GNC FUNCTIONAL ARCHITECTURE DESIGN AND IMPLEMENTATION OF THE LISA DRAG FREE CONTROL SYSTEM

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ABSTRACT

The LISA (Laser Interferometer Space Antenna) mission consists of three identical spacecraft in a triangular formation with an inter-satellite distance of 2.5 million km, flying in a heliocentric orbit, to study gravitational waves. Each spacecraft contains two test masses, which are controlled via electrostatic sensing and actuation, and two telescopes that point towards the other two spacecraft, with a variable inter-telescope angle to maintain formation tracking. The science experiments consist of leaving the TMs in free fall in the direction of the line-of-sight between spacecraft while being suspended in the other directions using the electrostatic actuators. The spacecraft performs a drag-free control by following the TMs' geodesic path using micro-Newton thrusters while simultaneously maintaining formation. A sophisticated optical metrology system will measure the distance between TMs of opposite spacecraft with pico-metre accuracy and provides accurate relative position and angles with respect to the spacecraft to meet the stringent performance requirement.

A study[1] was performed for ESA in Phase A/B1 to investigate control system architectures and advanced design methodologies. This paper will present the outcomes of this study covering various topics of the GNC design activities such as the control problem formulation, constellation acquisition strategy and state estimation filter.

1 INTRODUCTION

The LISA (Laser Interferometer Space Antenna) mission is one of the most challenging endeavours to be undertaken by ESA with the objective to study gravitational waves. The mission consists of three identical S/C (Spacecraft) in a triangular formation (see Figure 1), with an inter-satellite distance of 2.5 million km, flying in a heliocentric orbit. Each S/C contains two TMs (Test Masses) that are confined within an electrode housing with electrostatic sensing and actuation capability. Two telescopes are present, pointing towards the two other S/C, which includes a sophisticated OMS (Optical Metrology System) to measure the distance between TMs of opposite S/C with pico-metre accuracy. To maintain formation tracking, the angle between the two telescopes (i.e., breathing angle) is variable so that it can keep the opposite S/C within its FoV (field of view).

The science phase of the LISA DFACS (Drag-Free Attitude Control System) consists of leaving the TMs in free fall in the direction of the LoS (Line-of-Sight) between S/C while being suspended in

[1] This activity was carried out and led by SENER Aeroespacial, Spain, in collaboration with DEIMOS Engenharia, Portugal. This activity was funded by the European Space Agency (ESA), contract no. 4000129130/19/NL/CRS.

the other directions using the electrostatic sensor and actuator. The S/C will perform a drag-free control by following the TMs' geodesic path using MPS (Micro Propulsion System) with micro-Newton thrusters while simultaneously maintaining formation via attitude control and corresponding telescope breathing angle commands. The pointing requirements to maintain formation are achieved via laser measurements of the relative angles with respect to the LoS between S/C.

A study was performed for ESA by SENER Aeroespacial as part of a development risk mitigation activity in Phase A/B1 with the objective to investigate control system architectures and advanced design methodologies. The full nonlinear DKE (Dynamics. Kinematics and Environment) models, which include all the DoF (Degrees of Freedom) of the coupled S/C, TM and telescope dynamics were developed by Deimos Engenharia to perform the validation activities of the GNC (Guidance, Navigation and Control).

The LISA S/C, once in a heliocentric orbit, will execute a sequence of operations that consists of:

- Inertial pointing of the individual S/C (including slew manoeuvre to target)
- Release of the two TMs (either sequentially or simultaneously)
- Acquisition of the constellation formation
- Science observations

Within this study activity, a complete GNC was designed and implemented that is capable of autonomously executing the above sequence, including all the necessary functions for mode management, guidance, navigation (state determination), control, actuator managers and the switch between sensor/actuator HW (Hardware) depending on the phase within the sequence.

This paper presents the design process of the GNC. Considering the large quantity of work performed, a general overview is provided of the design activities covering various GNC areas of relevance. In particular, the focus will lie on the following topics:

- GNC function architecture and control problem formulation
- Guidance strategy of the constellation formation acquisition
- Kalman filter for S/C attitude estimation based on the TM dynamics

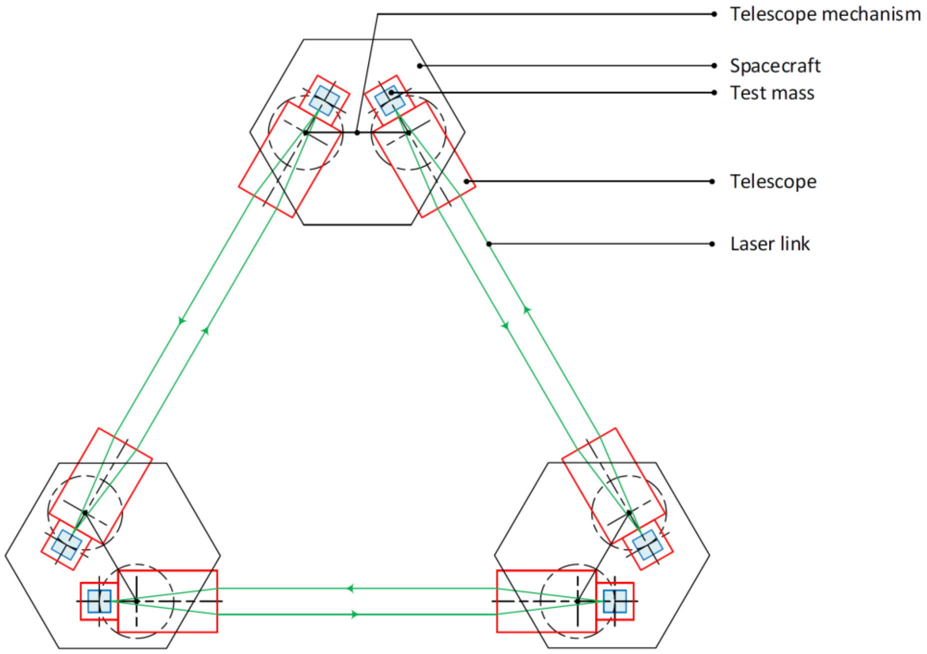

Figure 1. LISA Constellation Formation

2 CONTROL PROBLEM FORMULATION

The LISA DFACS needs to control a total of 16DoF, which are:

- S/C attitude (3DoF)
- TM relative position (2x3DoF)
- TM relative angle (2x3DoF)
- Telescope breathing angle (1DoF)

It is a complex MIMO (Multiple Input Multiple Output) system that demands a proper assessment. In fact, as the S/C transitions through the various phases in the above sequence, the number of DoF to control varies as well. This requires a careful design of the control architecture and definition of the control problem formulation as it drives both the GNC functional architecture and the intended control design and analysis methodologies. An analysis of the control problem led to the identification of a potential controller sub-division as follows:

