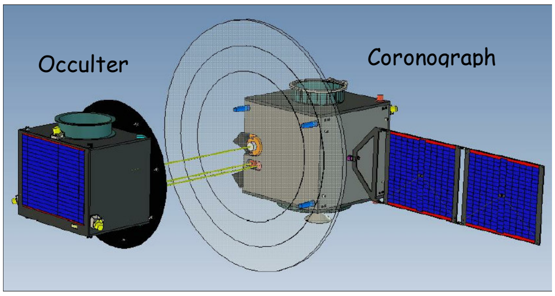

Fig. 1. PROBA 3 formation

2.1 Mission Requirements

The coronagraph mission relies on a very accurate and stable positioning of the entrance pupil in the shadow area projected by the Occulter satellite. This leads to longitudinal and lateral relative positioning requirements that are coupled: for an inter-satellite distance of 150m, the extreme values are respectively 74mm and 3mm (L0 and D0 in Fig.2). The lateral position is controlled with respect to the distributed instrument line of sight (LOS) defined as the virtual line between the centre of the occulting disk and the Sun.

To keep the optical axis of the pupil pointed towards the Sun, the Coronagraph satellite shall control its absolute attitude with respect to the Sun with an accuracy of 20'' cross the LOS and 0.5 deg around the LOS. Attitude stability requirements are also defined for the Coronagraph to avoid smearing effects in the image (2.5'' cross the LOS over 10s, 1'' around the LOS over 10s). These stability requirements drive the choice of the propulsion system.

The Occulter satellite is less constrained in attitude (0.5 deg cross and around the LOS, no stability specification). The specification is derived from the need to control the shadow area size with respect to the observed sun radius.

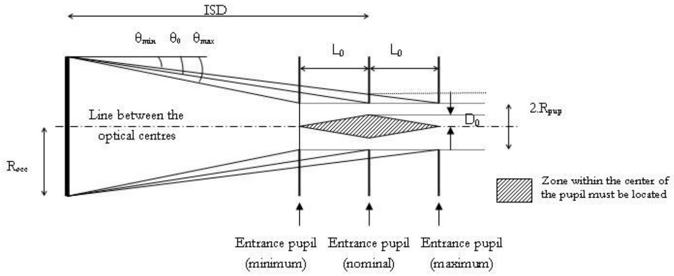

Fig. 2. Relative positioning requirements for PROBA 3

2.2 *GNC architecture and design*

As the Coronagraph satellite shall remain in the shadow of the Occulter, a leader-follower strategy has been selected for the formation control. The Occulter is a free-flyer controlling only its absolute attitude with respect to the Sun whereas the Coronograph position is controlled with respect to the Occulter to ensure the correct Coronograph entrance pupil positioning. As for the Occulter, the Coronograph absolute attitude is controlled with respect to the Sun.

The main trade-off at GNC system level is the selection of the actuators. Two options have been envisaged: the use of proportional electrical thrusters or pulsed cold gas thrusters.

The first option relies on linear control techniques with independent Single Input Single Output (SISO) controllers for each axis. Thrusters can be used for both attitude and position control or coupled with wheels. Feasibility has been evaluated through covariance analysis and demonstrated for ionic thrusters with an actuation noise of 10μN/√Hz. The attitude stability requirement is constraining with this technology.

The second option uses cold gas pulsed thrusters for position control and wheels for attitude control. Position control is achieved through dead-band control techniques whereas attitude control is based on a linear approach with independent SISO controllers. The tight attitude control threshold prevents using thrusters for attitude control (actuation numbers would largely exceed thrusters qualification). This architecture has been recommended as based on flight proven actuators. Moreover this solution is lighter and the reachable minimum impulse bit (MIB) is lower with pulsed thrusters than with proportional thrusters.

Attitude estimation for coronagraph uses star trackers and ephemeris data as it is not possible to use fine sun sensors, the sun being occulted by principle of the mission. Relative position estimation is based on an optical metrology (CLM, Coarse Lateral Metrology) for the line of sight measurement and Radio Frequency metrology for the range measurement.

The Radio Frequency Metrology (RF) is derived from GPS technology. Through the exchange of RF signals between sets of antennas located on both spacecraft, and differential phase measurements, this equipment provides estimations of the lateral and longitudinal relative positions with a centimetre and degree accuracy respectively. The Lateral measurement accuracy is not sufficient to meet mission needs (a few arcsec) and is only used for formation initialisation up to CLM acquisition.

