Analytical optimization and test validation of the Sub-micron Dimensional Stability of the CHEOPS Space Telescope's CFRP Structure

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ABSTRACT

The CHEOPS (CHaracterising ExOPlanet Satellite), which is an ESA mission developed in cooperation with Switzerland and a number of other member-states, is the first one dedicated to search for transits by means of ultrahigh precision photometry on bright stars already known to host planets. The optical design is based on a Ritchey-Chretien style telescope to provide a de-focussed image of the target stars.

The telescope's mirrors M1, M2 as well as the focal plane detector are supported by a thermally controlled CFRP structure suspended on isostatic mounts. The dimensional stability of the structural system supporting the optics is a key requirement as it directly impacts the instrument's accuracy. The M1 and M2 mirrors are supported by a tubular CFRP telescope design which has been optimized by analyses down to carbon fibre layer level with the support of extensive sample test results for model correlation and accurate dimensional stability predictions. This sample characterization test campaign has been conducted on samples with different carbon fibre layups (orientation and stack sequence) to measure accurately the Coefficient of Thermal Expansion (CTE) over a wide temperature range extending from -80°C to +80°C. Using the correlated Finite Element Model, the fibre orientation layup that minimized the relative displacement between the M1 and M2 mirrors, including the consideration of the thermo-elastic contributions of the isostatic mounts on the overall stability of this optical system, has been identified and selected for the baseline design of the CHEOPS Structure.

A dedicated Structural and Thermal Model (STM2), which was then refurbished to a PFM, was manufactured and tested with an ad hoc setup to verify the overall structural stability of the optical train assembly [2]. The relative distance between M1 and M2 was measured under thermal vacuum conditions using laser interferometer techniques. Thermal cycling tests were initially conducted to eliminate and characterize settling effects. Then, the structure's stability was measured at three stabilised operational temperatures: -5, -10 and -15°C. The thermally induced M1-M2 misalignment on the optical axis was measured to be between -0.156 and -0.168 micron/°C. Relative mirror tilt and lateral centre shifts were also measured. The obtained focal distance, tilt and centre shift stability between mirrors M1 and M2 were all compliant with the system level requirements such that both an STM and PFM model of the CHEOPS CFRP Structure were successfully qualified and delivered in due time for integration on the spacecraft.

Keywords: CFRP, structure, space telescope, exo-planet, sub-micron stability, low temperature

1. INTRODUCTION

The CHEOPS mission (CHaracterising ExOPlanet Satellite), a mission partly founded by ESA and partly by member states of the CHEOPS consortium, is the first one dedicated to search for transits by means of ultrahigh precision photometry on bright stars already known to host planets. By being able to point at 60° off the equatorial region, it will provide the unique capability of determining accurate radii for a subset of those planets for which the mass has already been estimated from ground-based spectroscopic surveys. It will also provide precision radii for new planets discovered by the next generation ground-based transits surveys (Neptune-size and smaller) [1].

The telescope will reside on a spacecraft (S/C) platform providing pointing stability of < 4 arcsec rms over a typical 48 hour observing period. The S/C will be 3-axis stabilized but nadir locked. The S/C will provide 60W continuous power for instrument operations and allow maximum 1.2 GBit/day downlink. The S/C will be provided by Airbus-ECE Espacio based on the AS250 S/C bus [1], [2] and [3].

The optical design is based on a Ritchey-Chretien style telescope to provide a de-focussed image of the target star. An industrial study has led to a suitable optical design, which also minimizes stray light onto the detector utilizing a dedicated field stop and a baffling system. This design meets the requirement of 20 ppm for a 9th magnitude star stray light onto the detector even in the worst case observing geometry on the baseline orbit. The detector is thermally controlled at ~10 mK to minimize noise by coupling the detector to a radiator (see figure 1) that is always exposed to deep space [1]. All optical components are supported by a structure mainly made out of CFRP. An overview of this structure, called CHEOPS Optical Telescope Assembly (OTA) is given in figure 1.