- LoS control problem
- TM control problem
- DF control problem

LoS Control Problem

The LoS control problem consists of aligning the telescope boresight axes to the LoS between S/C. Four measurements are used, which are the azimuth and elevation angles of the two telescope axes with respect to the LoS, which are symbolically referred to as α and β in Figure 2. There is a unique combination of S/C attitude and telescope breathing angle where the telescope axes align with the LoS hence the azimuth the elevation angle errors will uniquely determine the error angle in S/C attitude and breathing angle that the control function must correct. This LoS control problem can be divided further and be performed by two separate control functions, which are:

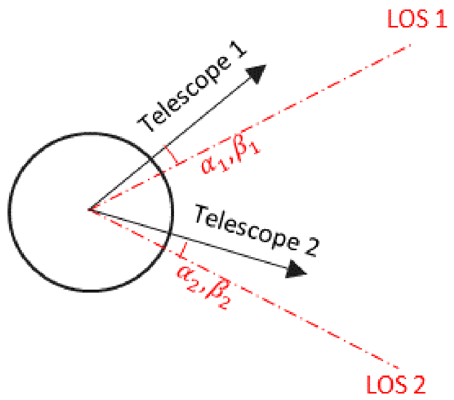

Figure 2. LoS Control Problem

- S/C attitude control
- Telescope breathing angle

This separation is deliberate as the telescope local controller will be a separate entity from the GNC and will be operated at a higher frequency with higher sampling rate. The GNC will then provide the (delta) breathing angles to this local controller. The S/C attitude control function will use MPS and STR (Star Tracker) when in standalone mode and LDWS (Long Differential Wave Sensor) when in formation relying on the LoS angular error measurements.

TM control problem

The two TMs need to be maintained at their rest position and attitude via the use of electrostatic sensors and actuators. The TM reference frame with respect to which the position and angle errors are defined is fixed to the telescope housing which means that the motion of the S/C and telescope will affect the tracking target of the TM controller. (Note that the telescope rotation axis coincides with the TM rest position to minimise the effects of the telescope motion). The electrostatic forces and torques are small and will hardly affect the motion of the S/C hence it can be assumed that the

TM controller will not affect the LoS controller performance. However, the opposite is not true as the LoS control does affect the TM controller via the motion of the telescope housing origin, i.e., the TM's tracking reference.

The effect of the LoS control can be mitigated by applying a feedforward term to the TM control actuations. The MPS commands of the S/C attitude controller will deterministically lead to a linear accelerations of the TM's tracking reference, which can be converted to the corresponding electrostatic actuation commands for compensation, which would not only reduce transient effects but also impose less restrictions on the control bandwidth tuning of the TM controller.

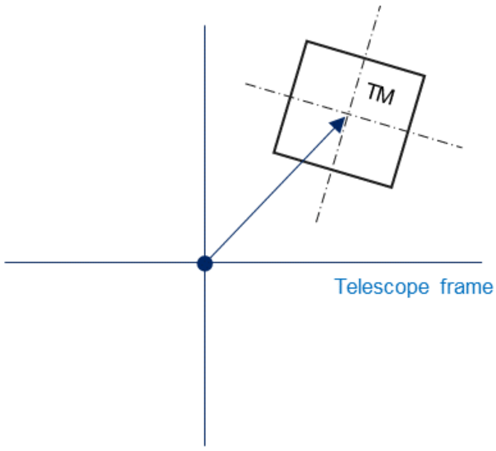

Figure 3. TM Control Problem

A diagonal control structure is foreseen leading to a SISO (Single Input Single Output) control per axis, which is convenient from an architectural implementation point of view as the mission requires deactivating the TM position control in 1 and 2 axes during the science observation experiments. Having separate SISO control functions allows for easy (de)activation depending on the active DFACS mode.

DF control problem

The DF (Drag Free) science experiment consists of releasing the TM position control in the direction of the LoS, while maintaining the attitude and lateral position closed loop control via electrostatic actuation. The DF controller will command MPS forces to steer the S/C such that the TMs remain at the rest position in LoS direction.

A 1DoF controller per TM will command the necessary force along the corresponding LoS (see F_1 and F_2 in Figure 4). But as Figure 4 shows, the two LoS directions are not orthogonal hence the total MPS force command is constructed such that the projections on the LoS are equal to the individual commands of the 1DoF controller. This approach allows decoupling the two 1DoF controllers leading to a diagonal control structure of the 2DoF DF control. (Naturally, the dynamics coupling is present in the LTI (Linear Time Invariant) plant model and is taken into account during the control synthesis and analysis).

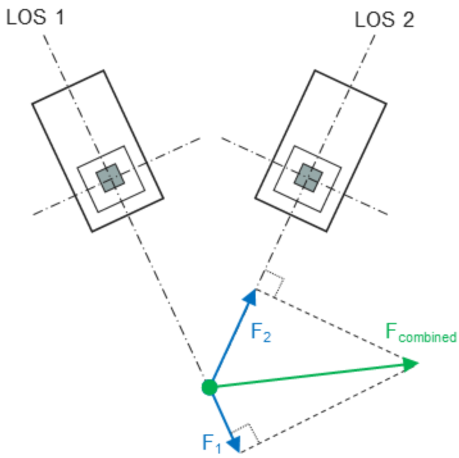

Figure 4. DF Control Problem

As it is obvious from Figure 4, the total MPS force has a component perpendicular to the both LoS directions, which will push the S/C sideways. The TM closed loop control based on electrostatic actuators will maintain the TMs on the LoS but since this lateral MPS force is deterministic, a feedforward term is commanded to the TM control so that the electrostatic actuator can directly compensate it. This will not only improve the TM position performance but it will also relax the bandwidth requirements of the involved controllers during the synthesis process.

3 CONTROL SYNTHESIS AND ANALYSIS APPROACH

In theory, it is possible to design a single 16DoF controller for the science phase but that approach was discarded in favour of designing sub-controllers as presented previously for practical reasons. The LISA DFACS consists of a series of mode transitions where the number of DoF to be controlled is increased. The proposed controller subdivision will allow a GNC function architecture implementation where the various functions can be (de)activated and (re)initialised depending on the active mode. A GNC function architecture was envisioned at an early stage with practicality and future implementation in mind but considering the coupled nature of the S/C, TM and telescope dynamics and the various controllers, an in-depth analysis was performed as well to assess the potential impact on the MIMO control design process and to choose a suitable design methodology.

The LoS and TM controllers can be treated as two control functions in series where decoupling can be performed by separating the control bandwidths. However, it is important to highlight that the DF and LoS controllers affect each other via the MPS actuation and control bandwidth separation is not easily done, if not impossible. A proper MIMO synthesis and analysis technique was thus considered mandatory.

