CUBESPEC: HIGH RESOLUTION SPECTROSCOPY FROM A CUBESAT PLATFORM

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ABSTRACT

The CubeSpec in-orbit demonstration mission will monitor the spectral line deformations of different β-Cephei pulsators with pulsation periods between 8 and 24h over a 100 days period. This showcase mission will allow physicists to learn more about the observed stars inner structure through asteroseismology and show the feasibility of high-resolution spectroscopy from a small economical satellite. The platform, payload and ground segment are developed by KU Leuven in collaboration with industrial partners arcsec, who delivers the Attitude Determination and Control System (ADCS), and Space Inventor, responsible for the spacecraft structure and main satellite avionics. The payload, designed and built in-house, consists of an off-axis Cassegrain telescope made entirely of a low coefficient thermal expansion ceramic, a high-resolution echelle spectrograph, and custom-built electronics to read out the CMOS science sensors, control the beam steering mechanism and monitor the payload temperatures. To cope with the inherent pointing stability limitations of CubeSat ADCS, CubeSpec adopts a dual-stage pointing control strategy with a second control loop that corrects for residual pointing jitter by redirecting the payload input beam. The second stage, denominated High-Precision Pointing Platform (HPPP), has its own sensor and actuator to measure and compensate for the residual ADCS pointing error. Launch is expected in the course of 2026.

1 INTRODUCTION

Astronomers have access to a wealth of observatories on ground and in space to characterise objects in the universe via analysis of the electromagnetic radiation received from these objects. Specific astronomical questions require time series of observations. Long and uninterrupted time series are typically done from space to avoid interruptions due to day/night cycles and weather circumstances. Large space telescopes are very costly, allocating them for long time series measurements comes at an excessive price. Performing analogous observations from small and economical platforms like CubeSats can drastically drop the cost and make it even feasible to dedicate a mission to monitor a specific set of stars. Several small space telescopes have been developed for long duration photometric monitoring, e.g. to detect exoplanets [1]. So far, high resolution spectroscopy has not been achieved on small satellites due to the challenges with available space and pointing stability. The CubeSpec ESA In-Orbit Demonstration (IOD) mission sets as its objective the demonstration of high spectral resolution observations from a small and economical CubeSat platform. The platform and payload design make it possible to adapt it to a broad range of astronomy missions with only minor changes. The mission is funded by the Belgian federal science policy office BELSPO as part of the ESA GSTP programme and developed by the KU Leuven Institute of Astronomy and Department of Mechanical Engineering. Launch is expected in the course of 2026.

2 MISSION REQUIREMENTS

The primary goal of the CubeSpec demonstration mission is to monitor the spectral line deformations of β-Cephei pulsators with a pulsation period between 8 and 24h with at least one observation every 100min over multiple weeks. The key mission requirements flown down from the demonstration mission science case can be summarised as [2]:

- **Payload requirements:** The onboard payload spectrograph should deliver high-resolution spectra a resolving power of R $>$ 50000 and a Signal-over-Noise ratio (S/N) of at least 200 for the targets in the mission sample. The mission sample has been constructed of stars brighter than visual magnitude 4.
- **Time sampling:** In order to characterise the stellar pulsation modes from the time series of line profile variations, there should be sufficient sampling with 5 to 10 observations per pulsation period whereby every measurement can last up to a maximum of 15min to avoid temporal smearing of the line profile deformations. Every star should be observed over a 100 day period.

Figure 1 shows a simulated deformation of the spectral line of a β-Cephei pulsator similar to what CubeSpec will measure. The shown deformation contains information about the inner star structure through asteroseismology.