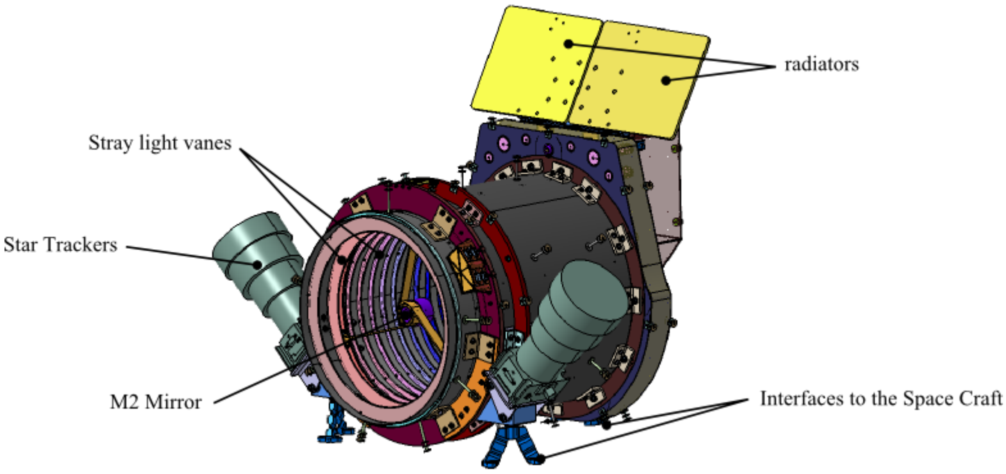

Figure 1: Overview of the CHEOPS OTA supporting the M1 and M2 mirrors, the Back End Optics (BEO) and Focal Plane Module (FPM).

The M1 Mirror is a 32 cm concave mirror that is fixed by 3 points to the Optical Bench. The incoming light from the observed object is concentrated onto an M2 mirror that is a convex mirror placed at about 30 cm from M1, on the optical axis and fixed to the telescope tube by a metallic structure called the "M2 Spider". The lighting is then forwarded onto the Back End Optics (BEO) that will redirect the light to the focal plane module and onto the detector (see Figure 2).

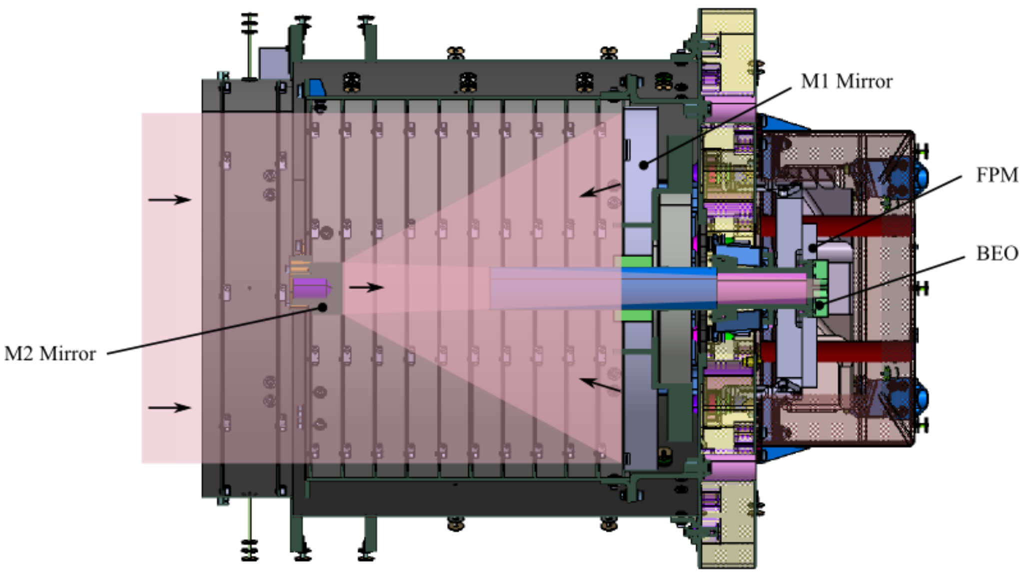

Figure 2: Optical layout of the CHEOPS telescope

During on orbit operation, the telescope tube is thermally controlled. The thermal control system that is placed all around the telescope tube is designed to maintain the temperature of the telescope tube at -10°C ±1°C but designed for a variation of ±5°C. The exact map of temperature was calculated with ESATAN at system level and provided as an input for the thermo-elastic optimisation and verification. To achieve the targeted optical performances of the instrument, the thermo-elastic deformation due to the variation of temperature was to be minimized. The on orbit stability requirements specified by the instrument Prime are provided in Table 1.