The coupled nonlinear equations of motion were derived (with a parameterisation that is specifically tailored to the control problem at hand) that includes the S/C position/attitude, TM position/ attitude and the telescope motion. It also includes the distinction between internal forces and torques (e.g., electrostatic forces) and external forces and torques (e.g., MPS and SRP (Solar Radiation Pressure)). This distinction between internal and external forces/torques was considered important to ensure proper behaviour in terms of momentum conservation. From this nonlinear model, a parameterised uncertainty LFT (Linear Fractional Transformation) model was derived for control synthesis and analysis purposes (see Figure 5, note that the corresponding state-space formulation is later used).
(*Note: An extensive validation campaign was performed, including comparisons with the DKE model, which was developed independently by DEIMOS Engenharia for the time-domain simulation tool*).

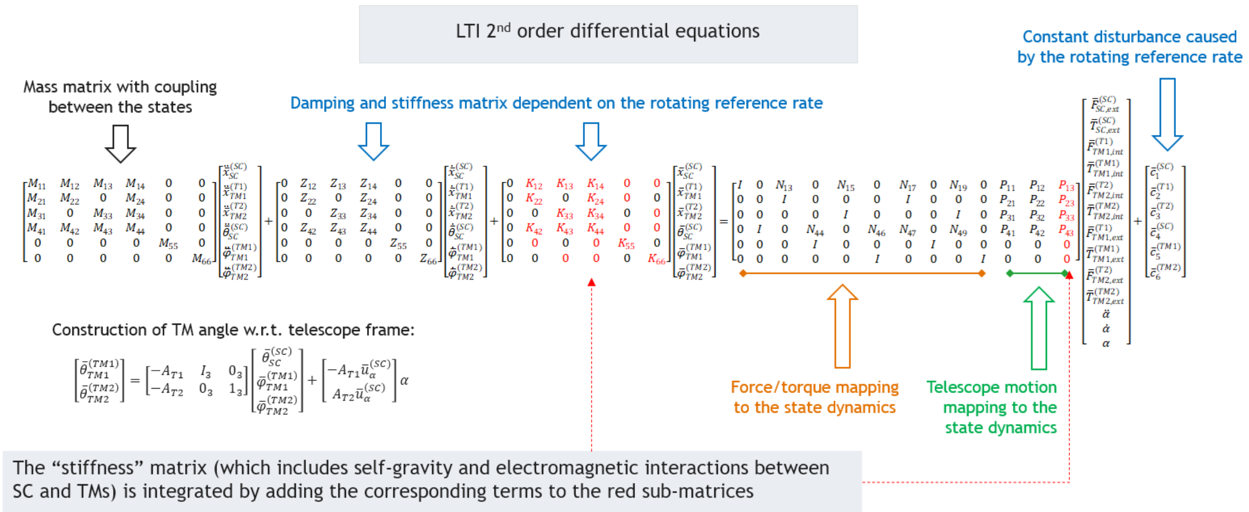

Figure 5. Linearised equations of motion

An assessment of the linearised model was performed to investigate the couplings between the DoF and to assess the MIMO design implications. The individual Input/Output channels of this model were evaluated for the three control problems (i.e., LoS, TM and DF) and their interconnections when active simultaneously. Based on this preliminary yet in-depth assessment, robust control design techniques based on (structured) H_∞ and μ-analysis were chosen as a suitable design framework for this study. First, the derived LFT model is sufficiently representative as there are no strong nonlinear elements that demand nonlinear design techniques. Second, the couplings are well defined and understood, many of which can be compensated via feedforward control terms. Nevertheless, important couplings remain, especially in the DF control problem as discussed previously. A sequential design approach (which can be re-iterated if re-tuning is needed) was adopted as follows:

- First, the LoS control problem is addressed with the corresponding I/O channel from the LTI plant model.
- Then the TM control problem is addressed where the LoS controller functions are treated as part of the generalised plant model that includes the LFT model's I/O channels for both LoS and TM problem. This way, the LoS control functions will reproduce the disturbances of the TM tracking references. The H_∞ synthesis routine will then ensure that TM control is adequately tuned considering all relevant disturbances.

  Figure 6 shows the interconnection block diagram for the TM position control synthesis where it can be observed that the generalised plant P includes the LoS closed loop dynamics (denoted as the P_{pre} block). This Figure serves as example to show how the LFT and H_∞ design framework can be used to design a controller within a MIMO system where other controllers are present.
- The DF control problem is then addressed where both LoS and TM controllers are treated as part of the generalised plant model. Here, since all DoFs are involved, the full LFT plant model is used. The benefits of this robust MIMO design framework become apparent as it supresses amplifications in the presence of various controllers with inevitably overlapping bandwidths where tuning based on engineering intuition is not trivial. (It must be noted that the sub-controller division was a deliberate design choice at control architecture level hence it is relevant to emphasise that the adopted design framework is capable of dealing with multiple controllers that are simultaneously active).
- The availability of the derived LFT plant model allows for parametric uncertainty modelling, which is later used for the robustness analysis.

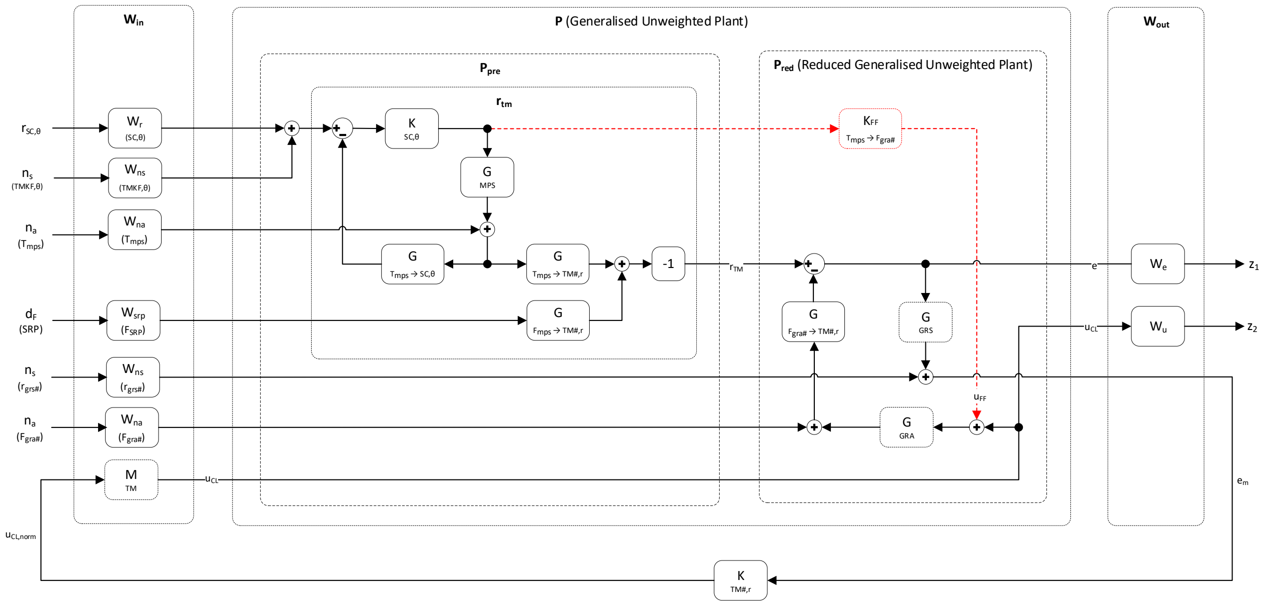

Figure 6. Interconnection block diagram for the TM position control

4 LISA DFACS MODES DESCRIPTION

Figure 7 shows the flow diagram of the LISA DFACS modes. A brief description of the functionality of each mode is given next.

