The performance of the CHEOPS On-Ground calibration system

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ABSTRACT

The CHEOPS space mission will measure photometric transits of exo-planets with a precision of 20 ppm in 6 hours of integration time on a 9th magnitude star. This corresponds to a signal-to-noise ratio of 5 for a transit of an Earth-sized planet orbiting a solar-sized star. Achieving the precision goal requires precise on-ground calibration of the payload to remove its signature from the raw data while in flight.

A sophisticated calibration system will inject a stimulus beam in the payload and measure its response to the variation of electrical and environmental parameters. These variations will be compiled in a correction model. At the very end of the testing phase, the CHEOPS photometric performance will be assessed on an artificial star, applying the correction model

This paper addresses some original details of the CHEOPS calibration bench and its performance as measured in the lab.

Keywords: exoplanets, photometric transits, stable light source

1. INTRODUCTION

CHEOPS measure measure the transit of exoplanets of radius ranging from 1 to 6 Earth radii orbiting bright stars. The required photometric stability to reach this goal is of 20 ppm in 6 hours for a 9th magnitude star.

The payload is engineered to be as immune as possible form the environmental changes: A baffle protects it from the high brightness of its low earth orbit surroundings and the sun. The detector and its read-out electronics (ROE) are thermally controlled to 10ppm and 50ppm respectively.

The quick pace of the satellite development and its low cost did not allow having an internal calibration system. Thus, the CHEOPS Instrument System (CIS) behavior will be calibrated thoroughly on the ground and only a small subset of the calibrations can be redone in flight. The main focuses of the calibrations are on the photonic gain value stability and sensibility to the environment variations and the Flat field that has to be known at a precision better than 0.1%.

To this purpose, a significant effort has been placed in the development of a CIS calibration bench. This bench produces very stable illumination patterns for the CIS: either a very uniform illumination on the Field of View of the instrument or a star that can be steered to any point of the field of view. The signal produced by the CIS can be measured and a model of the gain/flat field as a function of the different environmental parameters can be built. In [3] we have described the setup design, in this paper as the setup has come near to completion we will present some of its performances.

2. THE CHEOPS MISSION

CHEOPS is a space mission dedicated to the characterization of exoplanet transits by means of high precision photometry [1]. Its launch is expected end of 2017. It will be the first space telescope dedicated to search for transits on bright stars already known to host planets. By being able to point at nearly any location on the sky, 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 or refine exo-planet radii measured from the ground (Neptune-size and smaller). The main science goal of the CHEOPS mission is to study the structure of exoplanets with radii typically ranging from 1 to 6 Earth radii orbiting bright stars.

The instrument uses a single frame-transfer backside illuminated CCD detector cooled to -40°C and stabilized within ~10 mK. The CHEOPS has a Ritchey-Chretien style telescope with 300 mm effective aperture diameter, which provides a defocussed image of the target star. CHEOPS being in a LEO orbit a high performance baffled has been designed. The telescope is the only payload on a spacecraft platform providing pointing stability of < 2 arcsec rms. This relatively modest pointing performance makes high quality flat-fielding necessary and this is one of the main object of the calibration.

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Figure 1. The CHEOPS satellite L/h, and a cut through the CHEOPS instrument system R/h.

3. SYSTEM DESIGN

The requirements for the calibration system were described in [3]. Essentially there are 2 modes for the bench, a uniform illumination mode for the flat field calibration and a single point source to simulate a star and make photometric tests.

Optically the bench features

- a focal module where the point source creating the artificial star is located. This module is mounted on a Steward platform. A flat field source is also provided in the form of an integrating sphere
- a large off-axis 2540 mm focal length Ø457mm parabolic collimator to send the point-like artificial star to infinity
- a large folding flat mounted on a tip-tilt stage to explore the full field of view
- a large window to separate the bench itself in ambient air from the CIS sitting in a space environment simulator. Technically, this window is not part of the bench but we include it here because it is part of the bench performance budget.

