POINTING PERFORMANCE SIMULATION AND CORRELATION OF THE SENTINEL-4 SCANNER SUBSYSTEM

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ABSTRACT

The paper presents the support provided by the newly developed simulation environment through the overall design and MAIT phase of the Sentinel-4 scanner subsystem. The results of this multidisciplinary optimised system and the complexity of the cross-coupling management are reported. Finally the correlation of the scanner simulation against other analytical tools and available data from representative test models is shown.

INTRODUCTION

The Sentinel-4 mission is part of the Copernicus initiative for continuous monitoring of Earth atmospheric composition and air pollution using a high resolution Ultra-Violet and Near Infra-Red (UVN) sounder. As the instantaneous field of view is a slit on the earth, this kind of instruments needs to scan the scene in order to acquire an image. In contrast to LEO mission where the instrument platform provides the scan motion with respect to the scene, UVN is operating in a GEO orbit from a 3 axis stabilized platform. This configuration demands for a highly accurate mechanical scanner performing a 19 degree east-west scan to acquire the scene images. A second scan axis with 14 degree motion capability is needed in addition allowing locating the scan area at different latitudes, to support platform yaw flip manoeuvres, to view internal/external calibration sources and also for star calibration.

RUAG Space is contractor of the scanner subsystem (SCS) to be delivered to OHB and then AIRBUS for integration into the instrument. The scanner mirror dynamic and static pointing requirements in the micro radian range are extremely challenging in particular in presence of micro-vibration and variation of the thermal environment. One of the main challenges was therefore the prediction of the dynamic behaviour during operational phase in order to:

- develop appropriate closed-loop controller subcontracted to CRISA,
- fine tune the mechanical design including passive damping elements,
- provide inputs to prime contractor for determining end-to-end performances and exported torques.

SIMULATION LIFE CYCLE

The support provided by the scanner simulation environment evolves through the project cycle. Each phase has its own set of requirements that are summarised hereafter.

Conceptual Phase

During early conceptual phase, establishment of pointing performance are needed in order to select appropriate key components, establish second level requirements and define the key design drivers. During this phase, detailed information is often not available and therefore the focus is on running large number of simulations with different configurations, perform sensitivity analysis and support design iteration in order to ultimately commit to the contractual baseline.
The main outcome of the simulation performed during the proposal and negotiation phase was:

- the allocation of the error budget to each sub-elements,
- the definition of the control architecture
- the establishment of an acceptable imported micro-vibration profile and
- the introduction of a dedicated thermal-control to minimise thermo-elastic errors.

Development Phase

The consolidation of the design and component level testing allow improving prediction accuracy by modelling with higher level of detail each sub-element. During this phase, refinement of assembly tolerances and confirmation of the overall concept could be achieved and presented at the critical design review.
Correlation with a single axis breadboard and availability of encoder performances under the representative in-orbit EMC environment were the key elements in order to have accurate pointing prediction.
The provided updated scanner model to the control team allows parallel development on the Scanner Drive Electronic (SDE). In addition, managing lower level non-compliance could be performed by assessing the impact of it to the overall scanner performances. A key decision has been to actively compensate for misalignment and other repeatable errors thanks the two active axes coupled control capability.

Qualification Phase

The qualification of the control electronics was performed by running in real time the provided scanner model in the SDE Unit Tester (UT) ahead of the availability of the scanner mechanism. During this phase it was essential that the provided scanner model (i.e. plant) closely matches the flight hardware. This has been achieved by correlating the model with the available test data but also, where necessary, to modify the passive damping implemented in the flight hardware.

The UT models both linear (plant model transfer function, flex print) and non-linear (misalignment, flex spider and torque compensation) components of the mechanism. This detailed implementation of the plant in the UT allows verifying the performances of the electronics HW with a representative plant of the mechanism and compare it to the simulation results. In addition the necessary margin to be applied both at control and mechanism level could be simulated.