IAP (Inertial Attitude Pointing)

In this mode, the S/C only needs to control its attitude. The GNC receives a target attitude and a slew manoeuvre is performed.

RL1/RL2 (Release of TM1/TM2)

In this mode, the TM #1 or #2 is released. The GNC functions to control the TM translation and rotation are activated while the S/C attitude control of IAP remains active. The range of initial release conditions include scenarios where the electrostatic actuators are saturated due to large initial velocities. A dedicated control design that includes an anti-windup compensation scheme was developed based on the IQC (Integral Quadratic Constraints) approach. This has the advantage that formal analysis techniques for stability and robustness can be applied in the presence of nonlinear effects such as saturation, which is critical in this scenario.

RL3 (Release of TM1+TM2)

In this mode, both TMs are released.

KFI (Kalman Filter Initialisation)

Once the TMs are released, the Kalman filter (see section 6) is initialised. This filter uses the TM dynamics to obtain very accurate S/C attitude estimates and to estimate the SRP forces and torques. Since the filter needs to converge, it is not used in closed loop with the controller but is active in parallel.

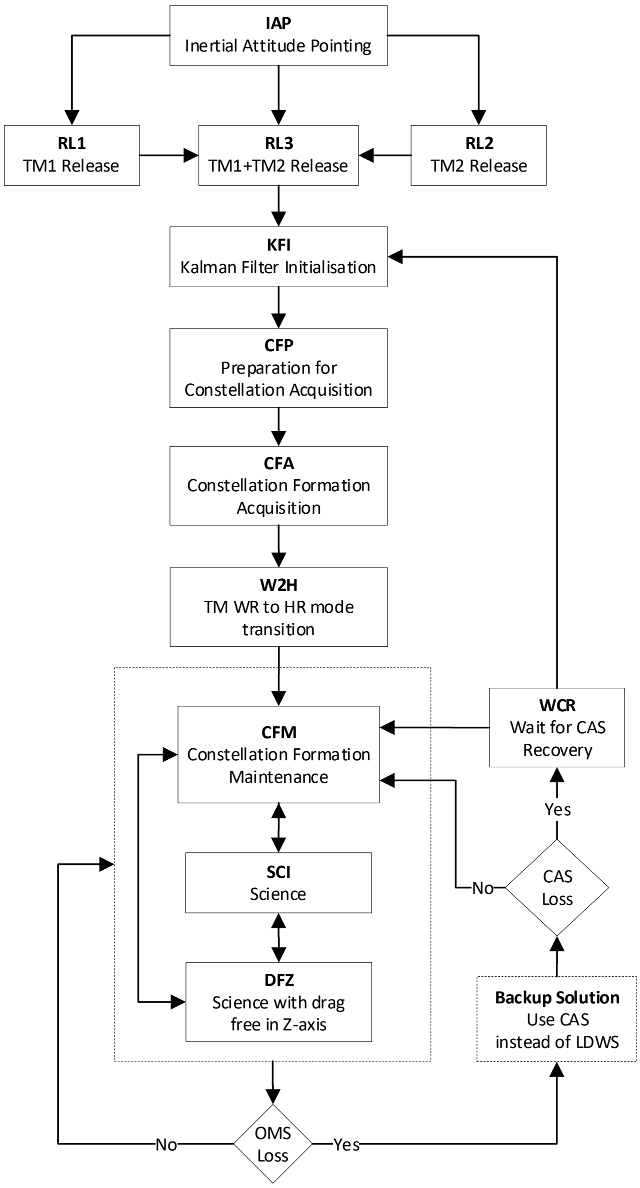

Figure 7. LISA DFACS Mode Transition Flow Diagram

CFP (Constellation Formation Preparation)

In this mode, the Kalman filter is converged and is used in closed loop to provide accurate S/C attitude data and a feedforward command to the MPS to compensate the SRP. The main purpose of this mode is to prepare the S/C for the constellation acquisition and to align the attitude and telescope axes as best as possible in accordance with the position of the other two S/C provided by Ground.

CFA (Constellation Formation Acquisition)

In this mode, a dedicated guidance function (see section 5) is activated to perform a scan pattern by combining S/C attitude and telescope motion. The GNC uses the CAS (Constellation Acquisition

Sensor) to detect the incoming lasers from the opposite S/C who are also performing a scan. When the telescopes of the two opposite S/C are aligned, the S/C attitude needs to maintain a pointing stability of 2 μrad in a period of 60 sec to establish the link.

W2H (TM Wide Range to High Resolution)

In this mode, the electrostatic sensors and actuator switch from WR (Wide Range) to HR (High Resolution). The WR mode is necessary to provide sufficient measurement range and actuation authority during the TM release and the scanning profile in CFA where the TMs are subject to a forced motion. For the science experiment, the HR mode is necessary to meet the performance requirements.

CFM (Constellation Formation Maintenance)

This mode serves to maintain the constellation formation without doing science experiments. The TMs are controlled in 6DoF with the electrostatic actuators. The control error signals for the S/C attitude and telescope breathing angle are provided by the LDWS that measures the azimuth and elevation of the lasers with respect to the LoS. To increase robustness of the system, the CAS will immediately provide the azimuth and elevation in case the laser link is temporarily lost so that the constellation formation is not broken and can be maintained.
Originally, for the sake of simplicity, the objective was to have a single tuning for the S/C attitude control function but simulation results have shown that a dedicated tuning for the science experiments was necessary to meet the stringent pointing requirements. Therefore, the S/C attitude control function is reinitialised here with a different tuning.

SCI (Science)

Here, the drag free science experiments is performed. The TM position control function in LoS direction is deactivated while the other 5DoF remain being controlled with the electrostatic actuators. The DF control function is activated, which will command the MPS to generate forces on the S/C to follow the free fall motion of the TM along the LoS. To meet the stringent performance requirements, the SIFO (Short Interferometer) is used to measure the TM relative position in LoS direction and the SDWS (Short Differential Wave Sensor) is used to measure the TM angles perpendicular to the LoS.

DFZ (Drag Free in Z-axis)

This mode is an alternative science experiment where the TMs are also released in z-axis, i.e., vertical direction. The TM position control in z-axis is deactivated and a dedicated control function is activated in its stead that consists of commanding MPS force to the S/C to keep the mean of the TM z-coordinated at zero while the electrostatic actuators are used to minimise the difference in z-coordinates.

