CloudCT: 10 COOPERATING NANO-SATELLITES TO CHARACTERIZE THE INTERIOR OF CLOUDS

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Abstract— CloudCT is a network composed of 10 cooperating nano-satellites to characterize the components of clouds. Distributed control algorithms in combination with computed tomography methods and miniaturization of satellites enable an innovative mission concept to improve our basis for climate predictions. This contribution describes the CloudCT mission and spacecraft design. Emphasis of is on necessary autonomous reaction capabilities and networked control approaches to enable the joint observation of target clouds from different viewing angles by this satellite network for subsequent camera data fusion.

1. INTRODUCTION

The contribution of clouds to the Earth's energy balance is significant through albedo of incoming Sun light and their capability to transport water through the air [1], [2]. Nevertheless, clouds are one of the mayor uncertainty factors in climate prediction models, as global measurement capabilities are limited and mainly related to satellites, complemented by local ground or air based observation data. Sensor data fusion of different viewing angles of the instrumentation enable even characterization of composition of the cloud's interior by computed tomography methods [3], [4].

Figure 1. The CloudCT satellites observing the same target cloud from different perspectives.

Computed tomography methods are often used in medicine to generate cross-sectional images of the human body slice by slice. Similar approaches are now envisaged by satellite networks (cf. Fig.1), where suitable baseline distances for sensors are provided by placement on different satellites. The joint observations require suitable attitude and orbit control systems to guarantee appropriate position and instrument pointing despite disturbances by the space environment. Here distributed control schemes are addressed in the context of satellite formation flight [5], [6], [7], [8]. Recent progress in miniaturization of satellites allows to realize related control system hardware even at the level of nano-satellites with a mass of just a few kilograms [8]. In particular, the standardization of CubeSat as multiples of 10 cm cubes pushed here cost-efficient implementation of small satellites a lot [9], [10], [11].

In this paper the CloudCT mission planned for launch in 2023, as well as current details of the satellite design will be introduced.

2. The CloudCT Mission

The CloudCT mission takes advantage of Sun as illuminator and measures the backscattered light from clouds (cf. Fig. 2). By computed tomography methods, similar to medical 3D body scanning, the distributed camera detectors on the satellites collect the backscattered light. With appropriate knowledge of the satellite's position and attitude, the post-processing software takes advantage of the more extended computing resources on ground to derive the inner structure and composition of the target cloud. The satellite orbit motion (around 28 000 km/h at an altitude of 600 km) and the camera properties set required control accuracies.

While position determination is crucial for data post-processing, in the measurement process it only enters for appropriate pointing to the target area. More crucial on performing the measurements are attitude control actions, based on pointing direction determination with a typical accuracy of better than 1° to generate by the control software the commands to the actuator hardware to align each satellite along the 3 rotational reference axes.

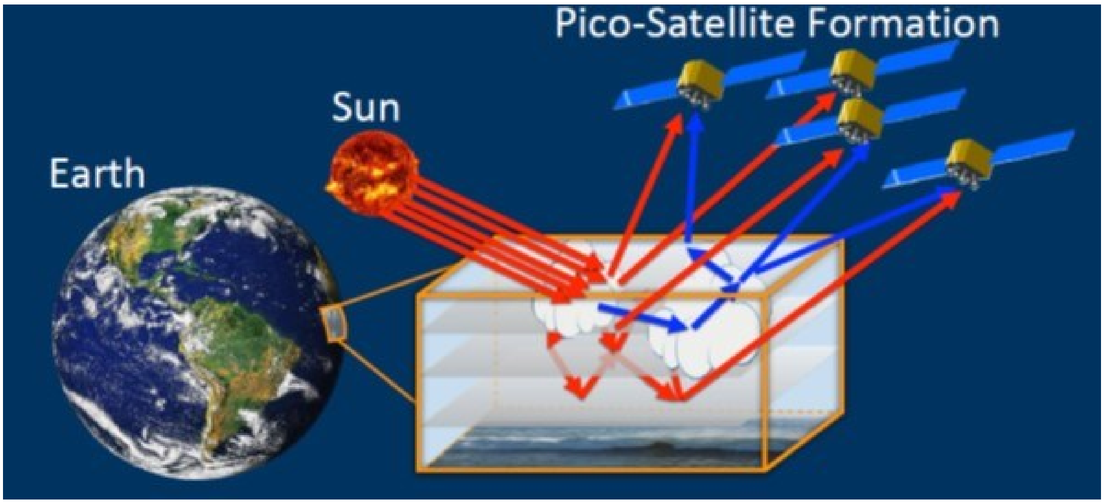

Figure 2. Observation principle of backscattered Sun-light by the CloudCT small satellite formation.