ARCHITECTURE

Scanner Mechanism

For closed-loop system Matlab/Simulink is a commonly used environment. A dedicated toolbox allows connecting rigid bodies with springs and damping elements. However in the frequency band from 5 to 500Hz use of simplified rigid body models were not suitable anymore for representing all necessary natural frequencies. The result of these constrains was a multidisciplinary approach, that allows to include modal analysis in multibody dynamic, and layering control system simulation over the embedded model. In addition to the modes related to the flex pivots based scanner, the mirror supporting yoke and the overall frame have been represented as flexible bodies in MSC-ADAMS as shown in ‘Fig. 1’.

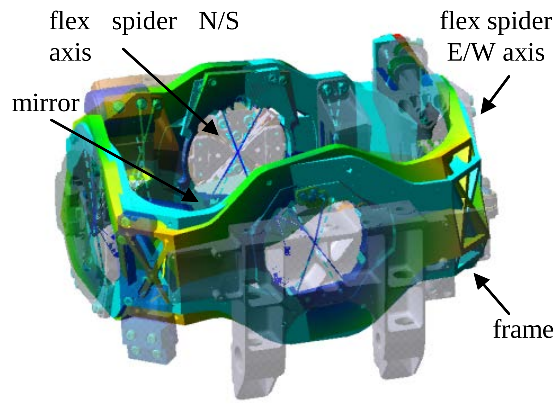

Figure 1. MSC ADAMS scanner mechanism representation, mode of the frame

Other natural frequencies identified using finite element model (FEM) analysis have not been represented after having checked that their influence on pointing performances and exported disturbance could be neglected. In the ADAMS model, the damping is to be set for each flexible element. This is not the case in the FEM representation that is dominated by structural damping. Therefore a one axis micro-vibration test has been performed in order to define the structural damping ratio of a given mode under micro-vibration. This ratio is then used in the FEM model and the generated transfer functions serves as basis to set individually each damping coefficient in the ADAMS model. Due to the number of transfer functions to be generated during this iterative phase, it has to be noticed that this can be achieved using ‘Eq. 1’.

$$G(s) = C(sI - A)^{-1}B + D \qquad (1)$$

With G(s) the transfer function and A,B,C,D the state space matrixes.

Co-simulations between Matlab and MSC-ADAMS have been performed. A week simulation was necessary for establishing the overall pointing budget and another one for running the exported torque cases. Such time is not compatible with a development phase and its iterative nature. Therefore a state space of the overall mechanism have been generated from ADAMS and implemented in the Matlab model. This reduces simulation time by a factor 30. However, this linearization around a dedicated working point produces inaccuracies when simulating the overall scanner motion. Two measures have been taken to solve this issue: i) implement most of the non-linearity in Matlab and ii) export multiple state spaces corresponding to different mirror positions.

Output from component level testing and various models like non-linear FEM analysis of the flex spider, magnetic field analysis including damping effect of the voice-coil and component level test data were used to create a representative scanner level simulation tool running under Matlab/Simulink. Those sub-modules representing the key electro-mechanical elements have been modelled using polynomial approximation or look-up tables. Uncertainties are implemented as factors and can be selected using a dedicated configuration set-up.

Controller

The selected control topology is a PID with feedforward. The pointing control is implemented with two nested controls for each axis:

- an inner current PI control;
- an external position PID control with a feed-forward term.

With the computation capabilities of the Floating Point Control Unit (FPCU), the feedforward is a great advantage as it allows a fine control of the mechanism movement on acceleration, speed and position. In ideal conditions the non-linear estimator is the exact inverse of the mechanism and then, the position control doesn't have to generate any torque. Actually, the PID control compensates any worst-case drift of the mechanism parameters while controlling only one state (position).

Prior to calculate the angle based on feedback from an incremental optical encoder, the FPGA normalize the SIN/COS signals to 1Vpp and 0V DC value, so the angle can be correctly identified by the interpolation table. In case the real electric signals have more noise than expected, a 2.5 kHz low pass filter has been added to both signals.

All the operational amplifiers used on the telemetry chains are modelled with the noise voltage at low (1/f) and high frequencies. Each noise source is multiplied by the number of operational in each telemetry chain and by the telemetry gain, to obtain the final noise before the ADC block.