WCR (Wait for CAS Recovery)

This mode has been added to cope with micro-meteorite impacts that cause a break in constellation formation. As shown in Figure 7, when the LDWS breaks lock but while the CAS still has the opposite S/C in its FoV, the system will autonomously return to CFM where it will try to recover LDWS lock. Considering the narrow laser beam divergence, a micro-meteorite can cause a sudden attitude disturbance where the opposite S/C loses CAS detection. As such, when the CAS suddenly loses contact, it is assumed that the other S/C has been hit by a micro-meteorite and the WCR mode is entered. Here, the system will use the S/C attitude as provided by the Kalman filter to maintain its orientation while it waits for the other S/C to recover, which is assumed to have gone to CFM. After a time-out, the recovery process is considered to have failed and the system will go back to KFI to reinitiate the constellation acquisition procedure.

5 GUIDANCE STRATEGY FOR CONSTELLATION FORMATION ACQUISITION

One of the critical areas is the constellation formation acquisition, which involves a dedicated scan and search strategy that combines S/C attitude manoeuvres with telescope breathing angle commands. A systematic search strategy has been designed, which has shown to be successful in Monte Carlo simulations, and is presented in this section.

To establish a link between S/C, each telescope emits a laser with a beam divergence of $2 \cdot 10^{-6}$ rad (half-cone angle) and has a FoV of $2.5 \cdot 10^{-6}$ rad (half-cone angle). To aid the acquisition process, a CAS (Constellation Acquisition Sensor) is used whose FoV is $225 \cdot 10^{-6}$ rad (half-cone angle), which can detect the incoming laser beam of the opposite S/C. (Note that the CAS FoV is selected such that it covers the expected position uncertainties of the opposite S/C at the start of the acquisition phase. Nevertheless, they can leave the CAS FoV afterwards due to attitude motion or orbital drift). One of the main challenges is the fact there is no information exchange between S/C, which means that the scanning S/C does not know whether the CAS of the opposite S/C has detected the emitted lasers. Another complication is the slow scanning velocity of $2.5 \cdot 10^{-6}$ rad/s, which is a limit imposed by the CAS properties and which causes the orbital motion to be of noticeable influence as the S/C will drift away since the acquisition process can easily take up to 1 hour depending on initial conditions.

The chosen guidance strategy consists of the following principles:

- Each telescope boresight axis is considered an independent entity → The two telescopes per S/C operate independently.
- A dedicated guidance function will compute the desired pointing direction of the telescope boresight axis in inertial frame.
- All six telescopes boresight axes are operated simultaneously.
- The desired S/C attitude and telescope breathing angle are uniquely determined by the commanded inertial pointing direction of the two corresponding telescope boresight axes.
- An additional guidance function will convert the two telescope axes into the corresponding S/C attitude and telescope breathing angle.

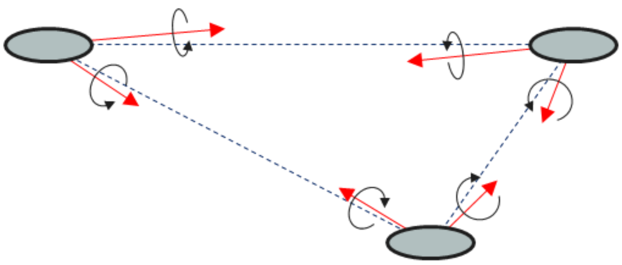

Figure 8. Visualisation of independently operating telescope boresight axes

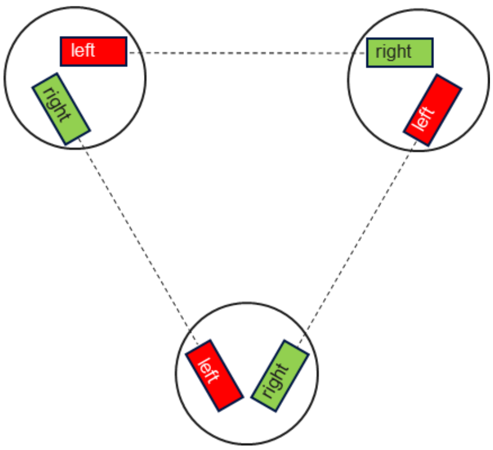

Figure 9. Right and left telescope pairs

Each S/C has two telescopes, which are conveniently denoted as the right and left telescope and they have the property that the telescope pairs of the opposing S/C are also formed of a right and left telescope, which is shown in Figure 9. A separate scanning strategy is thus developed for the right and left telescope in such a way that they will find each other

during the acquisition scanning phase.
This approach has the advantage that no explicit S/C identifier is required nor a sequential scanning procedure and instead, the same guidance functions are applicable to all three S/C and are executed simultaneously. The proposed scanning strategy consists of an iterative "scan" and "approach" search pattern.

Scan pattern:
A spiral scanning motion is executed around the estimated relative position vector to the target S/C. (Note that an initial estimate of the S/C position is provided by Ground prior to starting the acquisition phase). To account for orbital motion, an onboard orbit propagator will continuously recompute the relative position vector around which the scanning pattern is commanded. The scanning motion will continue until a maximum radius is achieved after which it will return to its centre and repeat the scan.

Approach pattern:
The approach pattern is initiated when the CAS detects the incoming laser at which point a new relative position vector to the target S/C is computed. The telescope axis is then commanded to move towards the newly recomputed target vector. This way, the emitted laser will point closer towards the target S/C and thereby increasing the chances to be detected by the opposite S/C CAS. Once the target vector is reached, the scan pattern is activated if its own CAS does not observe the incoming laser.

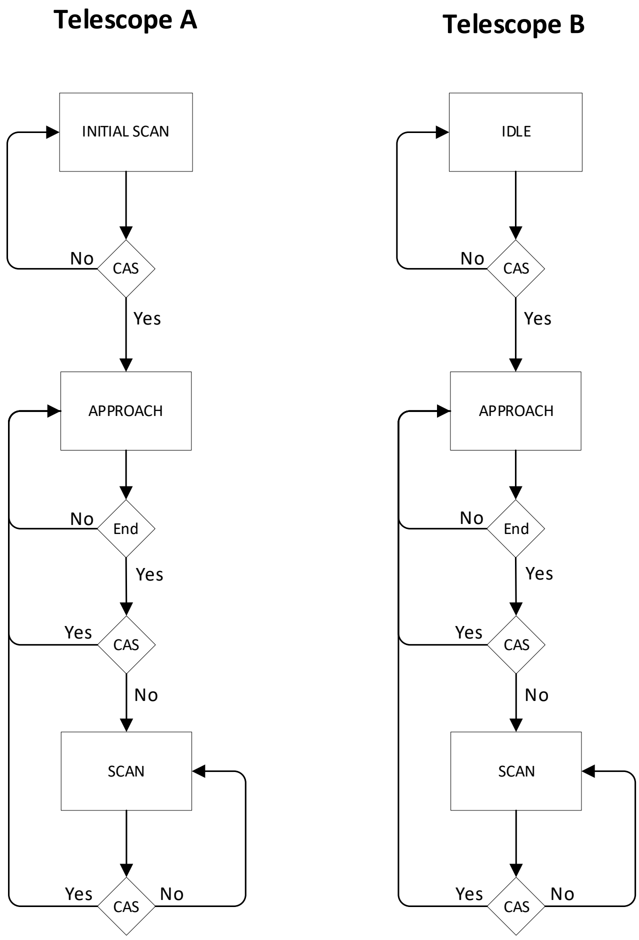

Figure 10. Search pattern logic flow diagram

In Figure 10, a flow diagram of the iterative scan-approach pattern is shown. (Here, telescope A and B refer to left and right). One of the two telescopes starts in idle mode and will simply wait until its CAS detects the laser of the opposite S/C after which the iterative search pattern is initiated. The iterative process can be summarised as follows:

- One telescope starts scanning (outwards spiral), the opposite telescope remains idle
- When the idle telescope detects the incoming laser, it will start the scan-approach procedure
- The scanning telescopes will iteratively switch between "scan" and "approach"
- The CAS is used to switch between "scan" and "approach"
- Both telescopes will eventually become aligned with the LoS between S/C and the laser links will be established

In Figures 11 to 16, the search strategy is visualised.

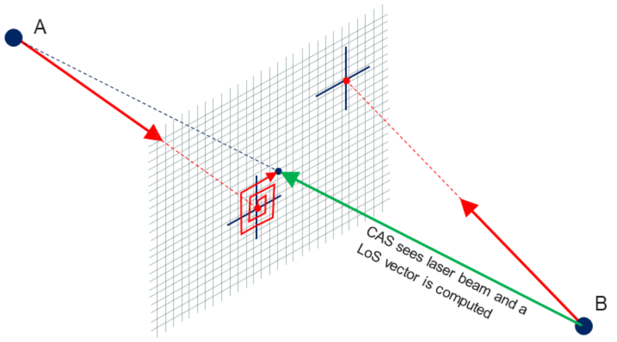

Figure 11. Scan procedure (1/6)

Telescope A starts scanning. Telescope B remains idle until its CAS detects the laser and recomputes the LoS (green vector).

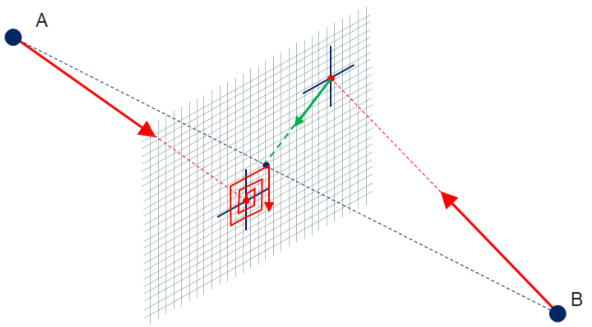

Figure 12. Scan procedure (2/6)

Telescope B moves towards newly recomputed LoS while Telescope A continues to scan.

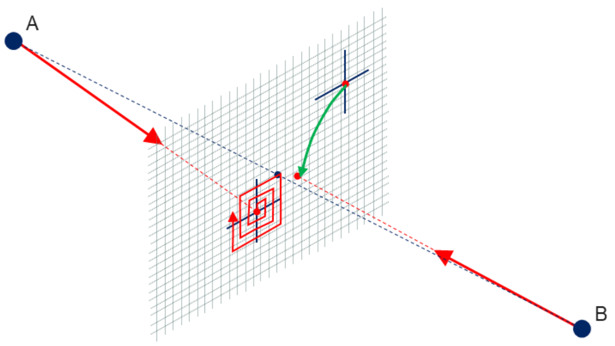

Figure 13. Scan procedure (3/6)

Telescope B arrives at the target LoS but due to uncertainties and errors, the opposite CAS does not detect the laser.

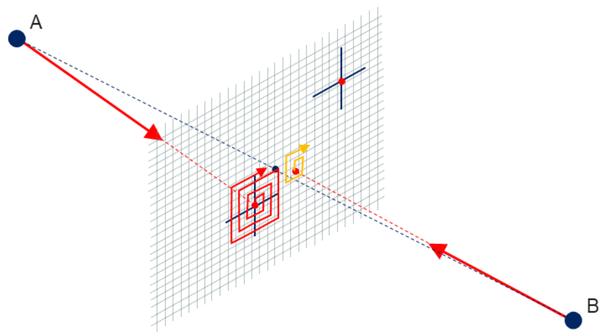

Figure 14. Scan procedure (4/6)

Telescope B initiates the scan pattern and meanwhile telescope A is continuing to scan.

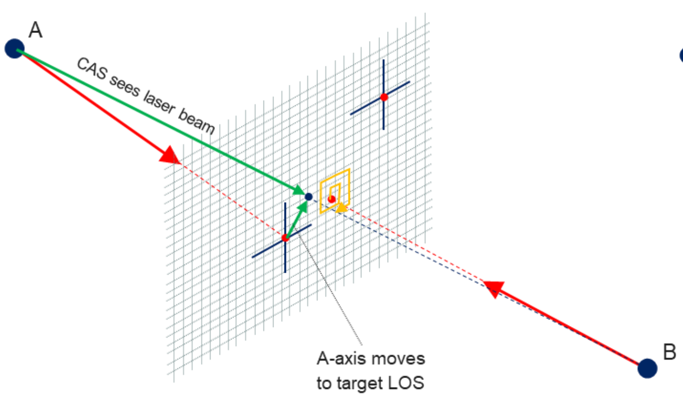

Figure 15. Scan procedure (5/6)

CAS of telescope A detects the laser. It will cease the scan and switch to the approach. Meanwhile, telescope B continues to scan.

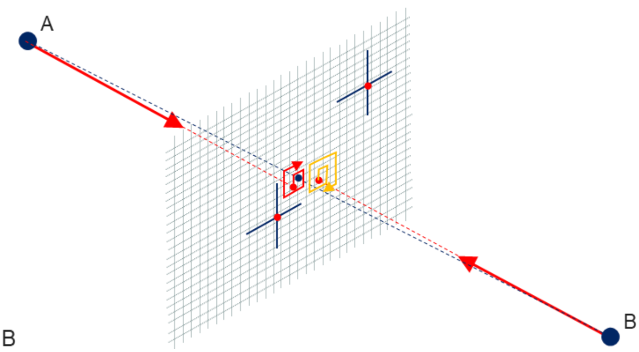

Figure 16. Scan procedure (6/6)

Both telescope axes are now closer to each other. Eventually, the lasers will fall inside the LDWS FoV and establish a link.