Table 1: On orbit stability requirements

On Orbit Stability	Requirement
M1-M2	
Defocus (x)	>0.72 µm
Tilt	>4 µrad
M1-BEO	
Defocus (x)	>9 µm
Tilt	>4 µrad
BEO-FPM	
Defocus (z)	>10 µm
Tilt	>20 µrad

Optimization method To reach the thermo-elastic in-orbit stability given in Table 1, a theoretical study, backed up by extensive sample measurements, was conducted. This study was then verified experimentally with a dedicated CHEOPS OTA Structural and Thermal Model (STM2), which was fully representative of the flight model in terms of mechanical and thermal aspects. Each of these phases are described in the following paragraphs.

The method followed is schematically shown below

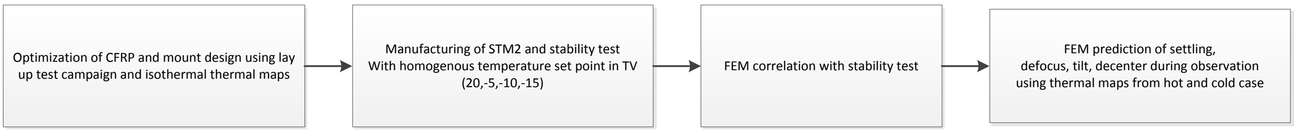

Figure 5 optimization and stability and settling requirement verification

Finite Element Model

First, a full and detailed Finite Element Model (FEM) was built (see Figure 3). The full 3D geometry was used as baseline for the FEM model. All thin structures were modelled by shell elements. Thick structures such as bipods, mirrors, mirror's supports were modelled with solid elements to fully capture the stress and strain distribution over the thickness. It was also necessary to fully mesh with solid elements the mirror themselves to capture the thermo-elastic behaviour of these key elements. The Optical Bench, which is a sandwich structure, was modelled with solid elements for its core and with shell elements for the facesheets. Special care was paid to model all connections as close as possible to reality without using contact elements. All inserts in the optical bench were fully modelled as well as the screwed connections from the different structures.

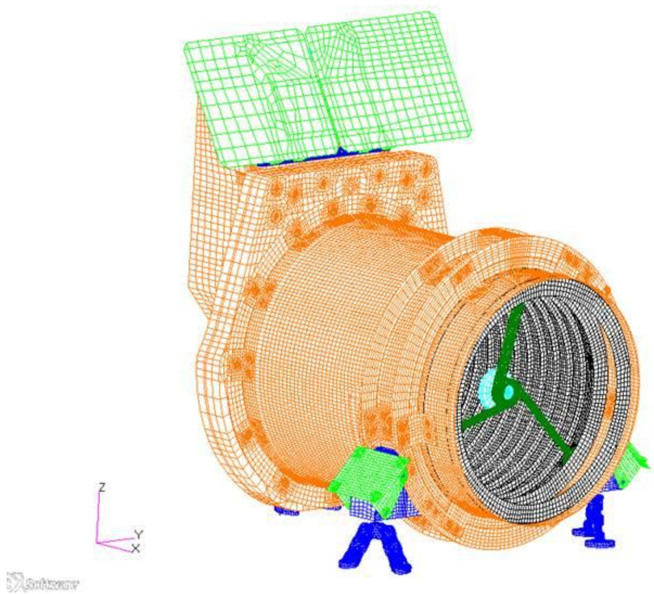

Figure 3: Overview of the Finite Element Model of the CHEOPS OTA

A system of cleats was used to attach the tubes to the optical bench, which are L-Shape CFRP structures that allow bolted connection on both sides. This approach was chosen to avoid the use of glued connections in the optical direction such to minimize the thermal expansion on this axis. In addition the designed dismountable fixation system allows a rapid mirror replacement. This was indeed necessary as the flight mirrors were not used for the qualification test campaign of the CHEOPS structure but dummy mirrors were used instead. This approach was used for both the STM and PFM.

All CFRP parts were modelled using MSC.Nastran PCOMP modelling method. This approach is based on the effective layup of each CFRP lamina and the stacking sequence to calculate the equivalent, homogenized stiffness of the laminate. It also allows to calculate the stresses in each ply as well as the interlaminate shear stresses. Using such method permits having a detail view on the effect of the orientation of each ply on the global properties, while keeping acceptable computational time. Thus, the orientation and properties of each ply can be explicitly taken into account in the overall stiffness, coefficients of thermal expansion (CTE), and moisture expansion (CME) of the structure.

The complete FEM model is composed of more than 450'000 elements. About 70% of these elements are solid elements, the rest being shell, bar or point elements. Standard quality assurance requirements for space flight structures were applied to the FEM modelling and analyses. Mass and centre of gravity verifications w.r.t. the CAD model were performed as well as element geometry checks, 1G check, static equilibrium, stiffness matrix maximal ratio, strain energy check, free-free check as well as zero stress checks. All these verifications were passed successfully.