The Coarse Lateral Metrology (CLM) provides an angular measurement of the lateral positioning errors with arcsecond accuracy within a few degrees field of view. A laser diode (located on the Occulter) acts as a pseudo star. The emitted light is omnidirectional (at least in a wide cone facing the coronagraph). The position of the pseudo star is measured in a frame linked to the coronagraph. The estimation of the relative position with respect to the sun (which is the parameter to be controlled) requires the knowledge of the coronagraph attitude and induces by principle a coupling between attitude and position measurements. This means that the attitude measurement shall be very accurate (a few arcsec). In particular spatial noises of star trackers have to be calibrated with the payload before each observation and a fine thermo-elastic stability shall be ensured between the star trackers and the CLM. Calibration is performed using fine Shadow Position Sensor (SPS) that measures directly the relative position of the Coronagraph satellite in the shadow of the Occulter, at payload level with an accuracy of 150μm.

The navigation function is performed with a dynamic estimator: an open-loop prediction of the perturbations is updated using sensors measurements and actuators commands, using a Kalman filter. The state of the vehicle (relative position, absolute attitude) is estimated at 1Hz. Performances have been validated by simulation and proved to be sufficient for the mission.

A fine GNC mode simulation tool has been developed to validate the design and assess the performances. The most constraining requirement is the relative lateral positioning requirement. Figure 3 shows the evolution of relative lateral position (specification is 3 mm) for the StarTracker and CLM baseline. The green line is the estimated state, the blue line being the true state. The bias between estimated and true state comes from the bias in attitude measurement (due to calibration residuals and thermo-elastic stability).

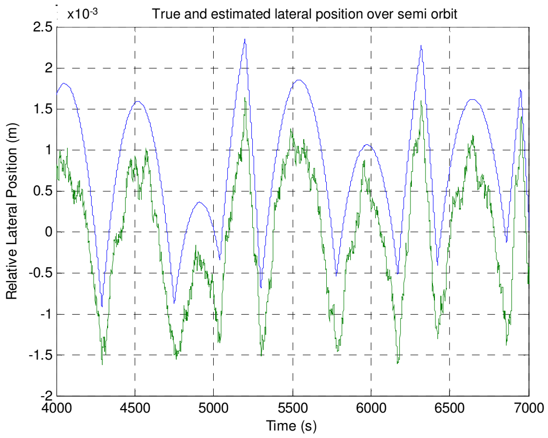

Fig. 3. Relative lateral position evolution

The performance reached is about 2.5mm and compatible with the mission needs. Such a performance assumes calibration residual of sensors low frequency errors and thermo-elastic stability better than 1'' which induce severe constraint on the platform design.

An alternative design has been elaborated. The principle is to use the payload in the control loop. Using the SPS provides then a direct measurement of what has to be controlled, thus removing the coupling between attitude and position measurement. Although given the better results for science observation this design limits the FF demonstration capabilities

3. SIMBOL-X

SIMBOL-X is a joint CNES / ASI (Agenzia Spaziale Italiana) program to develop a large focal X-ray new generation telescope. SIMBOL-X instrument covers a continuous energy range starting at classical X-rays and extending to hard X-rays i.e from 0.5 to 80 keV. It is using in this field a focalizing payload which until now was only used at energy below 10 keV, via the construction of a telescope distributed on two satellites flying in formation. SIMBOL-X permits a gain of two orders of magnitude in sensibility and spatial resolution in comparison to state of the art hard X-rays instruments. The telescope is distributed on two satellites flying in formation: a Mirror satellite collecting the X-rays and a Detector satellite (Clédassou, *et al.*, 2006)

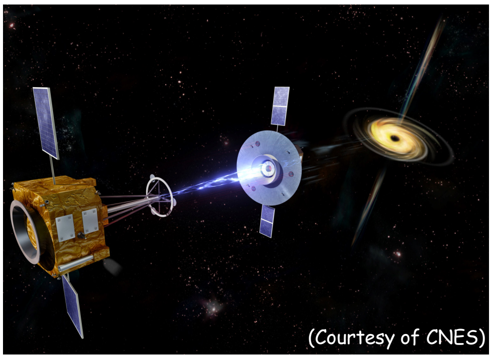

Fig. 4. Artist view of SIMBOL-X flight configuration

3.1 *Mission Requirements*

Control requirements are synthesised on figure 5. The main challenge of the mission from the GNC point of view is the feasibility of the Line Of Sight (LOS) restitution performance that requires accurate position and attitude estimation. The LOS restitution requirement is 3'' at 90%. This requirement is derived from the localisation needs of the observed sources and the necessity to reconstruct the observed images from the estimated LOS of the distributed instrument.