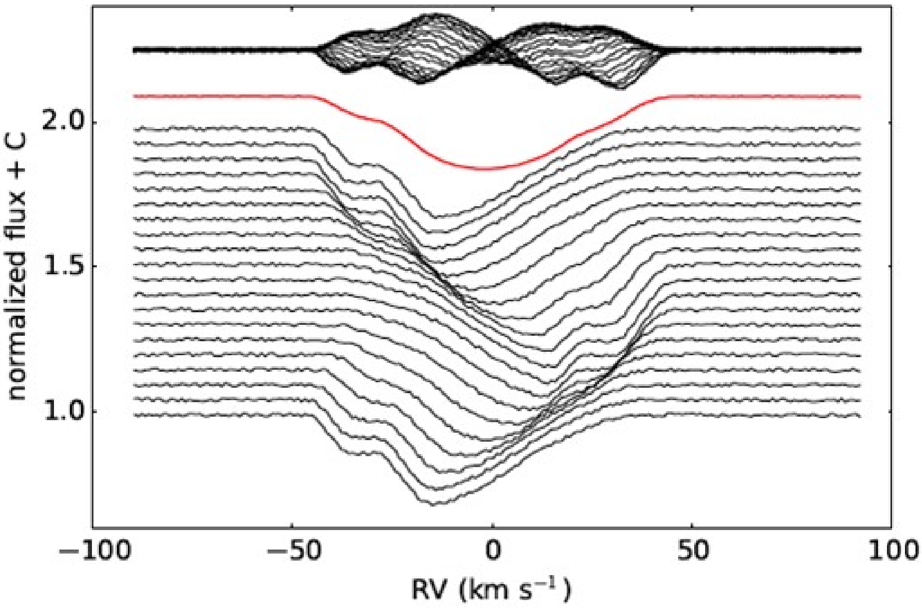

Figure 1: Simulated deformation of a spectral line in the spectrum of a massive star during a 15min observation, data adapted from [2].

3 MISSION PLANNING AND ORBIT SELECTION

Taking as drivers the science requirements, the maximisation of the science duty cycle, and thermal stability, a Sun-synchronous orbit is selected with the latitude of the ascending node around 6AM or 6PM. The orbit altitude lies between 500 and 550km to comply both with the 1 year mission lifetime and the space debris mitigation requirements (de-orbiting within 25 years) whereby 500km is kept as the baseline.
Spacecraft attitude control is subjected to several constraints. For instance, direct illumination of the payload by very bright sources (such as the Sun and the Moon) and direct exposure to the Earth or Sun

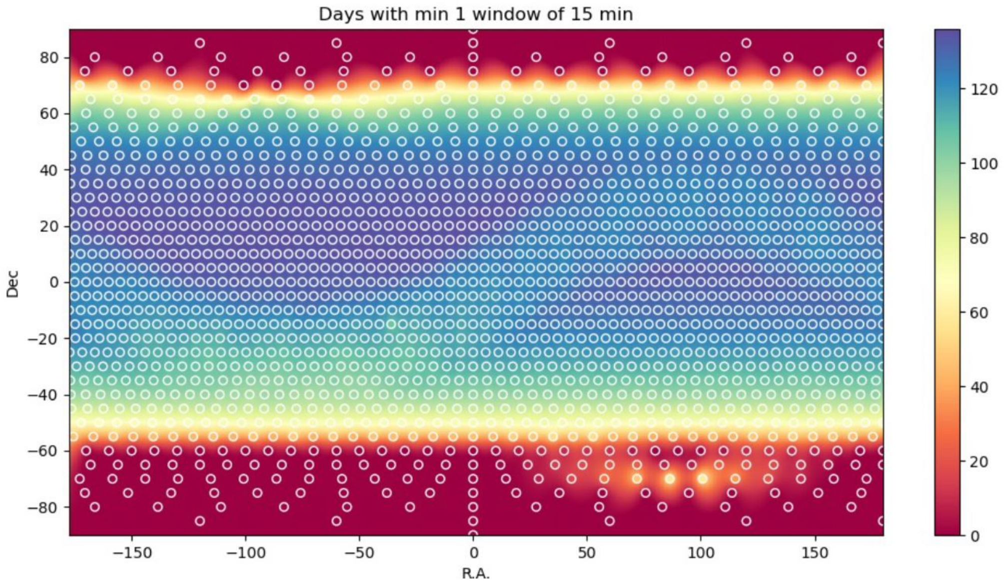

Figure 2: Number of visibility windows of stars of interest for the CubeSpec mission [3].

of the payload radiator should be avoided. These requirements translate into avoidance angles and lead to the identification of observation periods that apply to all constraints as shown by Figure 2. The figure indicates that there are no observation windows for stars close to the celestial poles, which are therefore unreachable for the CubeSpec mission. Several exercises have been performed to construct representative mission schedules to verify the feasibility of constructing a mission schedule that is completing an observation program fulfilling the mission requirements. These preliminary schedule showed that typically at least seven targets are observable within one orbit.