Thermo-Elastic Deformation

In ADAMS and in general when state space matrices are used, dynamic thermo-elastic deformations cannot be represented. The approach has been to separate this error contributor after assessing potential cross-coupling effects. Such cross-coupling mainly occurs on the control side when structural deformation modifies the distance between the encoder head and the disk and thus the electrical signal. Close collaboration with the supplier of the encoder allowed establishing variation of the electrical signal and thus knowledge of the angular error as a function of distance variation. Thanks to the thermally optimised design and thermal control, such error is of second order.
For establishing the structural depointing error under thermal variation during a day, thermal analysis without and with maximum voice-coil dissipation (i.e. including ECSS margin) have been performed. The thermo-elastic depointing error is limited to app. 3µrad within a day. In addition the voice-coil power dissipation can increase this error by app. 2 µrad when applying all ECSS uncertainty and motorisation factor as shown in 'Fig.2'. This error is less than 0.2µrad in nominal working conditions.

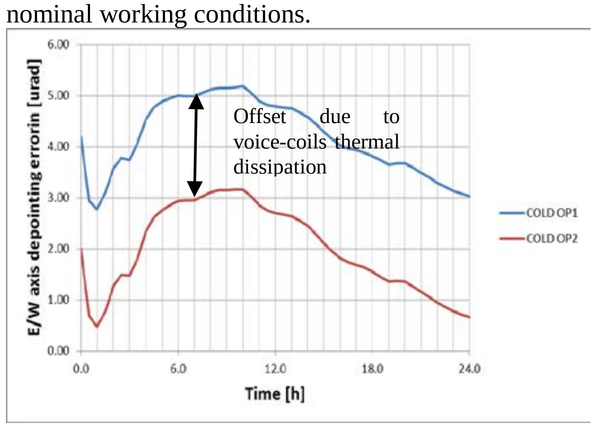

Figure 2. Pointing error over a day with (OP1) and without (OP2) voice-coil power dissipation

To arrive to such result it was important to have constant and low power dissipation of the active elements. The selected encoder does not significantly change its dissipation over the lifetime. Thus the main work has been to optimize the voice-coil design as well as reducing the angular torque of the flex spider. The main gain has been the implementation of a so called torque compensation unit. This dedicated design reduces the angular stiffness of the system without adding perturbation forces in the other directions. With this design, the power needed in nominal working condition is 0.2W on the E/W axis and less than 0.1W on the N/S axis. Without this features, the power demand would increase by a factor ten.

Metrology Error

Since the repeatable error is compensated, the potential inaccuracy of the estimation of this correction is to be considered in the pointing budget. The impact of the component level error and assembly tolerances on the overall two axis pointing measurement has been assessed with a dedicated mathematical model using a similar approach as for the scanner simulation.

PASSIVE DAMPING

During the course of the project the need emerged to reduce the exported torque in particular in the frequency range from 0.4 up to 200Hz. Various options have been explored both at mechanism and control level. The most promising has been the implementation of passive damping elements based on eddy-current effect using the existing passive magnets of the voice-coil.

A single axis breadboard has been used in order to verify the effect predicted by the magnetic analysis performed at part level. The damping ratio is extracted during a free oscillation test using three different methods: i) Half-Power Bandwidth Method, ii) Curve-fitting method and iii) Logarithmic Decrement.
This rotational damping ratio ξ is converted into in plane translational coefficient acting at the location of the damper using 'Eq. 2'.

$$\xi = \frac{c_{transl}}{4\pi \cdot f_n \cdot I \cdot r^2} \quad (2)$$

With I representing the inertia, r the radius w.r.t rotation axis and f the natural frequency at which the test has been made. The damping coefficient in Ns/m is set in the ADAMS model.

A free oscillation test has been conducted to determine the damping coefficient because this requires only the use of the scanner angular sensor. This means such determination can also be done, if necessary, in-orbit.
The disadvantage is that the rotational natural frequency is relatively low (i.e. less than 2 Hz) and slightly a function of the angular position. The best method allowing direct correlation with the experiment is the curve fitting method and the averaged logarithmic decrement in particular when enough oscillations are available.

Based on simulation, the passive damping has been increased from the original 0.02 Ns/m shown in 'Fig. 3' to 1.5 Ns/m per voice-coil. This damping is not only acting in rotation but also during in plane translation that has been identified being the main contributor to exported disturbances.