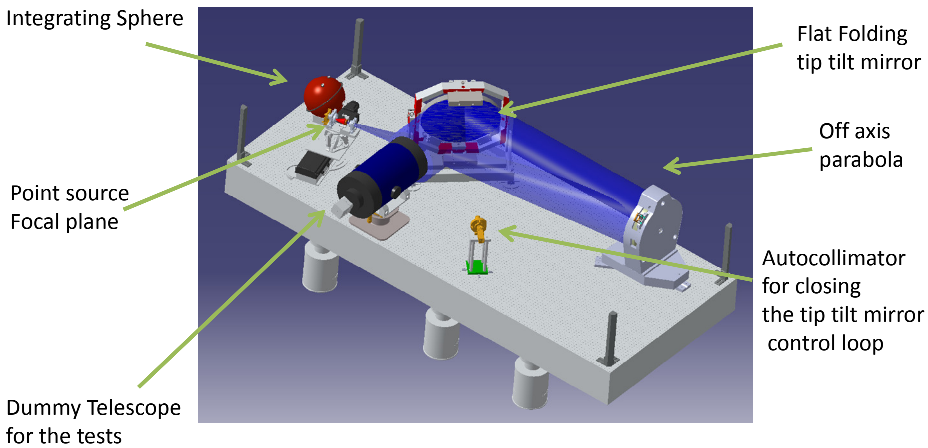


Figure 2. Side view of the calibration bench with the optical beam rendered in blue. This is the configuration used for the validation where a commercial telescope (in blue) simulates CHEOPS. The yellow device is a digital auto-collimator used to servo the folding flat in position.

The focal point module

This module is made of two elements. Only one can be at the collimator focus at any time.

a) a flat-field source in the form of a high grade integrating sphere with a high $\O_{ext}/\O_{port}$ ratio to insure good center-to-edge flatness
b) a point-source unit. This unit incorporates a number of functions
    a. An artificial star in the form of a single mode fiber simulating the object of interest in the field.
    b. 4 additional fibers in the focal plane that are used for the pupil tracking (see figure
    c. An apodizer which role is to transform the Gaussian-like energy distribution in beam coming out of the star fiber into a flat energy distribution as expected in flight. See section "optical budgets".
    d. A pierced mirror reflecting part on the light from the artificial star into a sensing fiber. See section "super stable source".
    e. A mask featuring 4 fiducials used to maintain pupil centration. See section "optical budgets".

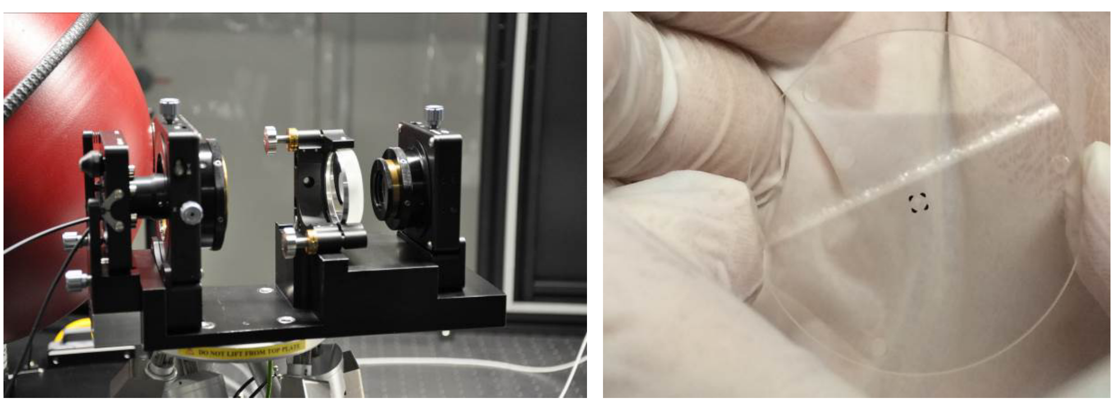


Figure 3. On the left, Side view of the focal plane module. On the right the mask, that allow for the masking of halves pupil on the 4 lateral sources.