4 SPACECRAFT LAY-OUT

Figure 3 shows an artist impression of the 12U (200x200x340mm³) CubeSpec platform, slightly more than half of the available volume is allocated to the payload.

4.1 Platform

In launch configuration, CubeSpec is confined to 2x2x3 units. After launch, three solar panels are deployed. Two of them are deployed under a 45° angle, while the third is deployed to 90° and features deployed triangular side foils forming a Sun and Earth shield protecting the payload radiator panel, The purpose of the payload radiator is to dissipate the heat from the science sensor and part of the electronics toward deep space. The telescope position deep inside the spacecraft maximises the Earth exclusion angle. The payload detector can survive short exposures to Earth or Sun, but nominally direct illumination is avoided during the nominal in-orbit phase to maintain the thermal stability.

The Attitude Determination and Control system (ADCS) delivered by arcsec has a standard architecture with 4 reaction wheels and a Sagitta and Twinkle star trackers. To maximise the Earth exclusion angle, the Sagitta star tracker is rotated 20° with respect to the spacecraft side pointing towards Earth. An X-band and S-band antenna patch panel attached to the side pointing towards Earth (6U side without deployable) foresees sufficient bandwidth for control, command, communication, and data transmission. The smaller field of view of the antenna and the absence of a wider field UHF antenna impose some extra requirements on spacecraft pointing during ground communication periods and no communication with the spacecraft is feasible at high tumbling rates.

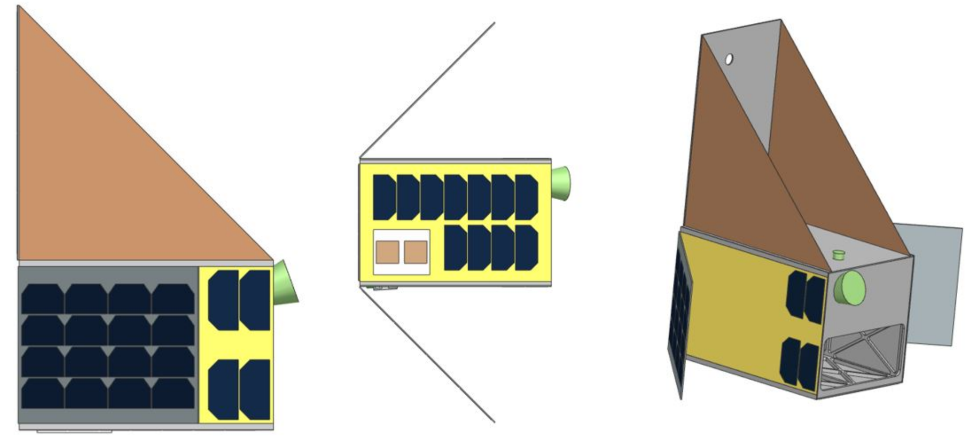

Figure 3: Artist impression of the CubeSpec Platform, the Field of Views of the two star trackers are indicated by the green cones.

4.2 Payload

CubeSpec's payload contains an off-axis Cassegrain telescope and compact high resolution spectroscope mounted on top of each other as shown in Figure 4. Two thirds of the available volume (118x208x300mm³) is allocated to the telescope and one third to the spectrograph described in [4]. The main components of the spectrograph are a slit (20x50μm² or 2.6"x6.5"), a dichroic beam splitter, a collimator, an Echelle grating, a cross dispenser and a Schmidt corrector to split the incoming light in different spectral bands. The dichroic beam splitter divides the incoming light between the spectrograph and HPPP whereby wavelengths not of interest for the science payload are diverted to the HPPP as indicated in Figure 5.