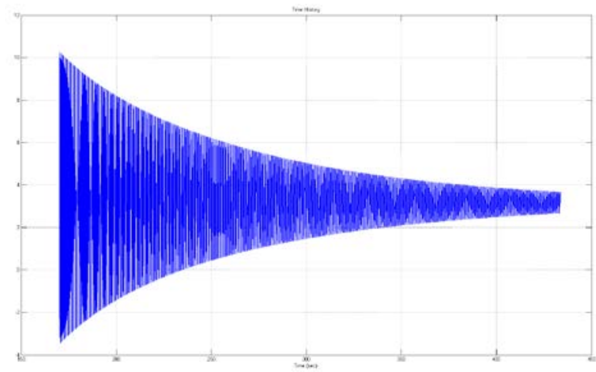

Figure 3. Free oscillation test performed with the single axis breadboard

The maximum damping potential of this design is 15 Ns/m. However this high value result in critical damping that was identified to be an issue in other area of the project. The back EMF of the redundant coil could also be used for providing damping when connected to a low impendence in OFF state. This however impacts the reliability due to the need for having both the main and nominal channel without failure. Moreover, due to design symmetry, this effect is occurring only during rotation around the axis.

The implemented damping reduces the exported disturbances by 30% to 50% at satellite CoG in the frequency band from 20 to 500 Hz.

Moreover the introduction of passive damping significantly reduces the translation in z that is erroneously interpreted as a rotation by the encoder.
This damping also minimise the time to stabilise the scanner around the mechanical neutral position in case of unexpected power OFF.

UNEXPECTED OSCILLATION

First time the scanner life test unit (LTU) is close-loop controlled with the scanner oriented in vertical orientation both EW and NS encoders measure higher oscillations than the metrology system monitoring the dummy mirror. Those oscillations are growing with time and, after approximately 3.5 seconds, the angular velocity is such that the SDE is loosing encoder count. This unexpected behavior occurs only when the scanner is mounted on the jig in vertical orientation and not in horizontal configuration shown in ‘Fig. 4’.

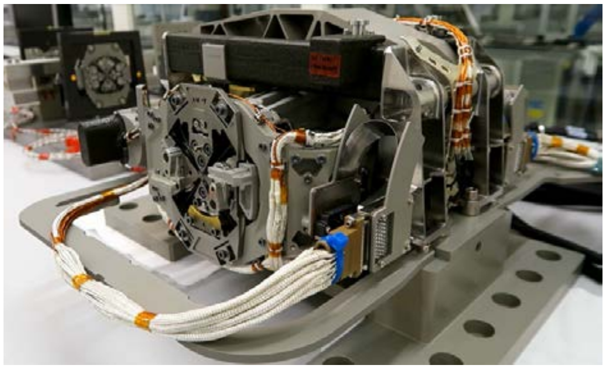
Figure 4. scanner subsystem life test model (horizontal) and, in the background, single axis breadboard

Investigation primarily based on free oscillation test and component level characterisation confirms that the as build LTU is conforming to the specification with the exception of the eddy current damping. However, correlating this damping in the SCS performance model did not lead to the observed oscillation.

Therefore an open loop test has been done in order to establish the transfer function between the voice-coil and the encoder angle. This allows a more accurate correlation of the scanner mechanism in ADAMS mainly by adjusting the frequencies in the range from 80 to 150Hz as reported in ‘Fig. 5’ and ‘Fig.6’.

Another aspect was the more accurate consideration of the z translation between encoder head and disk on the electrical signal. The projected angle only reports the rotation between two marker (or nodes) and thus the linear displacement is to be added. For this purpose an additional output has been created in the state space matrix in order to consider the tangential displacement between the sensor disk and the head (stator-rotor in ‘Fig 6’).

