Computed Tomography by a Formation of Ten CubeSats to Characterize Cloud Composition

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Abstract

In climate prediction models, major uncertainties relate to clouds as key contributors to Earth's albedo. The CloudCT mission, to be launched in 2025, therefore emphasizes the characterization of the interior of clouds as an objective in order to complement existing missions with an emphasis on cloud dynamics. A formation of 10 CubeSats generates inputs to apply computed tomography methods in the space environment. This innovative method catches backscattered Sun-light at clouds synchronously from different perspectives to generate 3D-images and density profiles of the cloud's interior. The payload consists of multi-spectral cameras with different polarization filters.

The satellite design challenges relate to implementation of formation control at nano-satellite scale. Essential components to be accommodated include a propulsion system for formation initiation and maintenance, accurate attitude determination and control for joint observations, networked control schemes to coordinate AOCS activities in the formation via inter-satellite links.

For testing these innovative observation and sensor data fusion methods appropriate facilities addressing multi-satellite cooperation levels have been established. Those are used in performance evaluations and in parameter calibration. Core equipment includes 2 high precision / high dynamics turntables, mobile robots, and air-bearing tables as unique infrastructure for hardware-in-the-loop tests related to control and operation activities.

CloudCT implements formation capabilities as basis for innovative distributed sensing technologies by using computed tomography methods to characterise composition of clouds. In this application challenges of attitude and orbit control system had to be addressed, as well as the coordination by a networked control system via inter-satellite links. This will open interesting perspectives for future multi-satellite missions forming sensor networks in orbit. Related application impact of CloudCT relates to further reduction of uncertainties in inputs for climate models, leading to improved climate predictions, but also assists in environment pollution monitoring.

1 Introduction

While distributed sensor networks play already a key role in ground-based observations, significant efforts are invested to take advantage in orbit, too [4]. The emerging capability to realize with cost-efficient nano-satellites even self-organizing formations of satellites supports innovative realisations of distributed sensor networks in orbit [13]. At Zentrum für Telematik (ZfT) experiences are based on the NetSat mission, with the objective to realize a satellite formation in 3D configurations by four nano-satellites (launched in 2020) [15]. As first application of these formation principles in Earth observation, the Telematics Earth Observation Mission (TOM) was implemented [9]. In TOM, three nano-satellites observe the same target area from different perspectives, generating by photo-grammetric processing 3D images of the Earth's surface. As next step CloudCT uses ten nano-satellites to form a self-organizing constellation to use computed tomography methods to characterize the interior composition of clouds [16,5,17,1] from observing back scattered sunlight from the clouds from different perspectives. CloudCT primarily focuses on warm convective clouds in tropical and subtropical latitudes. It also considers short-lived anthropogenic clouds, optical phenomena, and wide-area contrail detection [8,11,12,18]. Despite the small satellites' onboard processing limitations, simple algorithms can differentiate clouds from the Earth's surface using RGB images [7]. To achieve successful computer tomography, it is essential to capture sufficient images of the same target area. This requirement hinges on precise attitude detection and control for each individual satellite. Given that relative performance outweighs absolute performance, we envision a cooperative control approach, elaborated further in subsequent chapters.

2 The CloudCT Satellite System

The CloudCT project will deploy ten nano-satellites in 3U CubeSat form factor (with dimensions 10x10x30cm). A precursor satellite is implemented to test crucial system components, in particular the camera payload performance in orbit. Current plan is to launch the precursor satellite in end-2024, alongside the three TOM satellites. These initial launches will focus on testing formation flight aspects, too. The final ten CloudCT satellites are scheduled for launch in 2025.