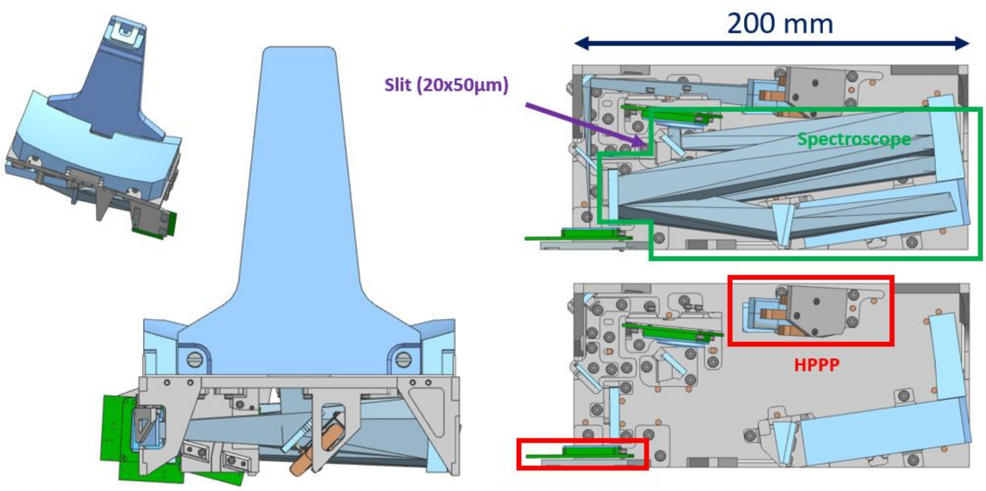

Figure 4: CubeSpec payload with off-axis Cassegrain telescope (top) and high resolution spectrograph (bottom). The figures on the left depicts the spectrograph with and without the optical rays.

One of the challenges faced during the design of CubeSpec is the small separation distance between the primary (M1) and secondary (M2) mirror of the off-axis Cassegrain telescope. This leads to a fast optical telescope design, with a focus that is very sensitive to changes in the M1-M2 mirror distance. To avoid thermal deformations and misalignments in flight the beam separating M1 and M2

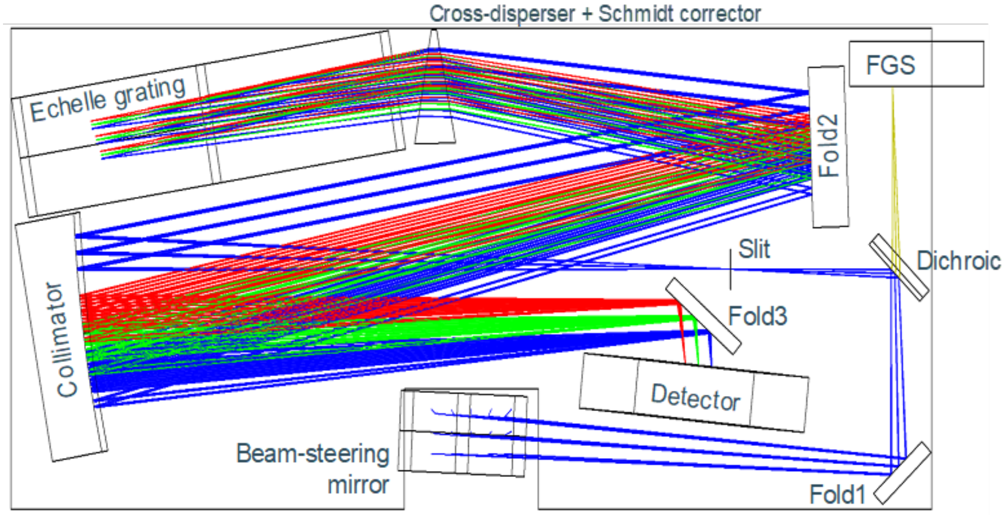

Figure 5: Lay-out of the optical payload onboard CubeSpec. The Fine Steering Mirror and the Fine Guidance Sensor are part of the HPPP, while the other components belong to the spectrograph.

is made of a ceramic material with low coefficient-of-thermal-expansion (CTE), such as Zerodur or Cordierite, making the instrument performance more robust to thermal instabilities. This comes at the cost of an increased vulnerability during launch. To check the feasibility of the proposed design a mechanically representative Macor dummy telescope has been constructed and tested on a shaker as shown in Figure 6. The design survived sine and random vibration tests as specified by the Vega launcher manual in all tested launch configurations [5], [6] where only the worst configuration was tested with qualification factors. The first structural mode of the beam lies at 209Hz.