ESATAN thermal maps were then imported in the MSC.Nastran model to get the most realistic temperature distribution. Linear thermoelastic analyses were then performed. Based on these results, the distances between the different optical elements were calculated.

Sample Test Campaign

The results of the FEM analyses are directly dependent on the properties of each CFRP lamina and the stacking sequence that constitute the lamina. Although the lamina theory is well established, the stiffness, mass density, CTE and CME of each lamina and laminate depend on the manufacturing process for the sub-micron stability required for optical structures in CFRP. To get the best possible numerical model, it was required to quantify these parameters by tests on samples, prior to manufacture the full structural and thermal model of the CHEOPS structure. This was done with an extensive test campaign on samples.

The first goal of this test campaign was to get an overview of the effect of lamina layup on the laminate CTE and CME properties. To this aim, a series of layups were tested (see list in Table 2). The second goal was to get stiffness and strength values for stress analyses. These tests are included in Table 2 as well.

Table 2: List of CFRP layup tested during the sample test campaign

Layup ID	Orientation of the lamina	Number of sample				
		CTE	CME	Traction	Compres-sion	3 point bending
1	$[0, 0, 0, 0, 0, 0, 0, 0]_s$	2	2	14	7	-
2	$[90, 90, 90, 90, 90, 90, 90, 90]_s$	2	2	6	-	-
3	$[0, 10, 90, -10, -10, 90, 10, 0]_s$	2	-	-	-	-
4	$[0, 20, 90, -20, -20, 90, 20, 0]_s$	2	-	-	-	-
5	$[0, 30, 90, -30, -30, 90, 30, 0]_s$	2	-	-	-	-
6	$[0, 40, 90, -40, -40, 90, 40, 0]_s$	2	-	-	-	-
7	$[0, 45, 90, -45, -45, 90, 45, 0]_s$	-	-	-	-	43
7	$[0, 50, 90, -50, -50, 90, 50, 0]_s$	2	-	-	-	-
8	$[0, 60, 90, -60, -60, 90, 60, 0]_s$	2	-	-	-	-
9	$[0, 70, 90, -70, -70, 90, 70, 0]_s$	2	-	-	-	-
10	$[0, 80, 90, -80, -80, 90, 80, 0]_s$	2	-	-	-	-

The stiffness, strength, CTE, CME and mass density results obtained from this sample test campaign were then used in the FEM model to gain a better prediction of the structural behaviour of the CHEOPS structure.

STM2 full scale stability test campaign

Using the results of the sample test campaign together with the detailed FEM allowed the identification of the best layup for the CHEOPS main telescope tube. The layup corresponding to the minimal thermoelastic deformation in the defocus direction in orbit was then selected as baseline for the STM design. This optimization was initially done applying homogeneous thermal working point to the telescope and then later it was possible to correlate the FEM with stability test results and verify the requirement using the predicted thermal map for the hot and cold case.

A full structural and thermal model was then manufactured according to the selected layup based on the FEM results outcome (see Figure 4).

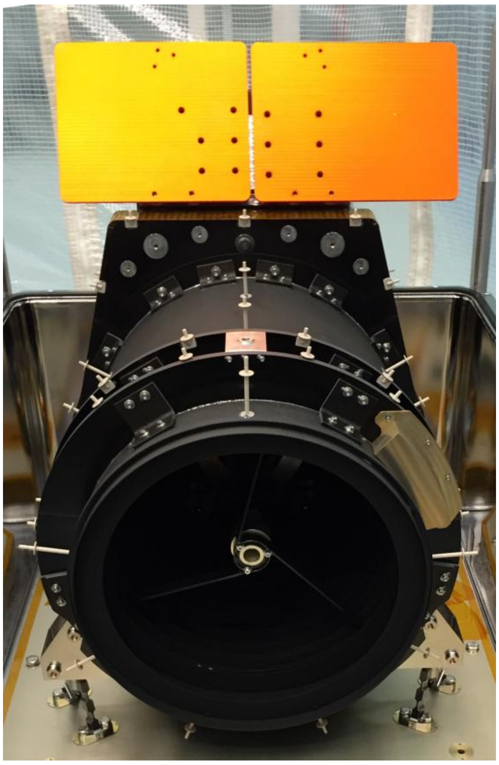

Figure 4: Structural and Thermal CHEOPS OTA model

Optical stability tests were then performed to validate the defocus, tilt and decentre of the M1 and M2 mirrors. These tests were developed in collaboration with TNO (Delft, The Netherlands) and performed at their facilities. A detailed presentation of the test method and conditions is documented in [4].