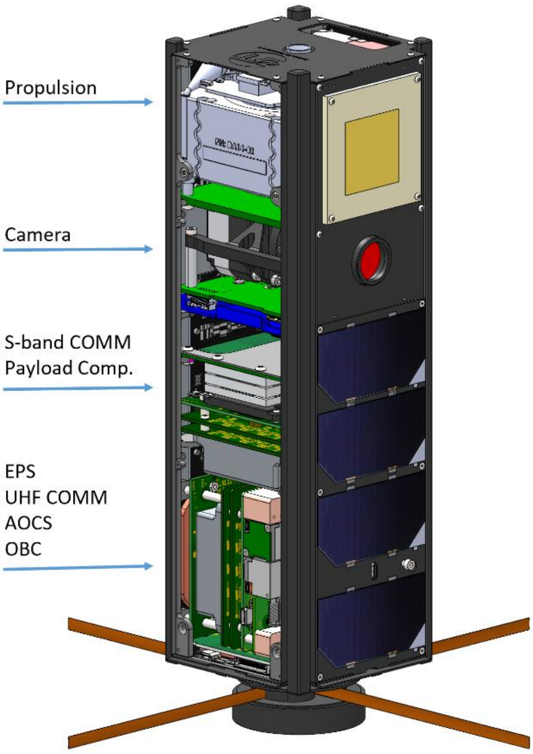

Figure 1: CAD Model of the CloudCT precursor Satellite

The CloudCT satellites are based on ZfT's 3U+ satellite platform. By adhering to the UNISEC Europe standard for electrical interfaces (http://unisec-europe.eu/standards/bus), this streamlined design enables rapid integration and testing of satellite components, ensuring compatibility across diverse missions (see [3]). Figure 1 shows the CAD model of the CloudCT precursor satellite. The key features of this satellite platform include:

- **Modular Subsystems:** All subsystems are modularly attached to a base plate (see Figure 1). Within the bottom 10 cm cube, essential avionics components reside, including the On Board Computer (OBC), Attitude and Orbit Control System (AOCS), Electronic Power System

(EPS), and Communication subsystem (COM). The top unit accommodates the propulsion system.
- **Redundancy:** To mitigate single points of failure, redundancy is implemented across all components except the propulsion system. For example: The OBC features two microcontrollers operating in hot redundancy, externally monitored by a watchdog. The AOCS adheres to redundancy principles, spanning from microcontroller redundancy to sensor and actuator redundancy.
- **Distributed EPS Architecture:** The EPS architecture effectively isolates power-related failures and tolerates multiple single failures, ensuring mission continuity even in the presence of defects.

The satellite platform comprises several essential subsystems: The OBC serves as the central brain of the satellite. It manages critical operations, including data processing, communication, and control. This flight-proven system operates in redundant mode, ensuring reliability even in the face of hardware failures. Tasks handled by the OBC range from executing mission-specific algorithms to coordinating subsystems. The EPS is the lifeblood of the satellite, providing continuous power to all components. Solar panels harvest energy from the sun, which is then stored in onboard batteries. Voltage regulation, distribution, and fault protection fall under the EPS domain. The Inter Satellite Link (ISL) unit enables communication between satellites within a formation or constellation. Utilizing UHF radio modules, it facilitates Telemetry and Telecommand (TMTC) exchange. ISL plays a crucial role in maintaining formation integrity and coordinated maneuvers. The performance in the NetSat mission demonstrated a feasible ISL distance of more than 100 km [15, 4].

The CloudCT satellites employ a sophisticated attitude control system to ensure precise orientation and stability. Its features are outlined in the following: The Attitude Determination and Control System (ADCS) relies on six miniature reaction wheels, positioned as redundant pairs along each of the 3 orthogonal reference axes. This configuration enhances agility while providing redundancy. We strategically allocated extra space for piggyback boards within the satellite. These boards interface with external components of the AOCS, including the star tracker and propulsion system. The AOCS incorporates a Linux-based computing board to handle mission-specific tasks, such as formation flying. This board tackles demanding computations that often exceed the capabilities of onboard microcontrollers. The satellite's panels host a distributed sensor suite comprising: Five magnetorquers; Four miniaturized CMOS camera-based sun sensors; Six Inertial measurement unit (IMU), strategically placed away from magnetic interference. The sophisticated control algorithms fuse sensor data and precisely manage the reaction wheels. When orbital adjustments are necessary, the chemical bi-propellant propulsion system comes into play. Fuelled by carefully balanced propellants, it provides thrust for maneuvers such as orbit raising, station-keeping, and deorbiting.