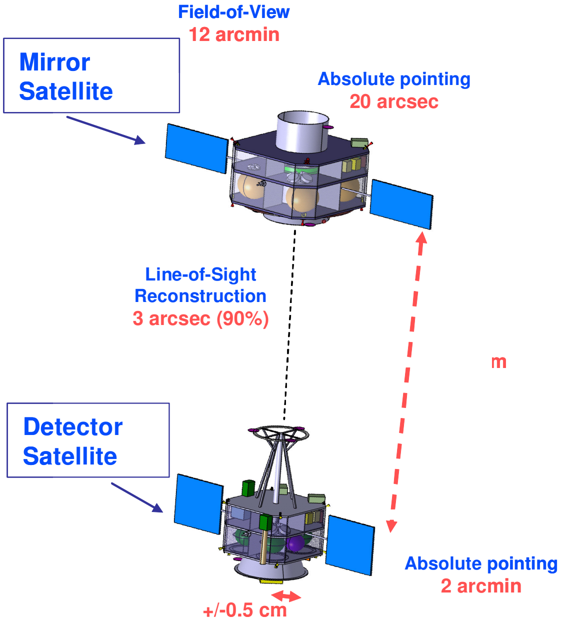

Fig. 5. Summary of SIMBOL-X FF requirements

3.2 *GNC architecture and design.*

The proposed architecture is comparable to PROBA 3, with a leader-follower strategy. The active spacecraft is the detector satellite which carries the FF sensors, similarly to PROBA-3. The attitude is measured by star trackers whose configuration has been refined to optimise attitude measurement and LOS restitution performances. The relative position is measured using the optical metrology (CLM) for the line of sight and the RF sensor for the range. The RF sensor is also used as a coarse range sensor for acquisition phases and safety of the formation.

Relative position and absolute attitude control is performed in a similar way to PROBA-3. 1N hydrazine thrusters are used for the transfer and the orbit control, the collision avoidance manoeuvres and the attitude control in safe mode.

A fine GNC simulation tool has been developed in order to validate the design and to assess performances budgets. This simulation environment has been developed in Matlab / Simulink and models the sensor suite, the navigation function, the control loops, the actuators and the environment of the SIMBOL-X mission. An iterative process has been used to design the GNC, validate its performances and improve the technical baseline.

4. DARWIN

ESA Darwin mission objectives are to detect Earth-like planets orbiting nearby stars and search for evidence of life on these planets. The proposed observational method is nulling interferometry. It allows for extinguishing the star light by several orders of magnitude while resolving the faint planets.

Many flight configurations have been studied for Darwin (Wallner, *et al.*, 2006). The most recent one, called X-array, is based on four Collector spacecraft and one Beam Combiner spacecraft flying in formation as an astronomical interferometer. The four collector spacecraft point the target star and transmit the received stellar flux to the combiner where beams are combined destructively (nulling) or constructively (visible part) for planet detection and observation.

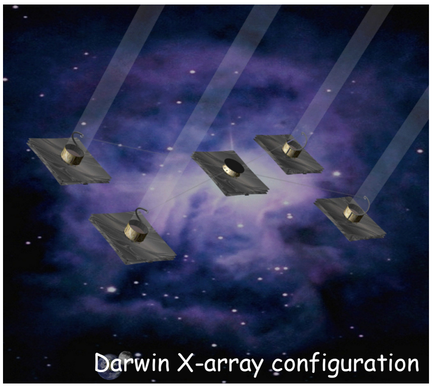

Fig. 6. Darwin in-flight X-array configuration optimized during "Darwin System assessment study" for ESA.

4.1 Mission Requirements

GNC requirements are derived from the desired nulling depth. The main requirements are on Optical Path Difference (OPD) and relative pointing control with nanometre and milliarcsecond accuracy respectively. The last requirement on relative pointing translates two constraints: the necessity to equal the incoming beam flux at hub entrance and the necessity to get enough flux to preserve the interferometer efficiency.