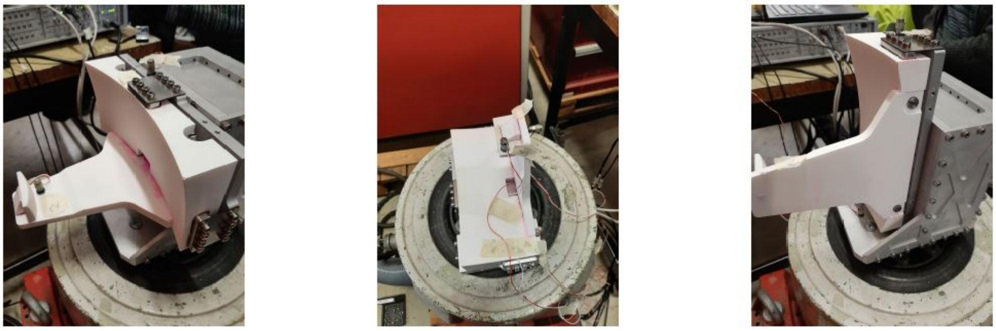

Figure 6: Macor dummy telescope undergoing shaker tests in the three main mounting configurations during launch.

5 HIGH-PRECISION POINTING PLATFORM

Due to the lower inertia and the reduced performance of miniaturized sensors and actuators, traditional ADCS architectures are affected by an intrinsic limit in the achievable pointing accuracy [7]. In order to achieve the pointing performance demanded by the scientific requirements of CubeSpec, a second control stage is added on top of the ADCS. Differently from the ADCS this second control loop, called the High-Precision Pointing Platform, mainly works on the payload line-of-sight without affecting the spacecraft attitude.

5.1 Design strategy

Figure 7 shows the HPPP architecture. The outer loop depicts the ADCS in fine-pointing mode, where only star tracker and gyroscope measurements are used to estimate the orientation while attitude corrections are made with reaction wheels. The inner loop has its own accurate sensor to estimate the residual pointing error (Fine Guidance Sensor or FGS) and its own actuator (Fine-Steering Mirror or FSM) to change the payload line-of-sight. The CMOS technology-based FGS tracks the observed stars and calculates the difference between the actual and desired star position on the sensor, which is a measure for the residual pointing error. The desired position corresponds with the projection of the spectrograph slit on the FGS. A controller calculates a corrective action from the residual pointing error and sends it to the FSM. To ensure that the latter reaches the desired corrective orientation, a feedback control loop with strain gauges attached to the FSM actuators is present. This inner loop, working at very high frequency, ensures that the FSM reaches the commanded orientation in short time. Due to the strict dimensional limits, the 3 degrees of freedom FSM is developed in-house. The design combines a large actuated mirror with large strokes (7mrad peak-to-peak along two tip/tilt axes) and high first structural mode (810Hz).