The CloudCT satellites are equipped with a multi-channel visible spectrum camera and polarization filters. The camera uses a sensor chip with an integrated polarization filter. This enables raw image data generation containing 4 different polarization channels. It features a resolution of ca. 50m and a field of view of 101 by 74 km near the altitude of 500 km.

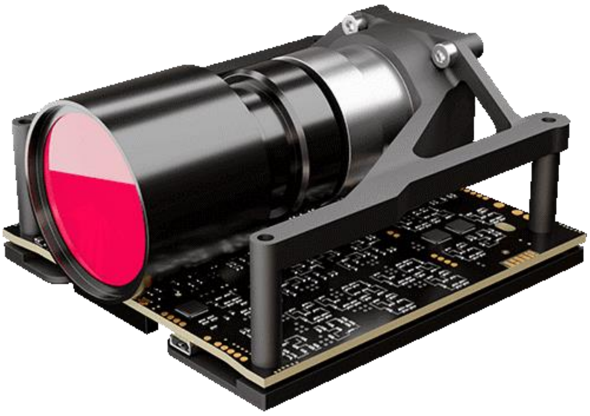

Figure 2: CloudCT Camera Payload

The camera payload being the central design driver, influences the mission design as well as satellite system design. The camera payload and components are housed in the central area of the satellites, occupying 1U volume. Payload components include the payload computer and S-band transmitter. The payload computer is developed with COTS components to command the camera module, store images, and transmit them to the ground station. The S-band transmitter will provide 1Mbps link to the ZfT ground station to download the raw images.

As a driver of the mission design, camera parameters were considered while running simulations to determine achievement of overlap needed for the mission objectives. The satellites can either dynamically reorient themselves towards specific targets, or remain in a static push-broom configuration. Generally, at least 80 percent overlap of images taken by adjacent satellites is desired. The optimization algorithm was fed by parameters from the controller design, such as bus pointing accuracy and knowledge errors.

This was instrumental in specifying requirements for the AOCS design and its components, as discussed in the following section.

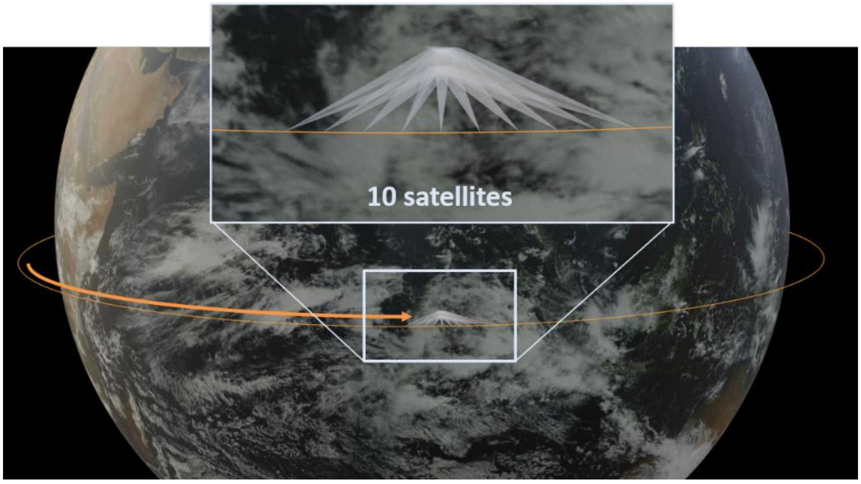

Figure 3: CloudCT Camera Payload Overlap

3 AOCS Design

CloudCT’s AOCS is based on the previous NetSat, QUBE and TOM 3U CubeSats. To fulfil the scientific mission goals, an overlap of the individual images of all satellites of at least 80% is required, which translates to a maximum Absolute Performance Error (APE) of 1.6° [10]. Statistical analysis of all error contributors and corresponding error mapping shows a feasible APE of 1.096°. Precise and reliable interaction between the various components is necessary to achieve this accuracy.

The required speed, accuracy, and reliability are ensured by a distributed integrated modular architecture, as depicted in Figure 4 [2]. The satellite's panels are each equipped with their own Microcontroller Unit (MCU) and a local bus. Therefore, pre-processing of sensor data and autonomous control of the components mounted on the panel is possible. By using the UNISEC bus, the AOCS MCU and the five panel MCUs can communicate with each other, which enables a close integration of all processors, sensors and actuators. In addition, sensor and actuator redundancy provides improved torque performance, accuracy, and reliability.