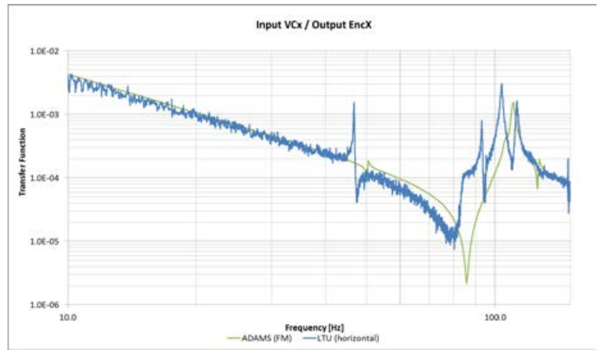

Figure 5. open loop transfer function voice-coil to encoder (E/W axis) compared to the original ADAMS model

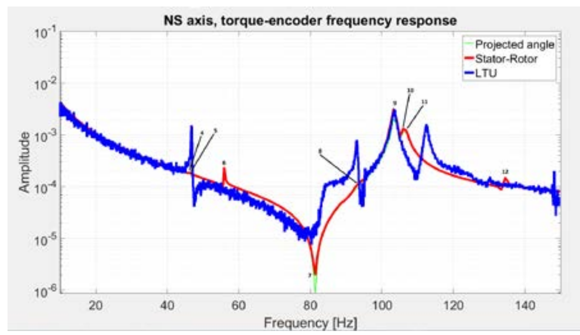

Figure 6. open loop transfer function voice-coil to encoder (N/S axis) compared to the correlated model

After this correlation, the simulation produces similar results than observed in the LTU test program with a stable behaviour in horizontal configuration and instability in vertical orientation as shown in ‘Fig 7’.

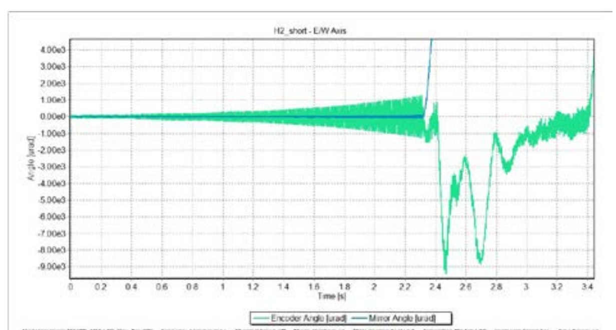

Figure 7. LTU simulation in vertical orientation, encoder angle versus time.

What is not directly visible in the open-loop characterisation test data but can be identified thanks to the simulation tool is that two modes (number 9 and 10 in ADAMS, see ‘Fig. 6’) get closer in frequency in the correlated LTU. This was not the case in the original plant and produces translation near 104Hz that, when properly reported in terms of encoder electrical signal, lead to the instability. Having two modes close to each other is due to an unluckily pairing of N/S and E/W flex spiders for which the stiffness is sensitive to manufacturing tolerances. The scanner orientation and impact of gravity slightly changes the stiffness and could lead to an increase in amplitude of those combined modes.

The simulation tool predicts a stable behaviour when restoring the eddy-current damping. This prediction could serve to refurbish the LTU without the need of exchanging the flex spider. Magnetic field analysis has been performed in order to update the design of the passive damping element. The achievement of adequate damping has been validated on the qualification model.

The implemented lesson learned is to correlate the model based on component level characteristics in order to avoid inadequate pairing of flex spiders before the assembly phase. The open loop characterisation test is also part of the test campaign for each model with an extended frequency range allowing accurately correlating the simulation tool without the need of a micro-vibration facility.

CORRELATION AND BUDGET

QM Correlation

The natural frequencies having the most significant impact on the pointing budget are related to the flex pivots. The translational stiffness of those elements has been estimated by measuring the deflection of the axis under gravity (i.e. gravity sag test). The rotational stiffness is measured at axis level and serves to tune the torque compensation unit.

The second step is the already described free oscillation test and finally the use of the newly introduced open-loop characterisation test described in the previous section. Figures 8 to 10 show the transfer function from voice-coil to encoder at neutral position after having correlated the flex spider stiffness. Only for the "QM corr" state-space matrix, the damping has been fine tuned.

On those graphics, the FEM generated transfer function only includes the projected angle while ADAMS uses in addition the rotor-stator displacement. As highlighted in previous section and 'Fig. 10', the impact of those translational modes on the encoder electrical signal is important to consider as they can influence the controller and generate a cross-coupling effect in the 100Hz region.