4. PUPIL STABILIZATION

The stability of optical power is determined not only by the stability of our light source (see next section), but by the stability of the optical power coupling between the calibration bench and the payload. A variation of this coupling is produced if there is a beam shift and the field in the pupil is not homogenous. This variation will depend on:

- Optical field homogeneity in the beam
- The amount of beam shift on the bench surfaces and between the bench and the payload
- The amount of beam shift on the vacuum enclosure entrance window and the homogeneity of its transmission
- The possible focus variation of the beam which will change the density of the field in the pupil even with a perfect source and no beam shift

Because of the need to have an unresolved point source to simulate the star, we are using a monomode fiber. Therefore the field distribution across the pupil will be close to Gaussian. This strongly varying distribution creates a high photometric sensitivity to relative motions that is unacceptable (refer to Fig 4). Therefore an apodizer has been introduced in the beam.

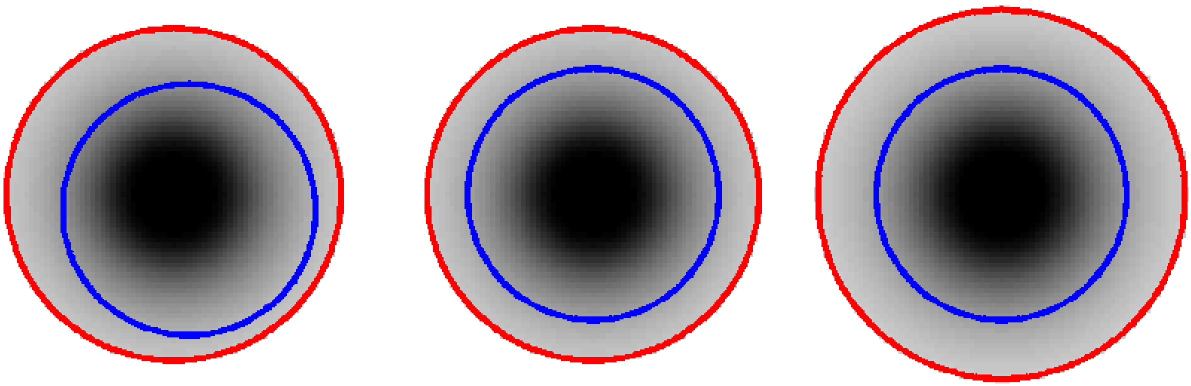


Figure 4. Diagrams underlining the pupil homogeneity problem: The calibration bench pupil is represented in red and its irradiance in is represented in gray tones. The CHEOPS pupil is represented in blue. The optical power measured by the CIS is the integral of the optical field entering its pupil. If there is a motion between the two pupils (L/h), the integral of the field in the blue pupil will vary and so will the photometric signal. If the beam of the calibration bench gets defocused due to temperature variations, then its beam will expand or contract coupling less, respectively more light into CHEOPS.

As described in [3] this apodizer is optimized in white light assuming the sensitivity of the whole optical chain from the source to the detector. The homogeneity obtained is not enough to ensure the stability of the flux thus it is necessary to have a pupil stabilization mechanism.

A set of 4 fiducial stars placed at 90° on a small circle around the reference star have been added. A mask is placed closely placed in front of these fiducials. The purpose of this mask is to make the pupil illumination of this fiducials as contrasted across the pupil as possible. So if the focal plane is tilted, it shifts the energy distribution across the pupil (Fig 5, center), this shift is going to be maximal for the half-moons. One of the half-moons will see a flux increase while to opposite one will see a decrease. Keeping the photometric ratio constant between the up and down, respectively left and right, half-moons forces the bench and CHEOPS pupil to be co-aligned. Since only tilts are involved, the image of the center star and the fiducials set put in the CHEOPS focal plane.