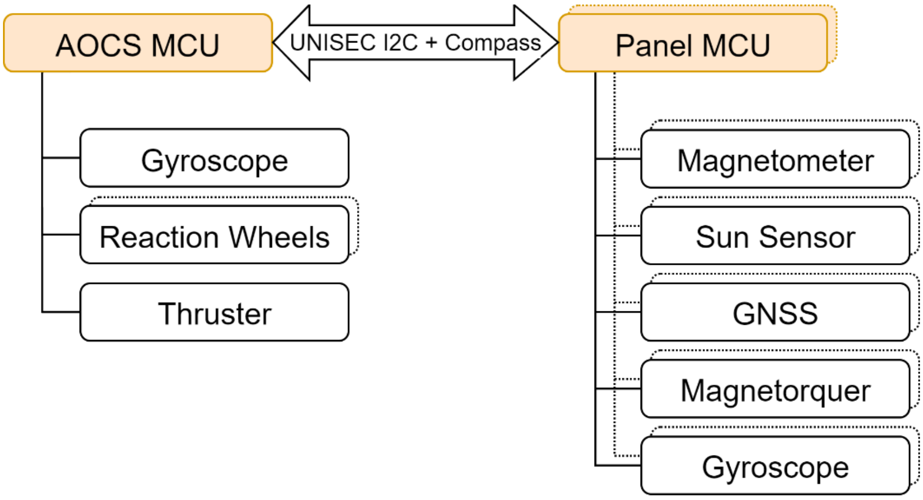

Figure 4: Distributed AOCS Architecture

The core of the AOCS software runs on a single-core ARM MCU and uses a Real-Time Operating System (RTOS) as the underlying operating system. The guaranteed timing performance enables the required precise and reliable interaction between all components. Furthermore, the available processing speed permits the usage of a complex Kalman filter, while also being efficient enough for a power-constrained 3U CubeSat.

The architecture of the AOCS software reflects the modular approach on the software level. Each processing step in the control loop, as well as all sensors and actuators are realized as separate software components with clearly defined interfaces and interactions. This modularity offers several advantages:

On the one hand, a flexible configuration of the whole AOCS subsystem and exchangeability of its building blocks is possible. Therefore, the system can be specifically tailored for the application scenario and – on a lower level - respective tasks. Since the components are clearly separated from each other and provide well-defined interfaces, a streamlined development process is possible. Tasks and responsibilities can be distributed more efficiently, which is particularly helpful for the development of complex and sophisticated systems, where many engineers, developers, and testers are involved. This also enables the focused (unit) testing of selected components without the need for a complex test setup.

Figure 5 shows the main components of the AOCS software and their major interactions. For the depicted AOCS components, different configurations and, in some cases, algorithm choices are available. In addition, several basic operating system services are provided, e.g. inter-subsystem communication via the Compass protocol, a file system, logging, scripting, and a watchdog mechanism.