6 S/C ATTITUDE ESTIMATION FILTER VIA TM DYNAMICS

The constellation formation acquisition requires a high attitude pointing accuracy and stability in order to obtain a lock between S/C due to the very narrow FoV of the laser beam. The STRs are not expected to provide the necessary accuracy to guarantee a successful acquisition hence the use of the TMs was proposed to improve the S/C attitude estimation. Originally, the idea was to use the TMs as accelerometers by observing the commanded electrostatic forces while maintaining their position at rest with respect to the S/C. Conversion to the corresponding S/C angular accelerations and integration would provide a propagation of the S/C attitude. However, due to systematic errors, this solution would inherently lead to attitude drift errors hence imposing a limit on the duration of the acquisition process, which can take several hours. Consequently, a different approach was selected consisting of a Kalman filter containing an onboard model of the coupled TM and S/C dynamics, while using sensor data from the STR and electrostatic sensors and control commands to the MPS and electrostatic actuators. The presence of the STR will bound the propagation errors and avoid any attitude drift issues.

During development, it became evident that the SRP had a significant influence on the observability of the states, which necessitated the inclusion of the TM rotational dynamics within the model. (Relying on TM translational dynamics alone, as originally envisaged, was not sufficient). In fact, the SRP force and torque were added as a state to be estimated in order to improve observability.

The LTI plant model for control design was reused as the onboard dynamics model for this filter but with some modifications. These tailored modifications include:

- Addition of the SRP force and torque as states
- Removal of the telescope dynamics
- Removal of the TM z-axis rotation

Impact of telescope dynamics

The dynamics of the telescope breathing angle occur at a frequency that is higher than the GNC sample time hence the Kalman filter model is not able to adequately propagate the telescope dynamics due to the differences in time scale. Therefore, the telescope dynamics were removed from the LTI model. However, during tests, the impact of the telescope motion was noticeable and the Kalman filter would observe its effect on the S/C and TM dynamics and would attribute it to the SRP force and torque hence contaminating the state estimation.

The following mechanism was therefore introduced in the Kalman filter to account for the telescope motion. The derived LTI plant model includes the telescope dynamics hence the kinematic relation between an instantaneous variation of the breathing angle and the resulting variation of the S/C and TM states can be computed and expressed via a linear mapping. The GNC will command the desired telescope breathing angle variation per cycle, which the local telescope angle controller will execute. This commanded delta angle is also sent to the Kalman filter, which will then compute the corresponding variation in the states related to the S/C angle, TM angle and position after each Kalman update. This way, the telescope motion becomes ”invisible” to the Kalman filter and will no longer contaminate the state estimation while still taking into account its dynamical effects on the S/C and TMs states.

Removal of TM z-axis rotation

The inclusion of the TM rotational dynamics was necessary to observe the effect of the SRP on the system. However, the TM rotation in z-axis coincides with the telescope rotation axis and since the TM housing is fixed to the telescope, any telescope rotation will directly affect the TM angle with respect to its local reference frame. This direct coupling between TM z-axis rotation and telescope motion led to significant perturbations that affected the performance of the Kalman filter. Therefore, this degree of freedom was removed from the LTI model leading to smoother dynamics in terms of state propagation. (The remaining two rotational degrees of freedom of both TMs were sufficient to observe the effect of the SRP).

Effect of self-gravity and internal electric field

The TMs are subjected to a constant acceleration caused by self-gravity and internal electric field. Despite being small, it was observed during validation tests in the time-domain simulator that it did have a non-negligible effect on the Kalman filter performance. As a result, a feedforward term was added to the TM state propagation within the Kalman filter to compensate this constant acceleration. (No dedicated estimation scheme was included here but rather a tuneable parameter for open loop compensation, which was assumed to be provided by Ground after e.g., the corresponding calibration. In any case, it is an effect to be considered and coped with adequately).

Simulation results

Figure 17 shows the S/C attitude estimation errors during a simulation run of the constellation acquisition phase. The top figures show a systematic error, which is caused by the systematic errors of the STR bias and misalignment and are thus unobservable by the filter. But for the scanning patterns to be executed successfully with the desired pointing performance, of relevance are the attitude errors with respect to the mean, which are shown in the bottom figures. The observed oscillations, which are in the order of 1 micro-rad are caused by the delays in the navigation module in combination with the scanning motion. The attitude error contributions of the Kalman filter when the scanning motion ends are well below 1 micro-rad.

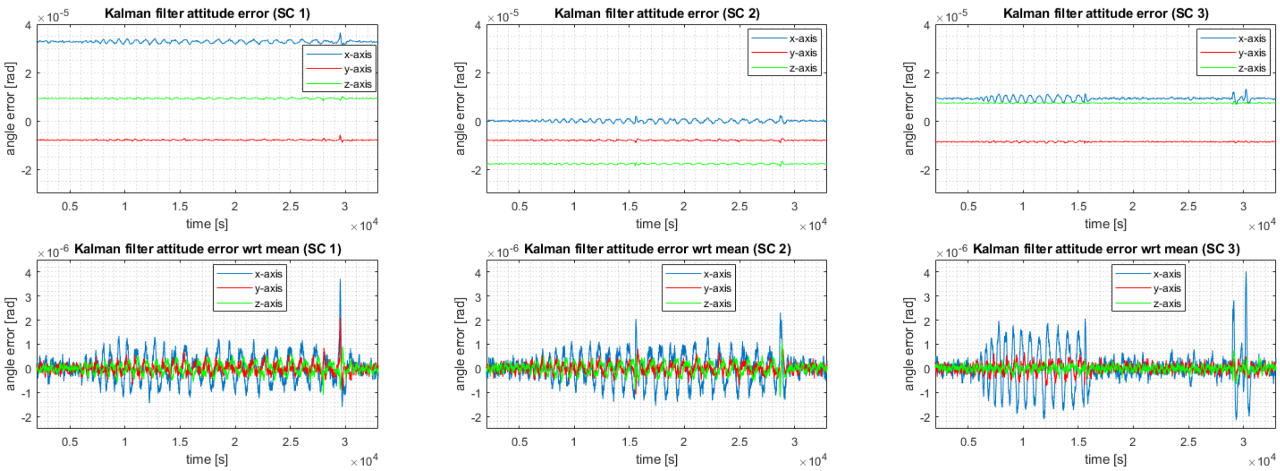

Figure 17. Kalman filter S/C attitude error

The developed Kalman filter meets its objective and provides the necessary S/C attitude estimation performance to successfully execute the scanning motion and to maintain the pointing requirements to establish the laser link.

Even though its raison d'être was the constellation acquisition phase, the estimation of the SRP force and torque has proven to be very useful and serves to provide MPS feedforward commands to the control functions. This is of particular relevance during mode transitions where the controllers and associated integrators are initialised thus leading to smoother transients and reduced overshoots.

The Kalman filter remains active after constellation acquisition and will provide the S/C attitude at al times. This is very useful as navigation backup solution during temporary loss of OMS tracking where the GNC can immediately perform actions to recover and reacquire the constellation.