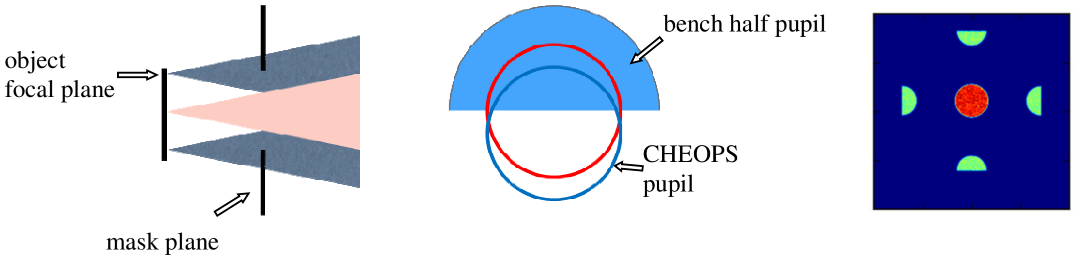


Figure 5: Schematic diagram of the pupil centering scheme. L/h figure: On the focal plane the central "star" emits and unobstructed beam. Two fiducial stars emit beam that are partially obstructed by a mask. Center figure: View of top fiducial beam at the pupil level. Because of the mask, the fiducial pupil is not uniformly illuminated. If the relative position between the calibration system pupil and the CHEOPS pupil changes, the amount to light that is coupled between the two systems will change. R/h figure: image of the central star and the 4 fiducials in the CHEOPS focal plane. If the relative position between the calibration system pupil and the CHEOPS pupil changes vertically, the ratio between the top half-moon and the bottom half moon will change and this ratio can be used as feedback in a control loop

To implement the pupil centering scheme, the focal plane module is mounted on a hexapod. We are using two degrees of freedom (DOF) to rotate the focal plane around the fiber tip. We are using another two DOF's to move the focal plane sideways to simulate the satellite pointing wobble and a last DOF to move the source along the optical axis to adjust the focus of the source.

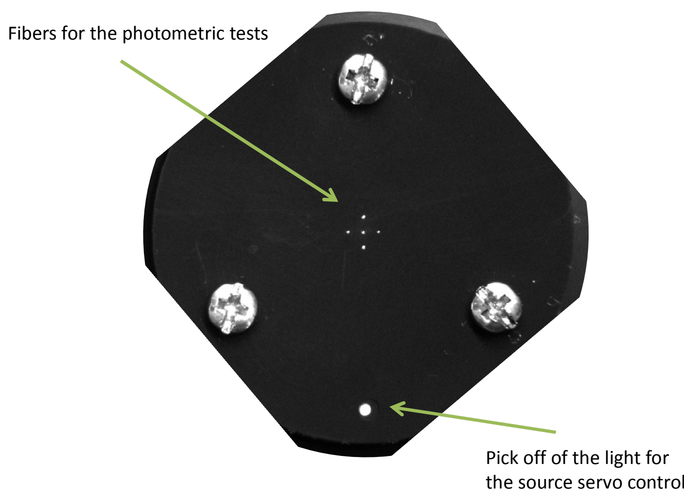


Figure 6. The picture shows the focal plane ferrule with the central star and the four fiducials. The dot at the bottom right is the fiber collecting the light from the pick-off mirror. The screws are holding the anti-reflection mask need to control ghosts.

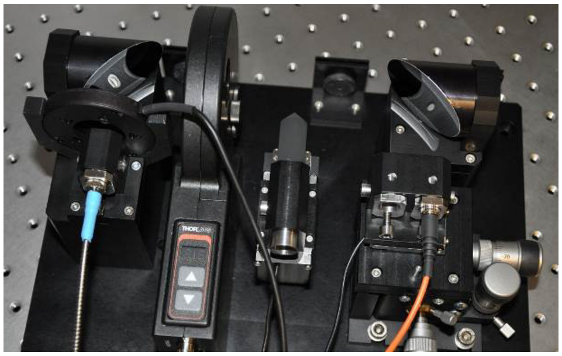
5. THERMAL DEFOCUS

A 1K variation of the ambient temperature will produce ~30 µm rms microns in focus (the table being made out of stainless steel). This will lead to a negligible warfront deformation but, will bring photometric variations. The collimator pupil diameter will vary but the total flux will stay constant. Thus the actual flux collected by the tested telescope would vary. Simple Geometry yield that a 10 micron defocus will produce ~ 8ppm photometric variations. In order to keep this error term low we measure the temperature of the table and use the hexapod to compensate the defocus in open loop.