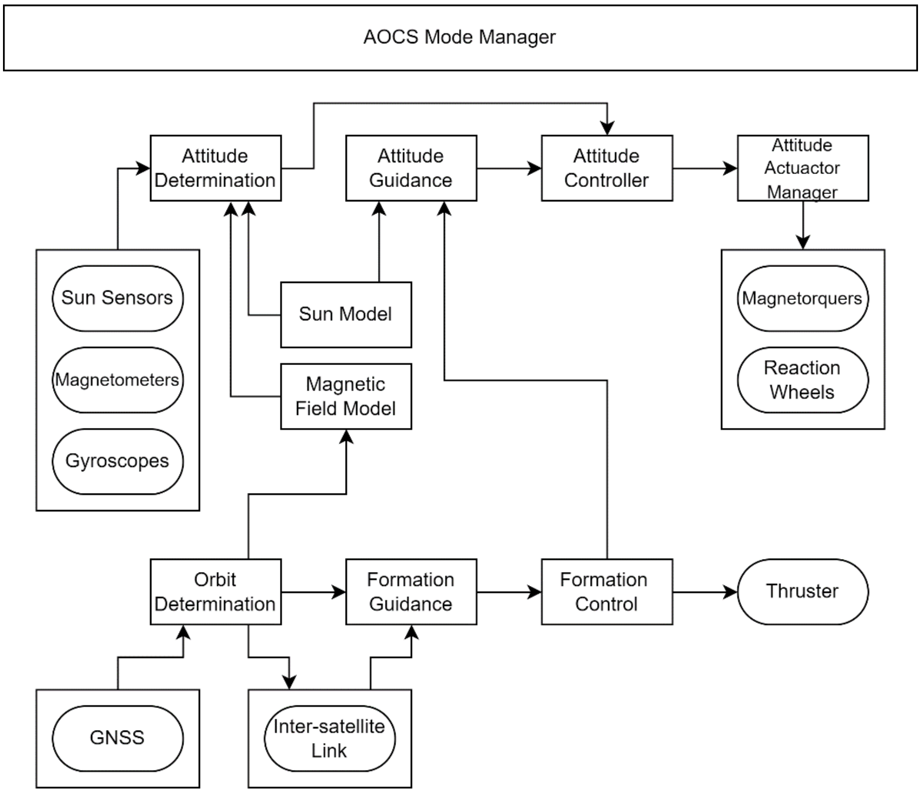

Figure 5: AOCS Software Components

Depending on the current task and state of the satellite, the appropriate AOCS mode is activated. The activation of the modes, the transition between them, and the monitoring of the general AOCS state is managed by the AOCS Mode Manager. The following modes are planned in the Mode Manager for the CloudCT mission:

- Safety Mode
- Detumbling Mode
- Sun Pointing Mode
- Target Pointing Mode
- Push-Broom Mode
- Formation Control Mode
- Command Mode

A description of the mission-independent AOCS modes (Safety, Detumbling and Sun Pointing mode) is addressed in [6]. Based on the currently chosen mode, the AOCS Mode Manager switches the different components on or off and configures them accordingly. Figure 6 illustrates this principle exemplarily for the Target Tracking Mode (active components/configurations are marked green). The goal of this mode is to continuously point towards a defined ground target during an overflight. Since the thrust vector cannot be simultaneously pointed arbitrarily during target tracking, formation or orbit maneuvers are not possible in this mode. Therefore, the respective components (Formation Guidance, Formation Control, Thruster) are switched off in the Target Tracking Mode. For the determination of the satellite's attitude an Isotropic Kalman Filter (IKF) implementation is used. The sensors and models required for the IKF are based on Sun Sensors, Magnetometers, Gyroscopes, Sun and Magnetic Field Models. To calculate the desired attitude for pointing to the defined ground target, the Attitude Guidance uses its Target Tracking algorithm. For the precise calculation of the required pointing direction, GNSS is switched on to obtain the exact position of the satellite. Both the measured/filtered and the desired attitude are fed into the Attitude Controller component, which uses a Quaternion Feedback controller to calculate the desired torque. The actuation of the desired torque is managed by the Attitude Actuator Manager. In the case of the Target Tracking Mode, the reaction wheels configuration is selected.

The explanations above describe the configuration for the Target Tracking Mode as an example to provide a better understanding of the general concept. For other modes, depending on the respective goals and tasks of the selected mode, other components may be switched on or off and other available algorithms and configurations may be selected.