Some mission phases require specific manoeuvres (rotation around line of sight, resizing) during scientific observation to improve instrument sensitivity. These phases imply to maintain the control performances while modifying the formation geometry.

A major challenge of the Darwin mission is performance allocation between the various subsystems. Darwin objectives being very ambitious and the science performance highly sensitive to the control error Power Spectral Density (PSD) shape, close interactions between GNC, system and payload teams is necessary to optimise allocation and derive a set of requirements compatible with the mission needs and actuators and sensors achievable performances.

An iterative process was followed with an initial top-down approach (GNC sizing from preliminary requirements) and then a bottom-up approach (assessment of the science performance and adjustment of the control requirement to account for sensors and actuators achievable performance).

During that phase a simplified modelling of the constellation combined with noise transmission analyse techniques is used to perform preliminary GNC tuning, sensor and actuator sizing and performance prediction.

4.2 GNC architecture and design

The overall GNC architecture is based on a two stages control scheme for both OPD and relative pointing control. The formation geometry is controlled with a µm/s stability and sub millimetre/arcsec accuracy while internal control stages at payload level allow reaching the nanometre/milliarcsecond level imposed by the scientific objectives. These internal control stages are based on specific actuators and sensors: Optical Delay line (ODL) and Fringe sensor (FS) for Optical path difference control, Steering mirrors and Fine pointing sensors for relative pointing.

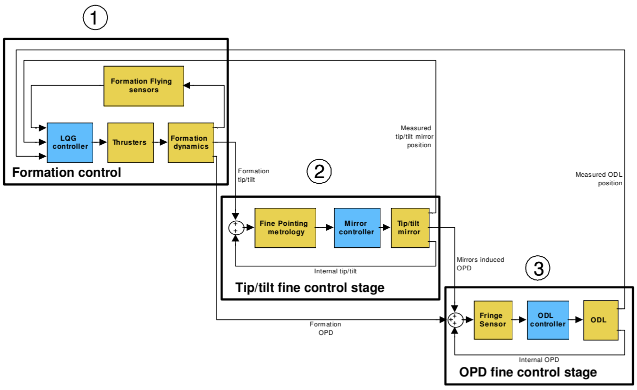

Fig. 7. GNC overall architecture

A centralised architecture is proposed for the formation control: the commands are elaborated by the beam combiner that collects all the available measurements and estimate the constellation state. The commands are then sent to the collector spacecraft for execution. This solution allows mitigating the sensor noise (through a centralised estimation) and optimising the control performances.

The proposed GNC laws feature a Linear Quadratic Gaussian (LQG) control with full Multiple Input Multiple Output (MIMO) estimator/controller taking into account all known couplings in the systems. The controller is based on the development performed in the frame of the ESA Interferometer Constellation Control Study (Beugnon, *et al.*, 2005). A constant gain filter is selected to limit computational load. The modification of the plants dynamics in some mission phase (array resizing for instance) is managed through gain scheduling techniques. The slow system dynamics (hours for a few metres relative motion) allows satisfactory frequency decoupling.

In order to meet the requirements of OPD control during the manoeuvre phases, a feedforward-feedback structure is implemented for guidance. The guidance module computes the overall constellation geometry that the GNC system must follow. Feedforward profiles are produced, with the target state as well as the profile of forces and torques necessary to follow the target trajectory. During manoeuvres as well as during static observation, the control law thus operates in the vicinity of the nominal trajectory and only compensates for small errors due to external disturbances or internal uncertainties.

The formation control is performed using Field Emission Electric Propulsion (FEEP). That kind of thrusters are necessary to reach the very low noise level required to meet the stringent control requirement (1µN/√Hz) while ensuring the high specific impulsion necessary for the mission.

Formation state estimation is based on optical metrologies for position, Star Trackers and fine pointing metrology for attitude.