3. Satellite System Design

In CloudCT 10 identical 3U-CubeSats with the dimensions of 30 x 10 x 10 cm and a mass of about 4 kg will be employed. All the necessary infrastructure subsystems are sketched in the overview of Fig. 3, like on-board data handling, telecommunication, power generation and distribution need to be accommodated, in addition to the attitude and orbit control system (AOCS), as well as the inter-satellite link.

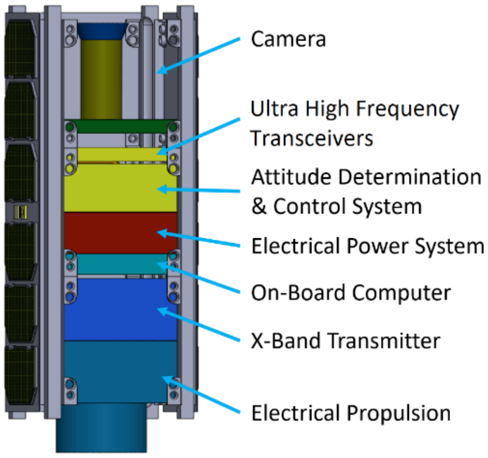

Figure 3. Basic design of the planned CloudCT spacecraft with its crucial subsystems within the dimensions 30 cm x 10 cm x 10 cm.

3.1. Attitude and Orbit Control Determination

Sensors to characterize the position and the pointing are required for the control activities as well as for post-processing. Orbit positions are regularly monitored by radar stations from ground with accuracies of about a few kilometers and provide a first rough localization for further refinement as well as backup functionalities in case of malfunctions. More accurate positions are derived from GPS measurements on-board. On each of the four 30 cm x 10 cm side panels one receiver antenna is mounted to enable continuous data acquisition for absolute position with accuracy around 10 m. Important are the relative distances between the satellites, which can be derived by differential navigation methods from GPS data. Alternatively, also time-of-flight-measurements of radio signals in the inter-satellite link allow to reconstruct with triangulation methods relative positions in the formation.

Attitude determination is crucial and is based on a range of sensors with changing accuracies according to environment conditions. On the dayside, miniature Sun sensors are most suitable to derive the Sun direction with high precision. Nevertheless, this covers only 2 degrees of freedom. Thus sensors like magnetometers, measuring the field lines of the Earth magnetic field and gyros determining rotation rates have to complement the inputs. Here well-established models of the Sun position at a given time and of the Earth's magnetic field are acting as reference to interpret the data to be fused by a Kalman filter.

In case high precision attitude determination below 1° is necessary, in addition star sensors are employed. Those are demanding volume for accommodation and introduce further restrictions, as pointing into Sun direction is to be avoided.

3.2. Control Actuators

With respect to orbit control an electrical propulsion system is foreseen. After the ionization process, the charged Indium fuel particles are accelerated in a high voltage electromagnetic field and ejected with significant velocities to provide a nominal thrust of about 330 µN. Maneuvers are time consuming as the specific impulse is limited, but electric propulsion exhibits a high fuel efficiency. Thus for the given application, it received preference despite its power demand.

Alternatively, as back-up also chemical miniature propulsion system using nitrous oxide (N_2O) and propene (C_3H_6) as fuel are considered, providing a controlled thrust between 0.4 and 1.4 N. This system exhibits faster control reactions and less power consumption, but also higher fuel consumption, leading to limited mission lifetime.