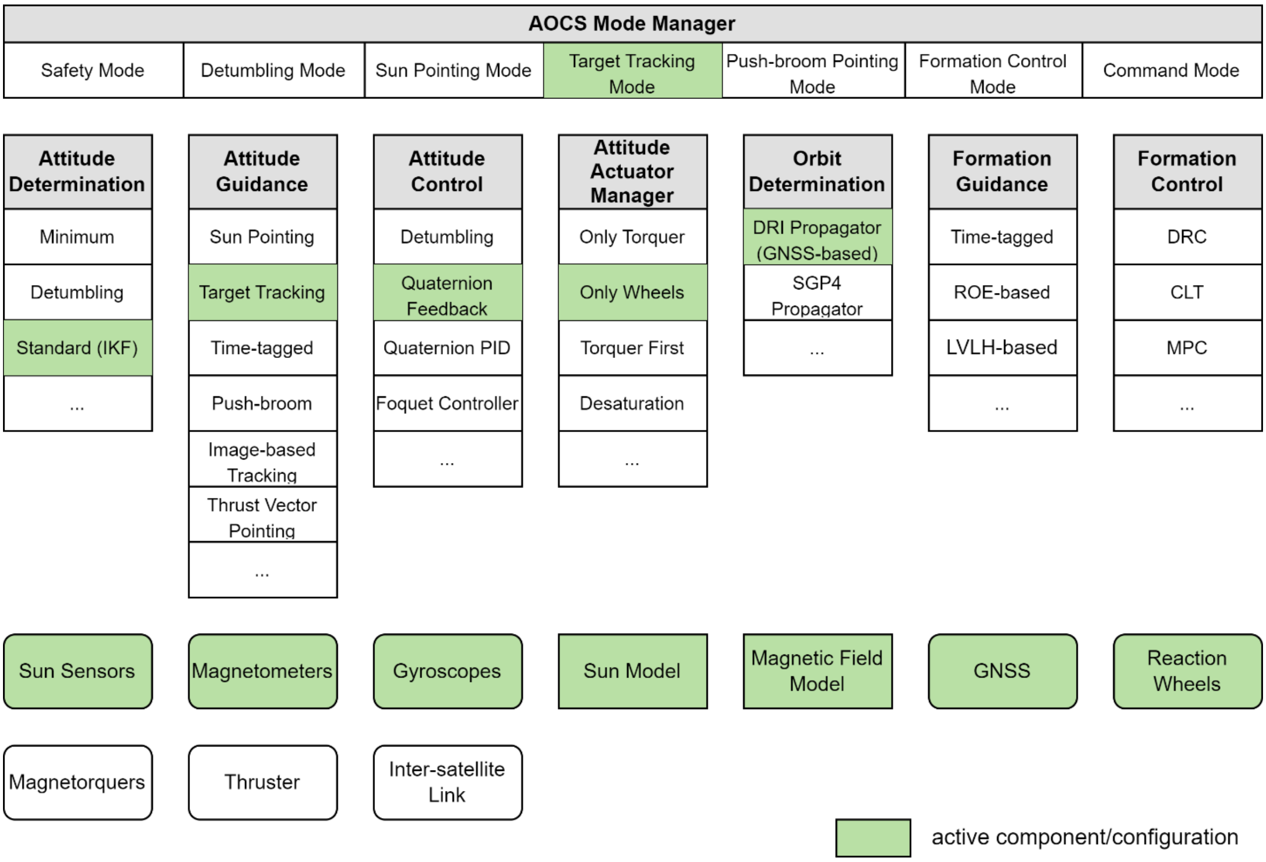

Figure 6: AOCS Components Configuration for Target Tracking Mode (active components/configurations are marked green)

To verify the functionality and reliability of the AOCS, a variety of different test environments is available, as depicted in figure 7. The first stage of testing takes place in a flatsat setup which is used in combination with a simulation framework providing virtualized versions of sensors, actuators and other components. Such a Hardware-in-the-Loop (HiL) setup enables testing of different components or aspects of the AOCS without the need for a complex test environment. For the next stage, the flatsat is replaced by the engineering model of the satellite for on-desk-tests. To also include the actual sensors and actuators, two environments are used in combination with the simulation framework. On the one hand, the satellites are mounted on two high-precision turntables for verifying the accuracy of the sensor measurements and filter outputs. The turntables are also used for sensor calibration procedures [14]. On the other hand, an air bearing setup provides an environment for testing the performance of actuators, i.e. magnetorquers and reaction wheels. For all stages of testing, a visualization tool helps to monitor the test execution and to analyze the results. Most of the described test environments and components have been developed in the course of the QUBE mission, and are described in more detail in [6].