6. SUPER STABLE SOURCE

For CHEOPS, we have chosen to use an LDLS [5] as primary source because its 10'000K color temperature offers both a flat spectrum across the visible and a high radiance that allows a sizable amount of power to be coupled even in a monomode fiber. We have measured that this lamp has a luminous power output variation in the 1-3% p2v range, i.e. 10'000 to 30'000ppm over 6 hours which is the duration over which the CHEOPS performance is specified. It is obvious that a lamp like that cannot be used without having its flux stabilized.

For this reason, the Observatory of Geneva has developed a luminous power control system that transforms the LDLS in what we call Super Stable Source [4]. Its performances are shown on figure 8.



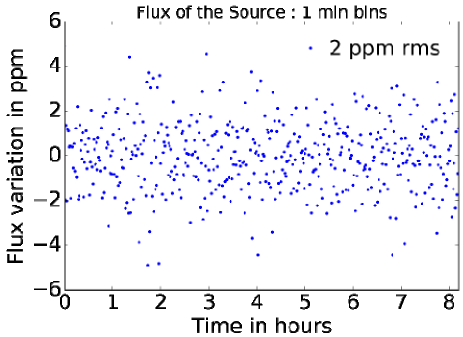


Figure 7. (Left) View of the super Stable source. (Right): performance of this source with stabilization. Stability is about 2ppm RMS when signal averaged in 1min bins

7. MEASURED PERFORMANCE

The whole setup has been assembled and is currently under validations. Here are some of the results obtained:

The wavefront of the collimator measured after alignment <90 nm rms. This does not include the apodizer and the necessary optical density, but is compliant with our 150 nm wavefront error budget.

The focal plane image is:

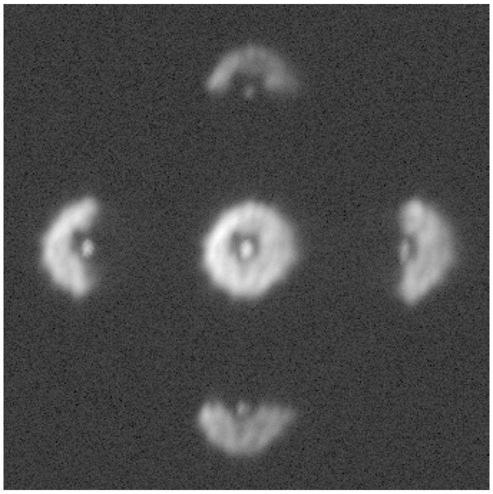


Figure 8 image of the focal plane in the star photometric mode. The central PSF is for the photometric measurement, while the 4 other PSFs are used to measure the pupil movements.

Tip-Tilt mirror servo

The flat folding mirror that sends the beam toward the VV that holds the CIS, is motorized for tip and tilt using high resolution actuators from PI. In combination with a high resolution autocollimator (Newport LDS-Vector) that measure its direction with a resolution of 0.1 microradians we build a servo system using a commodity PC that has a typical time constant of 1 second and a precision of 0.1 microradian

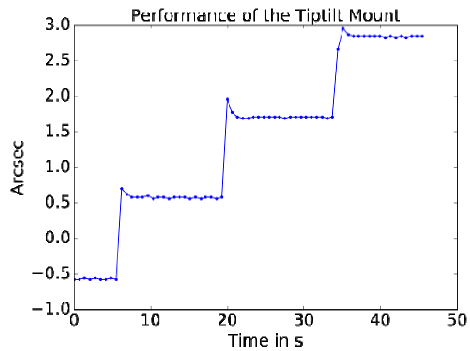


Figure 9 Performance of the titptilt mount in its control loop mode

Tip-tilt control from the payload itself

In order to compensate for the thermomechanical movement of the CIS we are using the payload images to directly measure the measure the relative tip-tilt of our calibration beam and the CIS inside its vacuum tank. With the jitter the performances achieved are below 0.3 arcesc.