7 SCIENCE OBSERVATION SIMULATUION RESULTS

An extensive Monte-Carlo campaign was performed to validate the DFACS performance in the presence of parametric uncertainties. For this purpose, a nonlinear simulator has been developed with high fidelity models for the DKE (developed by DEIMOS Engenharia) that includes the coupled dynamics of S/C, TMs and telescope. The simulator includes three independent S/C to simulate the orbital dynamics and to properly validate the constellation acquisition strategy. Sensor and actuator models were developed based on the provided characteristics and noise levels that were available.

In Figure 18, the time domain simulations results of the TM relative position error during the drag free science observation is shown. As can be seen, the error is in the order of 1 to 2 nm. Figure 19 shows the corresponding ASD (Amplitude Spectral Density) of the Monte-Carlo results together with the ASD requirements. As it can be observed, the requirements are met with good margins.

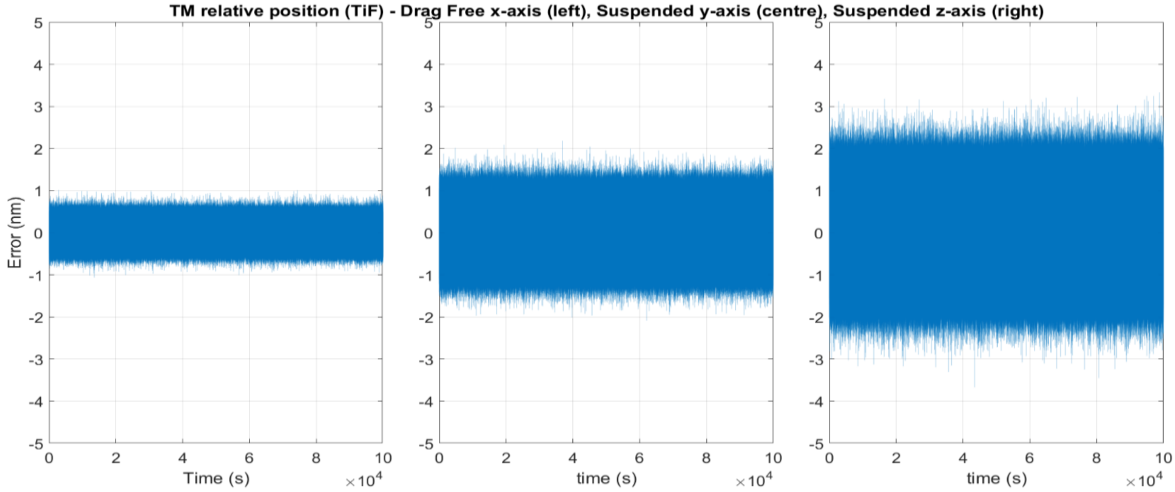

Figure 18. TM position error during science observations

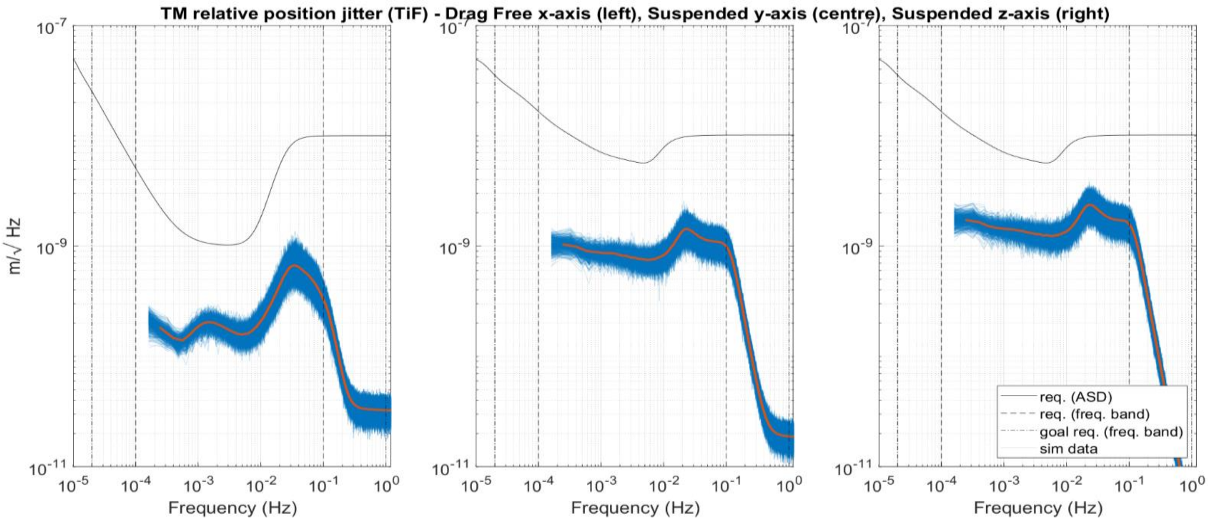

Figure 19. ASD of the TM position error during science observations

These Monte-Carlo simulation results have also shown that: the constellation acquisition strategy had a 100% success rate, that the anti-windup compensator during the TM release performed very well with electrostatic actuator saturations with worst case initial conditions, and that the Kalman filter for S/C attitude estimation provided the necessary performance leading to successful search patterns and lock of the laser links during formation acquisition.

8 SUMMARY AND CONCLUSION

A study was performed where a complete GNC was developed and implemented for the LISA science phase, capable of autonomously transitioning through all the modes; starting from inertial attitude pointing, to test mass release, constellation acquisition and science observation, including a dedicated mode to recover from micro-meteorite impacts. All the necessary functions (i.e., mode manager, guidance, navigation, control and actuator managers) were designed in accordance with the specified performance requirements and provided sensor/actuator characteristics.

In this paper, considering the vast amount of work performed, a selection of GNC topics has been presented to provide an overview of the scope of the design activities, which include the control problem formulation and design approach, guidance strategy for the constellation acquisition and the Kalman filter for high accuracy spacecraft attitude estimation based on the test mass dynamics.

A GNC architecture was defined where separate sub-controllers were identified to control the 16DoF of the spacecraft, two test masses and telescope breathing angle. H_∞ synthesis and μ-analysis techniques were therefore adopted as they were considered a suitable control design methodology in the presence of coupled dynamics and simultaneously operating sub-controllers with inevitably overlapping control bandwidths that can interact with each other. A high-fidelity parametric uncertainty LFT plant model was derived for synthesis and robust analysis purposes.

Monte-Carlo simulations were performed in a nonlinear simulator, containing the three LISA spacecraft, for proper validation of the test mass release, constellation acquisition, formation tracking and drag free control. Simulation result have shown that:

- the constellation acquisition strategy had a 100% success rate.
- the anti-windup compensator performed very well during the test mass release with actuator saturations with worst case initial conditions
- the Kalman filter worked very well and provided the necessary spacecraft attitude accuracy allowing successful constellation search and lock of the laser links.
- the performance of the drag free control of the test masses along the lines-of-sight met the stringent requirements with good margins.

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