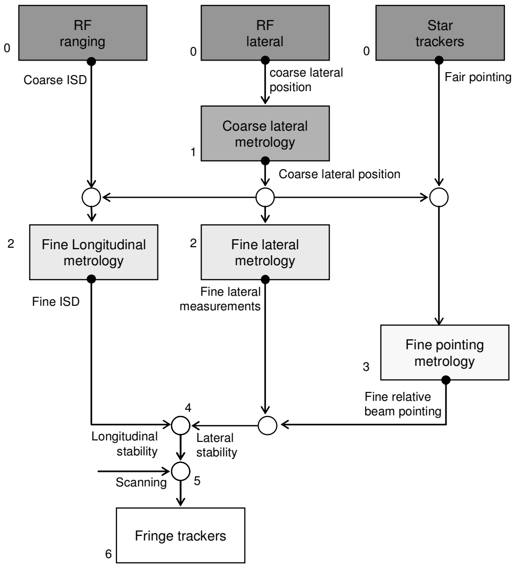

Fig 8. Darwin metrology acquisition principle

The sensor suite definition follows a bottom-up approach using sensors/actuators range, accuracy and dynamics, the starting point being the science observation mode and the payload control loops acquisition stages that are the most critical for formation control. The GNC system must for instance gradually bring the constellation into a state where the OPD and OPD stability are compatible with the Fringe sensor detection capabilities.

Absolute attitude measurement is performed using fine Star-trackers (STR). A Fine Pointing Sensors (FPM) inside the payload that provides measurements of the relative pointing (tip/tilt) error is used combined with STR for relative attitude control.

Coarse formation flying control relies on a Radio Frequency Metrology (RF) and CLM as SIMBOL-X and PROBA-3 missions. Several optical metrologies are then used for position control accuracy improvement. The Fine Lateral Metrology reconstructs the lateral positioning errors with a 10µm accuracy and a centimetre field of view. A near-parallel beam with a Gaussian profile is emitted from one spacecraft to another. Differential intensity measurements by an array of photodetectors provide lateral position offset in the frame of the emitter. The Fine Longitudinal Metrology provides measurement of the flyer-hub distance variation (relative measurements) with a 10µm accuracy. A monochromatic laser source emits from one spacecraft towards the facing one. A corner-cube reflector sends the beam back to the emitter. The incoming source beams are then combined to produce a fringe pattern. A fringe counter provides differential distance measurement.

The GNC design has been validated through a simulation campaign that allows consolidation of GNC performance and refinement of the sensors actuators requirements. Simulations show performances in line with the predictions. OPD control performance turned out to be the most challenging point.

5. PEGASE

The CNES Pégase mission aims at providing spectral characterization of hot Jupiters (Pegasides) and brown dwarfs together with the study of internal region of proto-planetary disks. The mission is based on a free-flying Bracewell type interferometer used in nulling mode and in imaging mode. The interferometer is constituted by two collector spacecraft equipped with a siderostat and a central spacecraft (Hub).

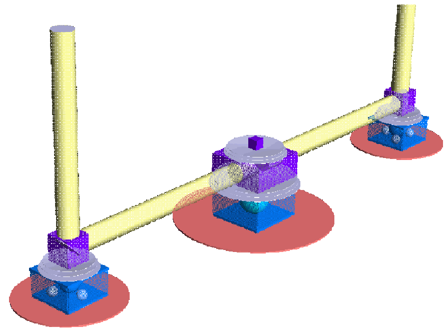

Fig. 9. Pégase formation configuration

5.1 *Mission Requirements*

The observational method is the same as the one used for Darwin mission. The selected targets being larger and brighter the mission requirements are nevertheless relaxed. The star light rejection level to be achieved for the targets characterisation is around 10-3. The OPD shall be controlled below 2.5 nm (rms) in nulling mode and below 5 nm (rms) in imaging mode. The relative pointing of the flyers transmitted beam with respect to the hub shall be below 30 milliarcsecond (rms).

5.2 *GNC architecture and design*

In 2006 and 2007, Astrium has performed 2 studies, financed by CNES, to define GNC architecture for the Pégase mission. The studies results in the development of two candidates architectures (Villien, *et al.*, 2007).

The first one based on "proportional thrusters" is directly derived from Darwin. For Pégase, FEEP could be replaced by proportional cold gas thrusters as the required impulsion budget is lower. The major drawback of such an architecture is that it relies on actuator that are still under development and whose performance still need to be demonstrated.

The second alternative is based on more mature actuators: wheels and pulsed cold gas thrusters: cold gas thrusters are used for position and hub attitude control, wheels for flyers attitude control. The limited performances of pulsed cold gas thrusters in term of Minimum Impulse Bit and Impulsion repeatability requires relaxing the control threshold at formation level while keeping control performance at payload level unchanged. A key issue for this architecture is then the performance allocation between the various control stages. As for Darwin, noise transmission analysis techniques were used for preliminary GNC sizing and tuning.