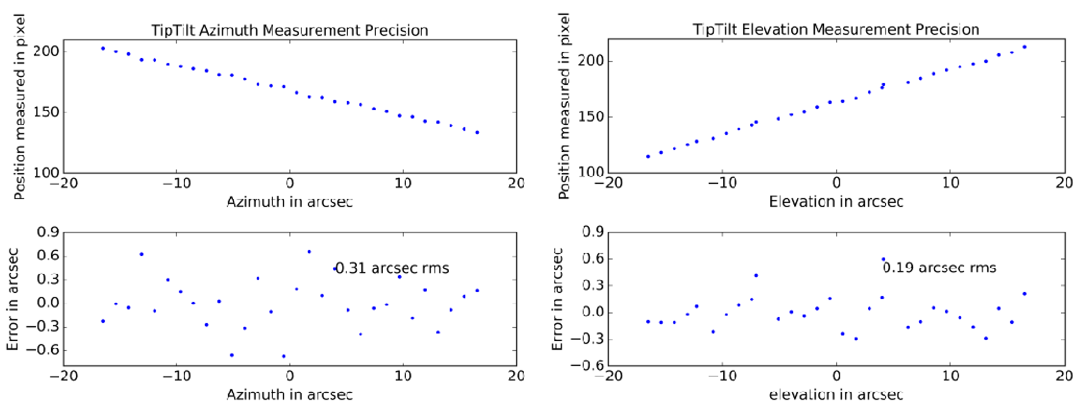


Figure 10 Graph showing the performance of the measurement of the tip-tilt using the dummy Payload CCD, these measurement have been performed in presence of the simulated jitter of the telescope. The PSF has been scanned using the Tip-Tilt mirror to produce these results. The achieved precision is around 0.3 arcsec

Pupil tracking servo

Pupil tracking is working using the photometry. If one build a signal using the top / bottom PSF flux and the Left / right flux one have a signal proportional to the pupil position.

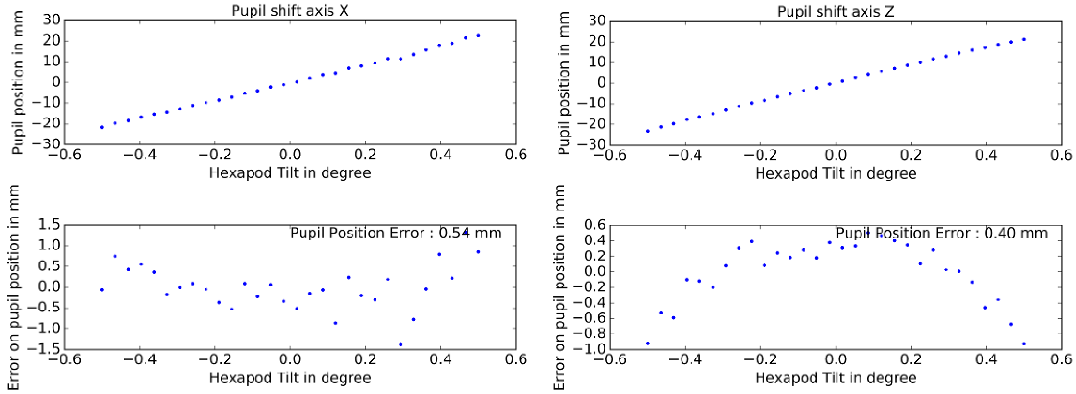


Figure 11 Graph showing the sensitivity of the pupil tracking measurement. The Hexapod below the focal plane is used to make the pupil scan across the pupil. T the achievable precision is better than 0.5 mm/ over the 300 mm pupil which is fine to ensure the performances.