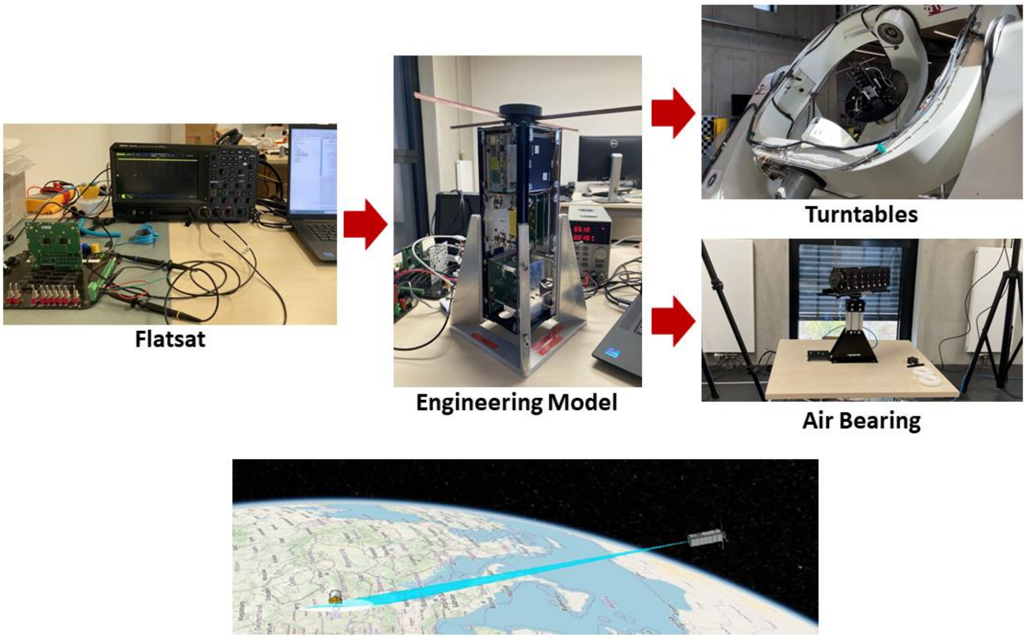

Figure 7: AOCS Test Environments

4 Formation Control

The CloudCT mission plans to operate 10 satellites in a string of pearls formation, with 100km separation between satellites. The overall extent of the formation will be approximately 1000km. The mission focus is warm convective clouds in subtropical areas, and all satellites need to observe the same target simultaneously for effective science operations. This is achieved with inter-satellite communication and formation control methods [1]. For formation control, two of the several autonomous formation control approaches are under development at ZfT and are applicable to CloudCT:

- The Distributed Robust Control (DRC) algorithm integrates robust control and distributed control using the consensus approach. Stability criteria, constraints, and optimization objectives such as rapid formation acquisition are formulated with the assistance of Linear Matrix Inequalities (LMIs). A method to utilize the maximum available thrust is used by the algorithm and includes collision avoidance measures. Utilizing the consensus approach ensures that the formation can be maintained in the event of propulsion system and/or Attitude Determination and Control System (ADCS) failure in one of the satellites.
- The Constraint Low-Thrust (CLT) approach comprises a controller and a reference governor. The reference governor directs the controller through the Relative Orbital Elements (ROE) state space. Applicability to impulsive, chemical bi-prop thruster is being investigated.

Further, a model predictive control approach is also being considered for the formation control of CloudCT and has shown promising results in recent investigations. As autonomous formation control is being actively researched, the satellite bus supports uploading and execution of time-tagged guidance files as a redundant formation control approach.

5 Conclusion

CloudCT is a nanosatellite mission using formation flight capabilities to realize distributed sensing technology. By employing computed tomography principles, the interior of clouds is characterized to reduce uncertainties in climate model predictions. Ten satellites, equipped with multi-channel visible spectrum cameras featuring on-pixel polarization filters, collaborate to acquire backscattered Sun light from a cloud from different perspectives. Solutions to critical space technology challenges related to formation control and satellite system design within the limitations of nano-satellite formations are outlined. This addresses the attitude and orbit control system, supported via inter-satellite links and networked control to achieve coordination of the distributed system of ten satellites. Thus, CloudCT advances self-organizing formation control technologies with promising technology application potential in future Earth observation by distributed multi-satellite systems.

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