The test was conducted under vacuum, at 20°C, -5°C, -10°C, and -15°C. Two measurements were performed for each temperature after its stabilisation. The temperatures were measured at 20 different locations to closely map the thermal gradients. Stabilisation criteria were used both on absolute temperature stability as well as on the gradients.

In summary, the CHEOPS OTA was equipped with M1 and M2 mirror dummies that supported reflective, parallel test mirrors. Using three interferometric lasers measuring the relative distance between the M1 and M2 mirrors at 3 different known locations, it was possible to derive the relative defocus, decentre and tilt of the two mirrors.

The FEM model was then correlated with the stability test. Using the correlated FEM model, settling and stability requirement performances were then predicted and compared to the requirement, as shown in the following chapter.

2. TEST STABILITY RESULTS AND REQUIREMENT VERIFICATION

As anticipated by the laminate theory, the CTE of each laminate is very sensitive to the lamina orientation. The layups tested (see Table 2) show either positive or negative CTE in the 0° direction depending on the lamina orientation and stacking sequence. For quasi-isotropic layup the CTE is nearly zero at -10°C. For unidirectional laminate, the CTE in the fibre direction is negative, which is a well known property for high strength, high modulus carbon fibres. Thanks to sample tests in the range of -80°C to +80°C, it is possible to get the full temperature dependency of the CTE over this range. As a matter of fact, the CTE varies significantly with temperature, which indicates that the best layup for a given operating temperature might be different for another operating temperature and application.

The results from the sample test campaign were used to compute the stability of the different optical elements. The most important requirement is the defocus stability of M1 and M2 as this directly impacts the science performance of the instrument. Thanks to the finite element model, it was possible to identify the different contributors to the overall defocus. In fact, the relative position of the M1 to M2 is not only determined by the telescope tube movement but also by the deformation of the M1 mounting structure and M2 Spider. Detailed analyses showed that the defocus is mainly due to the deformation of the M2 spider and of the telescope tube. The M1 mirror and M1 Mounts have relatively small contributions to the overall deformation.

Therefore, the material that was selected for the M2 Spider was Invar. Indeed, such material has a small CTE in all directions, typical value are between 1.0 and 1.6 ppm/°C, while having a relatively good strength and stiffness which is required to withstand the launch loads. An additional reason to choose invar was that it can be well machined, allowing the realisation of tight tolerances to guarantee the accurate positioning of the M2 mirror. On the other hand, the CTE of Invar is a given property that cannot be changed such that the contribution of the Spider to the overall defocus cannot be adapted easily.

Conversely to Invar, the CTE of the material of the telescope tube can easily be changed. Indeed, by changing the lamina orientation, the axial, radial and tangential thermo-elastic behaviour of the telescope tube is impacted. Using the anisotropic behaviour of CFRP, it is possible to search for the lamina layup that minimizes the defocus between M1 and M2. Using the full FEM model and thus taking into account stiffness relationships and induced deformations, the layup that minimised the defocus between M1 and M2 is the quasi-isotropic one (layup 7 of table 2).

With a quasi-isotropic layup, the CTE of the chosen CFRP is slightly positive at -10 °C. Thus, when the CHEOPS structure is cooled down the Telescope slightly contracts in all directions. The pairing with invar parts connecting the M2 to the telescope tube with a higher CTE than the CFRP one, intrinsic to the invar material, causes a pivoting effect of the M2 spider around the telescope tube's tangential direction, distancing the M2 from the M1 mirror. The two movements have the tendency to cancel each other out.

Using the system level thermal maps, the different on orbit stability criteria were calculated. As shown in Table 3, the prediction of the optical object distance variation meets all requirements. In particular, the stringent requirement for M1-M2 defocus is met with comfortable margin as the zero deformation was targeted.