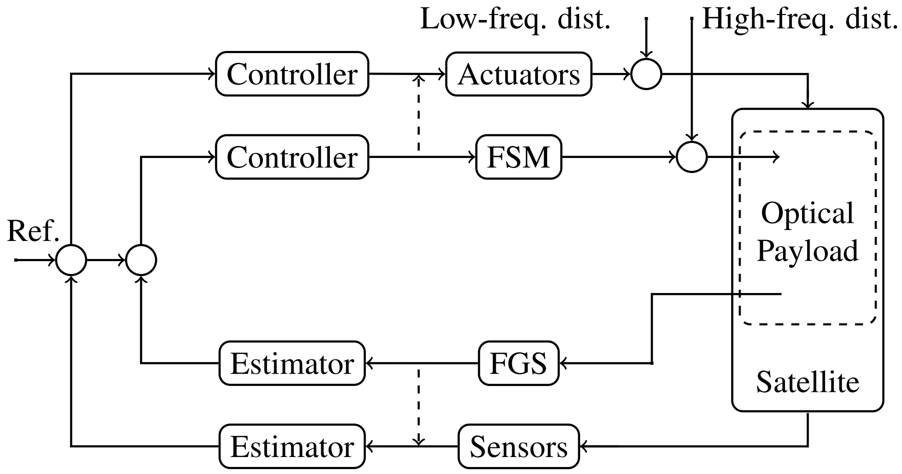

Figure 7: Control architecture of CubeSpec with the ADCS (outer) loop and the HPPP (inner) loop. [8].

Two communication lines between ADCS and HPPP are visible. The first one indicates the update of the ADCS attitude estimate based on the FGS measurement as this is the most accurate attitude estimate onboard the spacecraft. Providing the FGS measurement to the ADCS can be benefical as an improvement of the attitude estimation is expected. The second one indicates the HPPP command to ask for an ADCS offset to avoid FSM saturation. This command actively changes the spacecraft attitude. Due to the architecture of the FGS, only information along the payload cross-boresight axes can be derived and no additional information along the payload boresight is available, leading to a refinement of the attitude knowledge along two axes only. The ADCS is sampled at 10Hz, the HPPP at 40Hz and the FSM inner feedback loop at 1000Hz.

5.2 Preliminary results

Figure 8 and 9 show some preliminary results of Matlab-Simulink models of the combined ADCS and HPPP system as described earlier. During a 15min period, light passes approximately 53% of the time through the spectrograph slit, so the desired 80% is not yet reached but solutions to improve this value are being investigated. Within an observation period (Figure 8) two situations can be distinguished. First there are regions with a flat spot position at low values and second, there are regions with high values for the spot position. The flat regions correspond to a situation with working HPPP and show that the HPPP performs well, in the other regions the HPPP is turned off because the residual ADCS error is outside the FSM range. Therefore it is important to have a communication link between the two control loops to request an ADCS offset so that FSM saturation can be avoided. The time signal translates into a star movement on the FGS as indicated in Figure 9. The hexagonal FSM range is due to the FSM construction with three actuators on the vertices of an equilateral triangle.

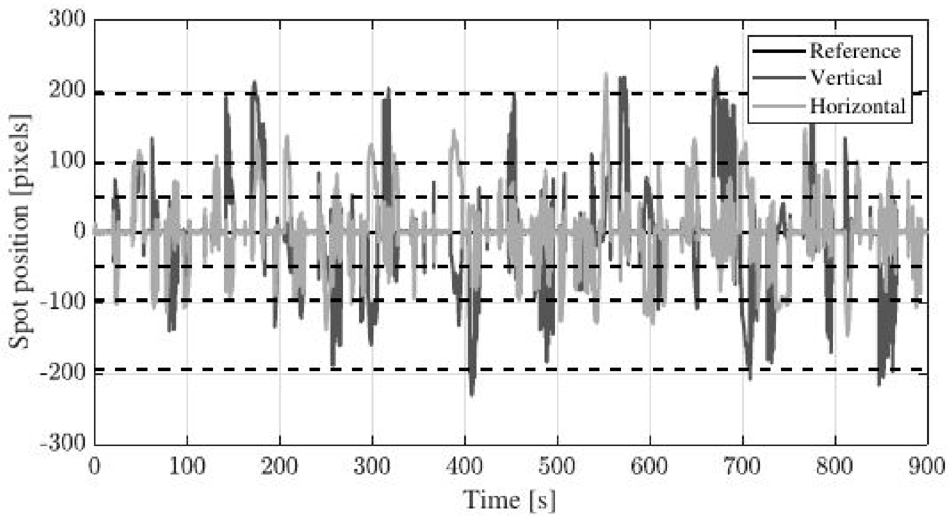

Figure 8: Preliminary results of HPPP simulations. Spot position in function of time for a 15 minute observation period.