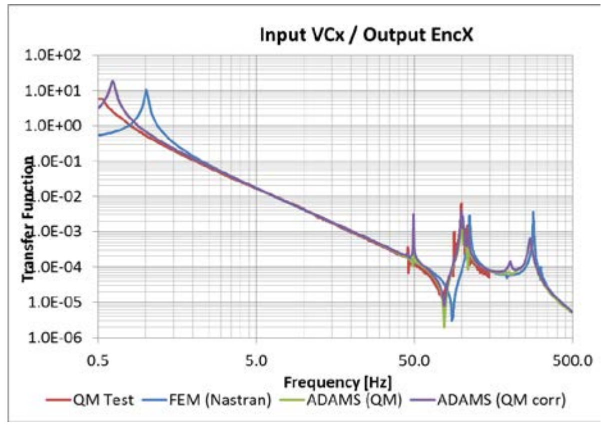

Figure 8. QM correlation, N/S axis transfer function from voice-coil to encoder

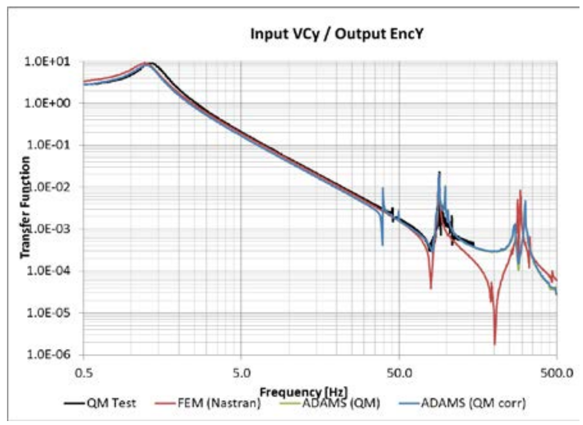

Figure 9. QM correlation, E/W axis transfer function from voice-coil to encoder

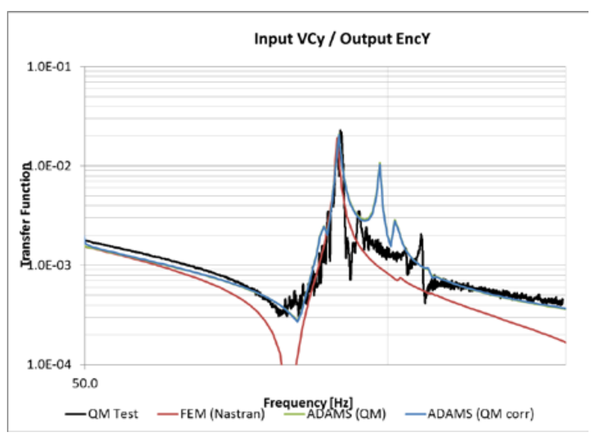

Figure 10. QM correlation, E/W axis transfer function from voice-coil to encoder - zoom in

Pointing Budget

The simulated 15µrad step and stare motion without injected micro-vibration is reported in 'Fig. 11'. The mirror (in blue) is more stable than the encoder noise thanks to appropriate selection of the controller bandwidth. What is also visible is the variation of the relative error between each step mainly due to the encoder harmonic error with a period of 349µrad. This is currently not compensated by the electronics even if all tests performed so far indicate that such error is relatively stable over the mission lifetime.

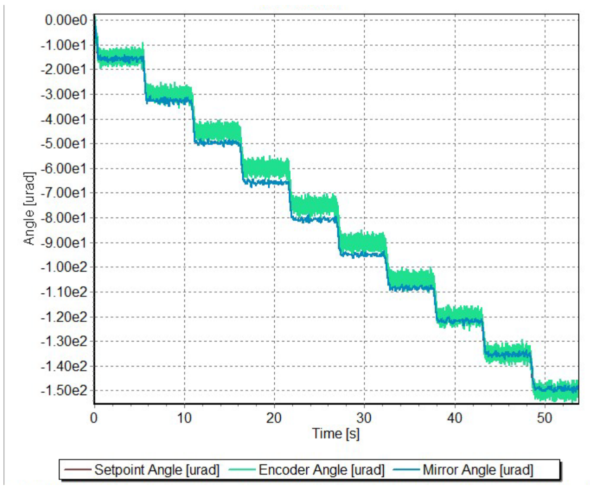

Figure 11. N/S 15µrad step and stare motion

During a scan, the error can be averaged within a dwell of 6.5seconds. This allows reducing the high frequency noise. The pointing error under micro-vibration within a 40 µrad/s scan is shown in 'Fig. 12' and compared to a linear best fit.