Table 3: On orbit stability requirement compared to the calculated FEM results

Optical Path	**FEM calculated**	**On-Orbit Stability Requirement**	**Status**
M1-M2			
Defocus (x)	-0.01 µm	0.72 µm	PASS
Tilt	0.34 µrad	4 µrad	PASS
M1-BEO			
Defocus (x)	-0.34 µm	9 µm	PASS
Tilt	2.10 µrad	4 µrad	PASS
BEO-FPM			
Defocus (z)	-0.01 µm	10 µm	PASS
Tilt	3.73 µrad	20 µrad	PASS

The results shown in Table 3 are obtained with an FE- model correlated to the STM full scale test campaign. During the STM test campaign, the temperature map was different from the on-orbit temperature map. As indicated in the Method, a homogeneous gradient was imposed, thus the requirement shown in Table 3 could not be verified directly. Therefore, the FEM model was used to calculate the defocus with a homogeneous temperature map and compared to the measured values. The results are shown in Table 4.

Table 4: STM test measured M1 and M2 defocus compared with the FEM prediction

Temperature	**Test Results**	**Correlated FEM**
From 20°C to -15°C	5.96 µm	5.95 µm
From -5°C to -10°C	1.1 µm	0.85 µm
From -10°C to -15°C	0.8 µm	0.85 µm

The achieved stability of the M1-M2 focus distance is thus -0.167 µm/°C between 20°C and -15°C. In the operating range of -5°C to -15°C, the defocus stability is smaller than -0.172 µm/°C.

The correlated model was also used to predict the pointing settlings due to 1g to 0g release, moisture release due to vacuum and thermo-elastic variation due to temperature variation between room temperature (20°C) and the operating temperature of -10°C. The FEM results together with the requirement are shown in the table 5.

Table 5: Settling stability prediction by FEM and requirements.

criterion	1g-0g Release	Moisture	Thermal	TOTAL	Requirement	Status
M1-M2						
Defocus (x)	-0.01 µm	-2.89 µm	4.47 µm	1.57 µm	16 µm	PASS
Decenter (y)	0.13 µm	-0.04 µm	0.89 µm	0.98 µm	16 µm	
Decenter (z)	7.13 µm	0.44 µm	-1.54 µm	6.04 µm	16 µm	
Tilt	3.413 µrad	0.045 µrad	2.881 µrad	6.338 µrad	110 µrad	PASS
M1-BEO						
Defocus (x)	0.92 µm	0.25 µm	-15.91 µm	-14.74 µm	29 µm	PASS
Decenter (y)	-0.02 µm	0.00 µm	0.04 µm	0.02 µm	29 µm	
Decenter (z)	1.95 µm	-0.08 µm	-1.47 µm	0.39 µm	29 µm	
Tilt	34.554 µrad	0.030 µrad	11.741 µrad	46.325 µrad	75 µrad	PASS
BEO-FPM						
Defocus (x)	1.41 µm	-0.38 µm	-10.98 µm	-9.95 µm	30 µm	PASS
Decenter (y)	0.00 µm	0.00 µm	0.60 µm	0.60 µm	30 µm	
Decenter (z)	-2.57 µm	-1.05 µm	-5.78 µm	-9.40 µm	30 µm	
Tilt	20.230 µrad	0.636 µrad	23.095 µrad	43.961 µrad	100 µrad	PASS

3. CONCLUSION

The combination of a detailed FEM and extensive stability test campaigns performed at sample level and on a full scale model allowed to optimize the M1-M2 mirror's defocus stability of the CHEOPS OTA. The sample test campaign established a reliable database of CTE, CME, stiffness, strength and mass density properties for a variety of lamina orientation and stacking sequence and for temperatures between -80°C and +80°C. This sample properties database was successfully used to optimize the layup of the CHEOPS OTA telescope tube so that all on orbit stability requirement as well as settling stability are met.

The STM full scale stability test campaign (see [2] for more details) shows that the chosen layup and design were effective in meeting the stability requirements. The measured stability of the CHEOPS OTA when subjected to a homogeneous temperature change is better than -0.172 µm/°C within the on orbit temperature range of -5°C to -15°C.

Using the FEM correlated to the STM test campaign and the calculated on-orbit thermal maps, the prediction of the on-orbit de-focus between M1 and M2 is -0.01 µm within the operating temperature range.

In addition, the settling stability requirements were fulfilled taking into account 1g to 0g environment change, moisture release, thermo-elastic deformation due to temperature change from room temperature (20°C) and on orbit operation at -15°C. The defocus between M1 and M2 due to the combine environmental changes is calculated to be smaller than 1.6 micron (see table 5).

The CHEOPS OTA STM and PFM were successfully qualified and delivered on time by Almatech to University of Bern. The launch of the spacecraft is now scheduled to be for 2018.

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