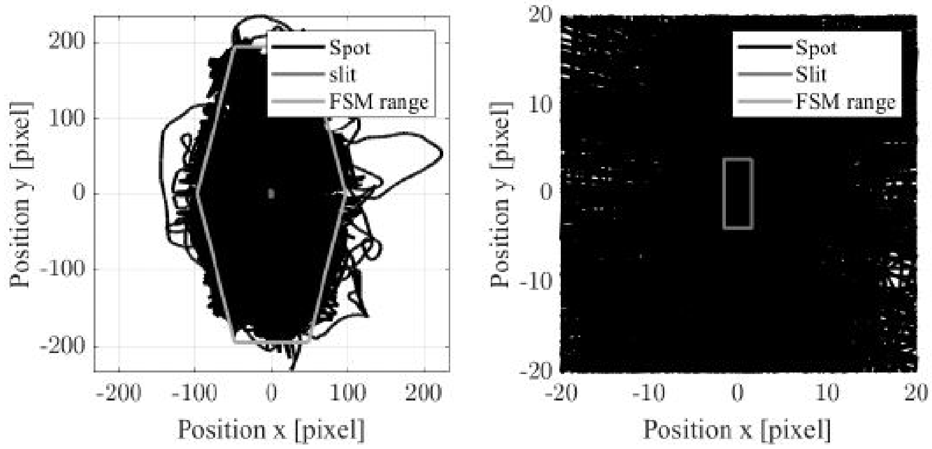

Figure 9: Preliminary results of HPPP simulations. Movement of the star over the FGS for the 15 minute observation period of Figure 8. The hexagonal shape indicates the FSM range.

6 ELECTRONICS

Except for some custom-made electronics, CubeSpec is based on the Space Inventor satellite platform. Overall communication happens through a CAN bus and the CSP protocol.

6.1 Architecture

Figure 10 summarises the overall electrical design of CubeSpec, the different modules are.

- **Power:** A Maximum Power Point Tracker module (MPPT-P4) receives the power generated by the solar cells and delivers it to the Battery (BAT-P4). The Power Distribution unit (PCDU-P4) distributes the power over the rest of the satellite.
- **Data handling:** The Space Inventor OBC-P4 (on-board computer) is responsible for all on-board data handling.
- **ADCS:** The ADCS is composed of four reaction wheels, two star trackers and a central controlling unit delivered by arcsec. A GPS receiver and Sun sensor delivers additional attitude or orbit information.
- **Communications:** The TT&C is handled by a S-band antenna while a X-band antenna downlinks the science data (STTC-P4).