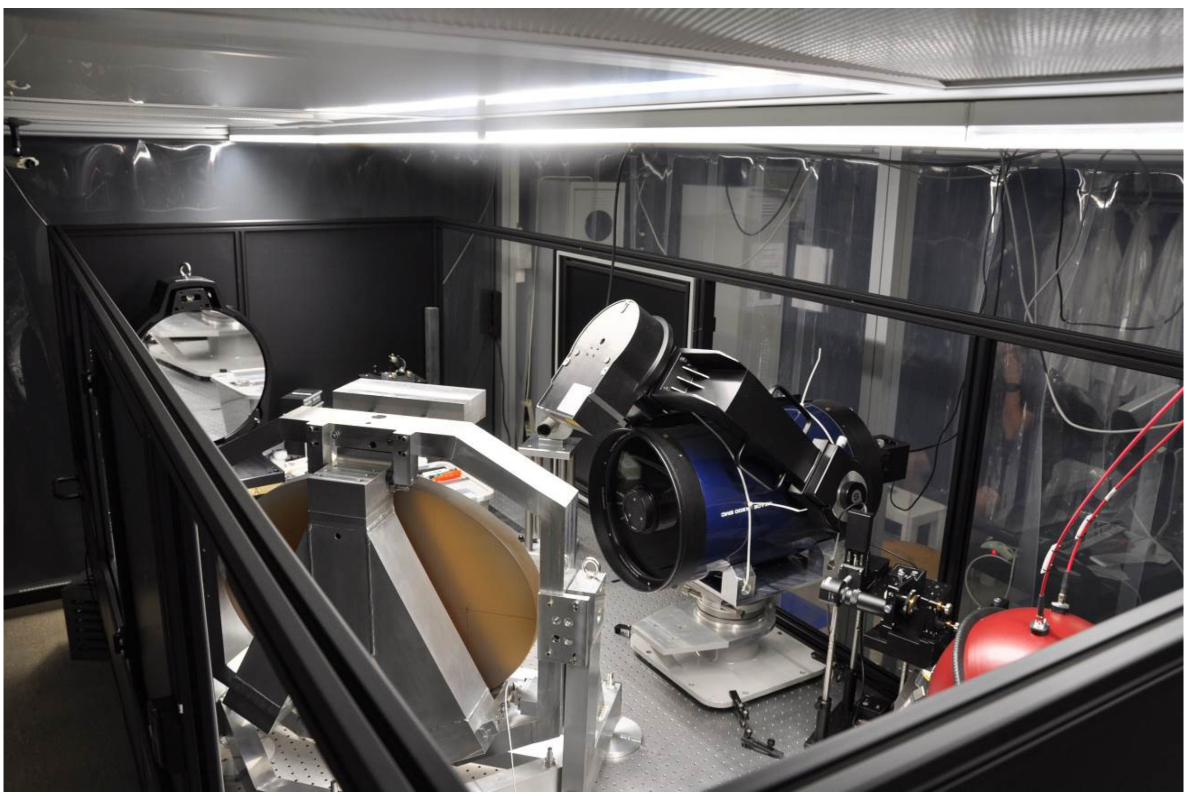


Figure 12. The CHEOPS calibration bench. The commercial telescope (in blue) simulates the CHEOPS payload. In operation the cover is fully closed

CONCLUSION

We have assembled and tested a complex opto-electro-mechanical setup capable of calibrating and validating the performances of the CHEOPS payload. The calibration system is now complete .The performances are in line with our expectations and with the performance budget. The system is now be relocated to the CHEOPS payload integration facilities and will serve to fully calibrate it in the course of 2017. To our knowledge it is the first time the end-to-end verification of the photometric performance of a photometric transit satellite is attempted.

REFERENCES

[1] Benz W. and the Cheops team, CHEOPS: scientific objectives, mission concept and challenges for the scientific community", the 4S Symposium 2014.

[2] V. Cessa, T. Beck, W.Benz, C. Broeg, D. Ehrenreich, A. Fortier, G. Peter, D. Magrin, I. Pagano, J.-Y. Plesseria, M. Steller, J. Szoke, N. Thomas, R. Ragazzoni, F. Wildi & the CHEOPS Team. "CHEOPS: A space telescope for ultra-hight precision photometry of exoplanet transits", International Conference on Space Optics (ICSO 2014).

[3] F. Wildi, B. Chazelas, A. Deline, M. Sordet, M. Sarajlic, "The CHEOPS' instrument On-Ground calibration system. ", Techniques and Instrumentation for Detection of Exoplanets VII, SPIE 9605-45 (2015).

[4] F. Wildi, B. Chazelas, A Deline. "A white super stable source for the metrology of astronomical photometers", SPIE 9605-63 (San Diego 2015).

[5] http://www.energetiq.com/DataSheets/EQ99XFC-Data-Sheet.pdf.

[6] T. Beck et al, "CHEOPS: status summary of the instrument development", SPIE, 9904-75, this conference

[7] N. Rando et al ,"ESA CHEOPS mission: development status, SPIE 9904-74", this conference