The critical points are the wheel perturbations. A detailed analysis of the perturbations through exploitation of characterisation tests and modelling is necessary for feasibility verification. For the selected wheel (TELDIX RSI-5/28, that fulfils mission needs in terms of mass, envelop, torque and momentum capacity), analyses demonstrated that the desired control accuracy can be reached but imposes a rigid spacecraft (first sunshield flexible mode above 20 Hz, compatible with the current Pégase design) and an accurate wheel velocity control through frequent off-loading. This last point is necessary to master the impacts of micro-vibrations and torque noise on the OPD.

The propose architecture impacts the overall mission design. The control performances required for science observations can't be achieved during the pulses generation due to the uncertainties on the pulse timing and amplitude. The transient errors induced by the impulses are nevertheless compatible with the fringe sensor measurement domain and can be rapidly damped by the OPD control loop (a few seconds). The scientific observation phases must thus be splitted into elementary observation sequences, where the constellation is free flying, interrupted by pulse control phases. Dead band control phasing is thus necessary to avoid interrupting too frequently the free-flying phases.

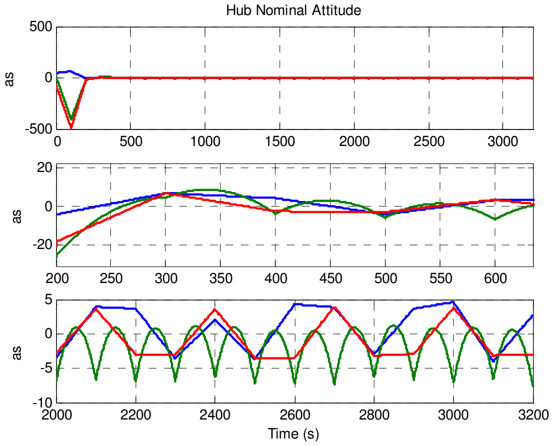

Fig. 10. Dead-band control synchronisation for the hub attitude.

The major challenge for the GNC design is then the dead-band control synchronisation. Specific algorithms have been developed and tested and show good robustness. This synchronisation requires accurate position, velocity and perturbations estimation as well as good pulse repeatability. Optimal Kalman filters have been implemented on each controlled degrees of freedom. This solution that allows rapid convergence during the free flying phase while keeping reasonable computation load has been preferred to the centralized estimator proposed for the proportional thrusters architecture.

A coupled wheel/pulsed thrusters control was designed for flyer attitude to ensure accurate wheel momentum control and master impacts on OPD. Coarse control and off-loading is performed with thrusters and fine control with wheels.

A reduced sensor suite composed of the RF and CLM metrologies has been selected. A fine OPD stabilisation being not possible at spacecraft level due to the control pulse impacts, usage of fine laser metrologies is not interesting. In counterpart, a fringe sensor compatible with higher OPD variation (a few tens of µm/s) is required for OPD stabilisation.

Complete simulations of the science mode have been performed for this architecture. The OPD control performance is critical and shows high sensitivity to the fringe sensor measurement noise, ODL stability and wheel noise. An OPD control performance around 3 nm rms is achievable for the selected wheels with a FS measurement noise equivalent to 2 nm rms at 20 Hz. This performance is compatible of mission needs.

6. ACKNOWLEDGMENTS

The above results have been obtained through FF system and GNC studies supported by ESA, CNES, DLR and BNSC.

7. REFERENCES

Beugnon, C., E. Buvat, M. Kersten, S. Boulade (2005). GNC design for the Darwin spaceborn interferometer. Proceedings of the 6th ESA International Conference on Spacecraft, Guidance, Navigation and Control Systems.

Clédassou, R,P. Duchon,P. Ferrando (2006). Simbol-X: An Hard X-Ray Formation Flying Mission. 57th International Astronautical Congress.

Villien, A., J. Morand J, D. Michel, P. Guidotti (2007). GNC for the Pégase mission, 17th IFAC symposium on automatic control in aerospace.

Wallner, O., K. Ergenzinger, R. Flatscher, U. Johann (2006). DARWIN Mission and Configuration Trade-Off. Proceedings of SPIE Vol. 6268 626827