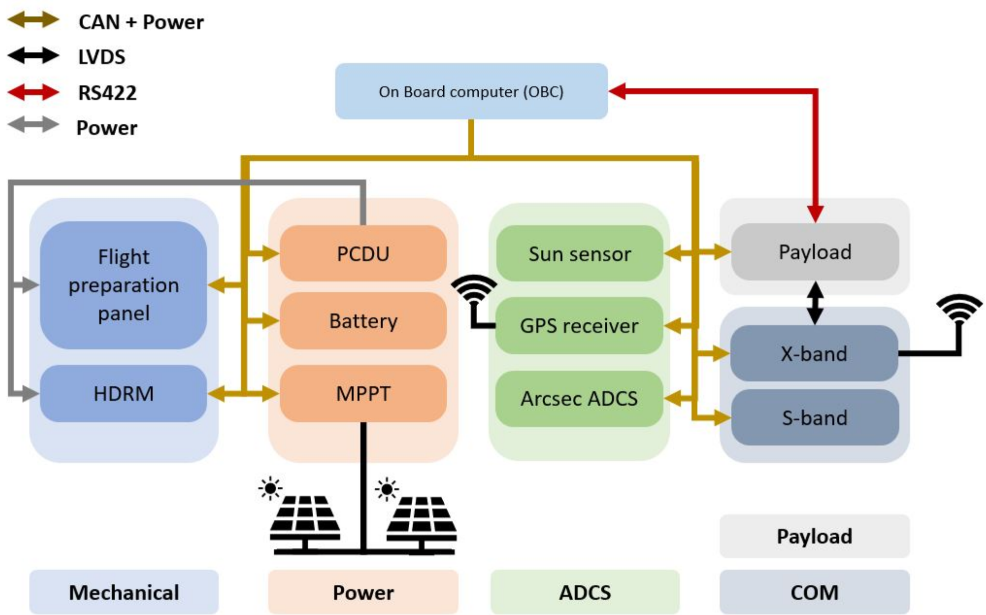

Figure 10: Electrical architecture of the CubeSpec platform

6.2 In-house developed components

KU Leuven is responsible for delivering the Payload Control Unit (PCU). Figure 11 shows an overview of CubeSpec's PCU. The PCU is managed by a Xilinx Zynq 7000 SoC FPGA integrated with an ARM processor. The Zynq 7000 communicates with the OBC over a CAN bus, employing the CubeSat Space Protocol (CSP) for enhanced communication. Closely integrated with the Zynq 7000 is the Main Electronics Board (MEB), which interfaces the FPGA with the other payload modules, and distributes power to those modules.

The science detector and FGS both use the Gpixel GSENSE2020BSI sensor. The sensor requires accurate control signals and outputs high-speed data. In order to maintain signal integrity of the control and data signals, each detector will have a Detector Board (DB) which provides localised detector readout using an FPGA. The data is finally sent to the MEB using a Multi-Gigabit Transceiver (MGT).

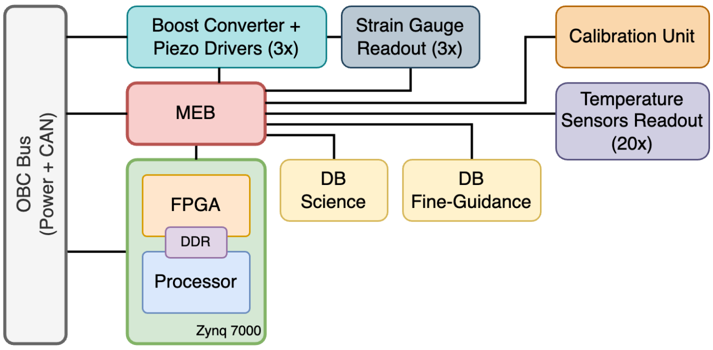

Figure 11: Overview of the payload electronics architecture.

To drive the piezo actuators of the FSM, three separate piezo drivers are needed. Each driver consists of an op-amp that outputs a 10-100 V drive signal. A boost converter will provide the op-amps supply voltage by up-converting the spacecraft's 28 V bus voltage to 120 V. Different temperature sensors monitor the temperature at key locations and are use for spacecraft housekeeping.

Finally, to calibrate the optics after launch, a calibration unit will be fitted on-board. The exact details of the calibration unit are still to be determined.

7 CONCLUSIONS

During its showcase mission, the 12U CubeSpec platform will monitor the spectral line deformation of different β-Cephei pulsators and demonstrate the feasibility of high resolution spectroscopy from a CubeSat platform. Slightly more than 6U of the platform is allocated to the payload which contains an off-axis Cassegrain telescope and high resolution spectrograph with a slit measuring 2.6"x6.5". The platform has two star trackers to estimate its attitude and three deployable solar panels to guarantee sufficient power. During one orbit at least 7 stars are observable but due to restrictions on the spacecraft attitude targets close to the celestial poles cannot be observed. During a 15min observation period, light should pass 80% of the time through the spectrograph slit which imposes very strict pointing requirements that cannot be met with traditional ADCS architectures. Therefore CubeSpec implements a second control stage, called HPPP, that applies its correction directly to the payload"s line-of-sight, rather than controlling the orientation of the overall satellite. This system has its own set of sensors and actuators to estimate and compensate for the residual ADCS error. Due to very strict requirements, some key components such as the telescope, FSM and part of the electronics are developed in-house.

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