Both propulsion systems provide one thruster with adaptable thrust in direction of the spacecraft's main axis. For given orbit control maneuvers, the thrust vector must be oriented by the 3-axes attitude control system into the appropriate direction.

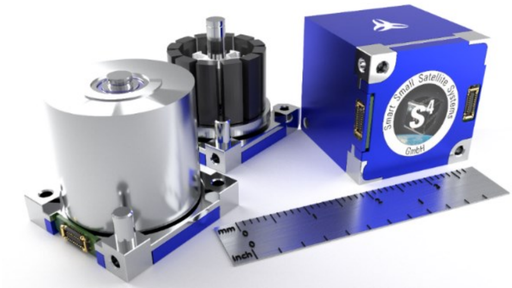

Figure 4. Setup of the miniature reaction wheel: the brushless motor in the middle, at left the rotational mass mounted and in the socket the motor control electronics is placed, finally at right in a cube of 2 cm the housing seals the complete reaction wheel for space conditions.

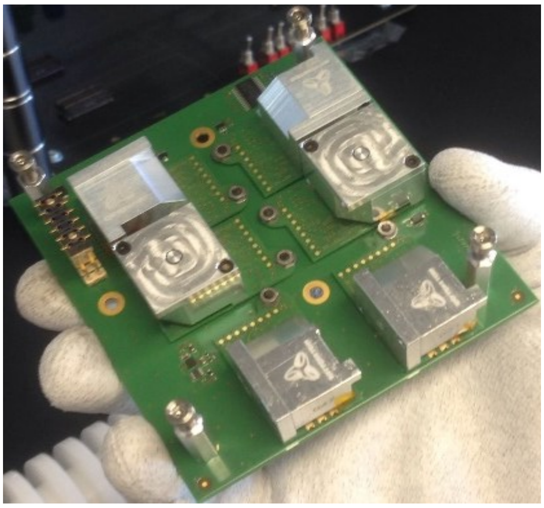

Figure 5. The 3-axes attitude control system board is hosts 3 reaction wheels pointing into the 3 reference rotation axes, as well as completely redundant set of 3 wheels symmetrically mirrored at the boards central axis.

The core component of own development of the 3-axes attitude control system is the miniature reaction wheel (Fig. 4) with the following performance characteristics:

- Momentum storage 2.0 mNms
- Nominal rotational speed 20 000 rpm
- Nominal torque 0.1 mNm
- Mass < 20 g
- Dimension 20×20×20 mm
- Power (nominal) < 300 mW

Three reaction wheels aligned with their rotational axes along the coordinate system axes form the attitude control system with an energy consumption below 1 W. As mechanical devices are a frequent source for defects in the space environment, redundancy concepts need to be included. Due to the very low power and mass demand, here redundancy in every axis is foreseen (cf. Fig.5). When the upper limit of the rotational speed is achieved, a desaturation process is initiated by magnetorquers interacting with the Earth magnetic field. In parallel, these magnetorquers provide an additional backup for attitude control, but can achieve only lower pointing accuracy around 5° and address only two degrees of freedom, as along the magnetic field line no gradient is available.

3.3 Control Software

The AOCS control software uses the position and pointing information in combination with models on-board and filtering in order to point the camera towards the observation target using the available actuators. In CloudCT further inputs from formation level need to be regarded.

4. Formation Control

Typical multi-satellite systems are organized as constellations, where each satellite is individually controlled from ground control. In contrast, satellite formations exchange control information via inter-satellite links to self-organize in orbit for appropriate configurations to realize the planned observations of the target area. Here in CloudCT, the camera fields-of-view should overlap by 80% to allow suitable computed tomography processing. This converts into pointing accuracies of 1° - 2° for joint observations.

Typical orbits in multi-satellite systems are designed such that disturbances level out during one orbit revolution. Simplest realization is place all satellites in the same orbit with same difference in true anomaly, in a so-called “string of pearls”. Another implementation are so-called “cartwheel orbits”, where the satellites rotate around a virtual center on the reference trajectory. This feature can be achieved by using orbits with a slight eccentricity, and selection of appropriate apogee position and difference in right ascension of ascending node $\Delta\Omega$.