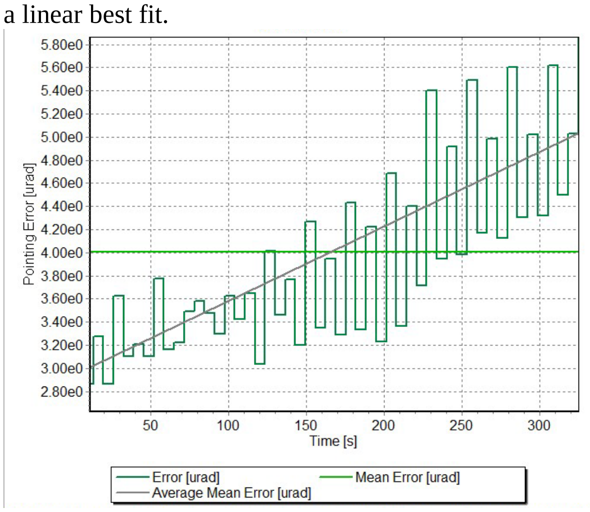

Figure 12. E/W relative dwell error during a scan

CONCLUSION

Developing a two axes scanner subsystem with an accuracy of a few micro radian and 20 degrees motion range is challenging. The use of self-developed flex pivots instead of using pre-loaded ball bearings is advantageous in order to have repeatable characteristics. This repeatable error as well as misalignment and encoder disk mark error is characterised on ground and corrected by the control electronic. However the impact of the large number of natural frequencies and cross-coupling effect on the close-loop controller need to be properly assessed. This has been mastered in the Sentinel-4 scanner sub-system project by establishing a detailed Matlab/Simulink model coupled with MSC-ADAMS.

The selection of the overall architecture, key component and the flow-down of the specification have been achieved mainly based on the outcome of scanner level simulation. During the project, the model allows to explore different options, run Monte-Carlo analysis and selection of appropriate passive damping elements in order to minimise exported disturbances. The close-loop model also supports investigation of an anomaly occurring during life testing and is part of the qualification activity.

In order to provide useful results, the plant is to be accurately represented including non-linearity. Therefore a multi-disciplinary approach is required where outcome of dedicated component level analysis and tests is used in the end-to-end simulation. Such approach allows accurate representation of each key element in nominal as well as in worst-case condition and application of the specified uncertainty factors. The structural elements, permanent magnets and eddy-current damping have been modelled using MSC-ADAMS and then exported as state-space matrixes in order to optimise simulation time.

The scanner model has been successfully used for qualifying the controller using hardware in the loop. The open loop test performed with the qualification model correlate with the original model and the scanner perform so far as expected. The foreseen qualification campaign will allow verifying the accuracy of the prediction under the representative micro-vibration environment and the exported disturbances.

The thermal challenge and thermo-elastic depointing have been mastered by adding the error to the overall pointing budget under various working conditions and including the ECSS motorization factors. Thermal mapping of the thermal cases have been performed including closed-loop thermal control in NX environment.

In conclusion, pointing performance simulation using an accurate model is necessary through the full project life cycle from proposal phase up to qualification. Currently, no facility is able to test the in-orbit conditions with combined micro-vibration, EMC, thermal-vacuum and over the full motion range. In this context, combination of simulation and test is required in order to demonstrate compliance to the requirements. Currently investigation is performed in order to extend the simulation model to include representative disturbance of the overall instrument. This would allow assessment of the pointing budget with the expected micro-vibration environment instead of using a conservative flow down of the input levels at sub-system interface.