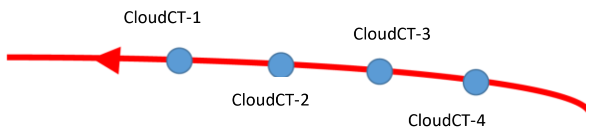

Figure 6. Satellites in the same orbit following each other in “string of pearls”.

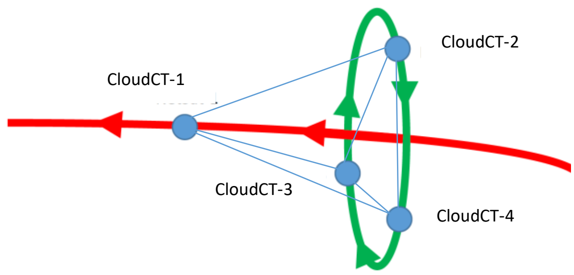

Figure 7. Configuration of 3 satellites in a cartwheel orbit around a virtual center (CloudCT-2, - 3,-4) in the same orbit as the leading satellite CloudCT-1 to form a Tetrahedron.

As there are perturbing forces, such as by example drag, third body gravity effects, solar pressure, acting on the satellite corrections are to be performed on a regular basis. Further transitions between different configurations (like Fig. 6 or Fig. 7) will be realized to optimize different observation types. Here via inter-satellite links planned trajectories are exchanged in order to avoid collisions, but also to optimize transfers with respect to time or to energy consumption. Relative distances in the formation are described by the Euler-Hill equations in a local reference frame related to one reference satellite in the formation [12], [5], [6].

With respect to optimization of observations distributed networked control schemes are applied, such as distributed consensus methods [13], [14], [15]. It will be compared to a Model Predictive Control (MPC) approach. The MPC [16] was already prepared for the NetSat mission with 4 satellites by our team.

5. Test of Control Functionalities on Ground

Complex systems like satellite formations are to be carefully tested on ground, to detect malfunctions and to include improvements. In particular attitude control approaches for observations require intensive testing. For this purpose, two high precision turntables were installed to simulate the attitude motions during a satellite pass and to coordinate joint observation strategies on different spacecraft. The turntable system is also used to assess performance of the inter-satellite link taking into account orbit dynamics.

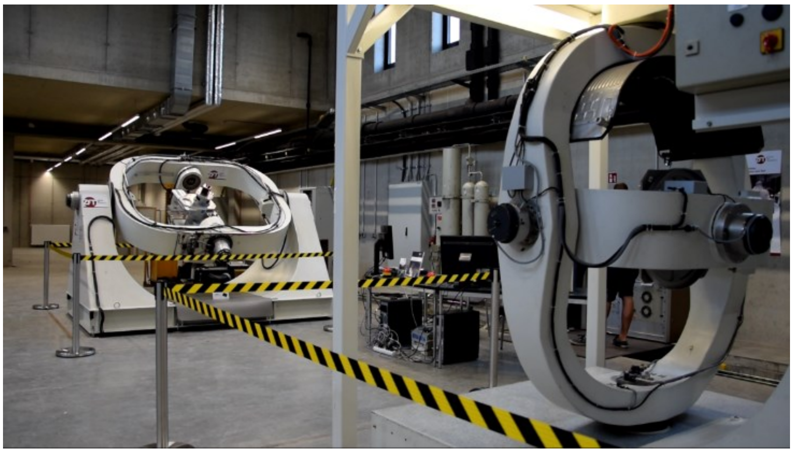

Figure 8. High precision, high dynamics turntables for testing relative attitude motion in a satellite formation to simulate inter-satellite links and joint camera observations

6. Conclusion

Space technology is currently moving from hierarchical systems to distributed cooperating formations in orbit. In this contribution related enabling control hardware and software aspects were analyzed, in particular with respect to the CloudCT mission. The challenging objective is to realize with 10 nano-satellites an innovative computed tomography approach to characterize the interior of clouds. Here synergies are exploited between image data processing and sensor networks in orbit based on nano-satellites. On this basis climate model will benefit from additional measurement inputs to improve predictions.

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