CloudCT – Computed Tomography of Clouds by a Small Satellite Formation

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Abstract: Clouds are recognized to be the main source of uncertainty in global climate models. Part of this problem is driven by lack of proper observations of shallow convective clouds. In context a distributed networked system of small satellites is used to use multipoint observations to characterize such clouds. A formation of 10 pico-satellites with high accuracy attitude determination and pointing capacity is used to retrieve 3D properties of clouds by a computed tomography approach, in high spatial and temporal resolutions. Data obtained by these measurements will be used to improve and train high resolution, cloud resolving models with the objective to improve longer term climate predictions.

1. INTRODUCTION

Clouds play a lead role in Earth's energy budget and water cycle, and contribute the largest uncertainty to our climate understanding [17]. Out of all cloud types, warm shallow clouds that are abundant and often below the instruments resolution, contribute greatly to this uncertainty [4], [2]. Current atmospheric retrievals use a plane-parallel assumption, which is incompatible with the 3D heterogeneous nature of warm convective clouds [13]. There is an acute need for improvement of cloud-resolving models that will capture correctly properties and feedbacks of such clouds. Outputs of such models would yield better parametrization scheme that describe the physics of warm convective and stratiform clouds, and the clouds' sensitivity to environmental changes in global climate models.
To address this challenge, CloudCT bridges an observational gap. The sensing approach uses cloud scattering-tomography, relying on a formation of small satellites. They will simultaneously image cloud fields from multiple directions. Scattering tomography is developed to derive the 3D volumetric structure of cloud fields, base-to-top profiles of droplets' size and their variance, volumetric distribution of optical extinction and rain indicators.

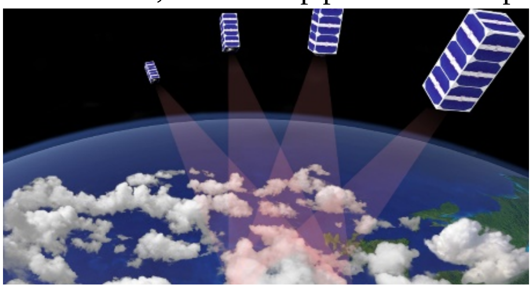

Fig.1: Multi-perspective cloud measurements by the satellite formation

Satellites at a mass of a few kilograms, so-called pico- and nano-satellites, were initially mainly used as motivating tool in system engineering education [14], but dramatic technology development lead to a majority of commercial satellites since 2014. Such picoand nano-satellites exhibit increasing performance capabilities, making them attractive for science applications [20], [12]. As launcher costs scale with mass, nowadays in particular multi-satellite missions, using sensor network technologies on-board of small satellites can be applied in-orbit to enable innovative observation methods [1], [6], [15], [16]. In CloudCT a formation of satellites will be realized, enabling self-organization in orbit. This is based on an electric propulsion system for orbit control to correct drift by orbit perturbations and relative navigation methods, to yield a formation topology offering optimal observation conditions.

In CloudCT, interdisciplinary synergies from pico-satellite system engineering, cloud modelling, and tomographic imaging are expected to enable new sensor network approaches for innovative Earth observation. This is expected to improve the input for climate models and therefore narrow their uncertainties. It will yield a database of 3D macro and micro structure of warm cloud fields, while setting the stage for next-generation global observations by distributed networked spacecraft.

2. CLOUD MODELLING

Unlike weather models, whose forecast time spans days, global climate models (GCM) predict climate trends in a scale of dozens of years. The typical resolution of GCM is 100 km and therefore, most warm clouds are in a sub-grid scale and have to be parametrized [11]. To reduce GCM errors, better understanding of cloud processes and sensitivities is needed. This is done using high resolution, cloud resolving models, which describe interactions dynamical, microphysical and radiative processes, as known in the state of the art. However, current cloud resolving models lack resolution and capacity to properly represent the nonlinear behavior of cloud systems, including aspects of cloud aerosol interactions, cloud feedbacks, mixing, turbulence, rain-processes and cloud-radiation interaction [8]. To study feedbacks, tune processes and validate models, shallow convective clouds are particularly important, but they are largely overlooked by current measurement methods.

In CloudCT, cloud resolving models will be used in two phases. At the early stage (modeling phase I) the cloud models will be used to train and validate the retrieval algorithms. The models will be used to simulate high resolution scenes. For each scene, the radiation signature will be calculated in accord to the sun and satellites geometries. This will serve as input for the algorithms that in return will be trained to retrieve cloud properties. The algorithms, the spectral regimes as well as the best satellite formations, will be optimized by interactively link the cloud resolving model results to the algorithm via radiative calculations. Once in orbit (modeling phase II) the flow of information between models and observations will be reversed. CloudCT will provide spaceborne data and products on macro and microphysical properties of warm clouds. These will serve to improve the capacities of cloud resolving simulations, in sub-cloud to cloud field scales. Measured macro-scale properties such as size distributions of clouds, spatial organization of clouds in the field and cloud evolution in time [5], as well as microphysical properties (e.g., liquid water content, droplets effective radius and variance), as well as their dependence on environmental thermodynamic properties, will test models for improving dynamical and microphysical schemes. Cloud trends observed as a function of thermodynamic and aerosol properties will help to pinpoint which part of a model should be improved. Moreover, differences between observations and simulations of transitions between cloud to a (so-called) cloud-free atmosphere will guide us on how to improve mixing and entrainment schemes. Better understanding of the main physical processes that control shallow warm clouds and their interactions will yield better and more realistic parametrizations of such clouds in GCMs, hence improved climate predictions.

3. COMPUTED TOMOGRAPHY APPROACH

To reduce uncertainties in cloud models we need to (a) image warm clouds, particularly small ones, in high resolution, and (b) analyze the properties of the clouds, based on the images. There is a challenge to focus on internal properties of clouds. External properties, such as cloud 3D shape can be derived by adapting rather standard multi-view stereo, based on images taken simultaneously from the satellite formation [19]. It is far more challenging to remotely sense, in 3D, internal characteristics such as cloud droplet concentration and size. Current methods for probing cloud characteristic assume a layered (one-dimensional) structure, in which radiation diffuses mainly vertically. In contrast, when dealing with small clouds, the cloud's periphery is not far from points inside. We thus derive retrieval based on 3D radiative transfer in a 3D heterogeneous medium.
The solution is motivated by medical computed tomography (CT). In typical medical CT, however, there is control over an active radiation source, and the imaging model assumes a linear relation to the internal content. In multi-scattering radiative transfer, the relation is non-linear, requiring analysis based on 3D radiative transfer. Reference [7] recently showed that such analysis improves Xray-CT. Nevertheless, in large scale remote sensing of atmospheric scattering, imaging is passive, relying on solar radiation. Recent progress addresses models and algorithms for scattering-based passive CT, including tests by using airborne data from JPL's AirMSPI instrument [9], [10]. To enable 3D sensing from the ground, a ground-based wide area dense network of untethered sky cameras was used [18]. These developments set the stage for spaceborne observations in CloudCT.
Spaceborne CT requires a large number of simultaneous viewpoints: this will be realized by a large formation of small satellites. Each satellite will carry radiometrically-calibrated optical cameras. Scattering by cloud droplets and other aerosols is pronounced in and around visible wavelengths. The ground resolution is expected to be about 50 meters. This resolution, obtained from low earth orbit, means pointing accuracy which challenges design and control of small satellites. While engineering the system, optimization of its parameters (wavelengths, formation topology, orbit, solar angles etc.) will be done using simulations of cloud fields by cloud resolving models, 3D radiative transfer, platform jitter and camera noise.

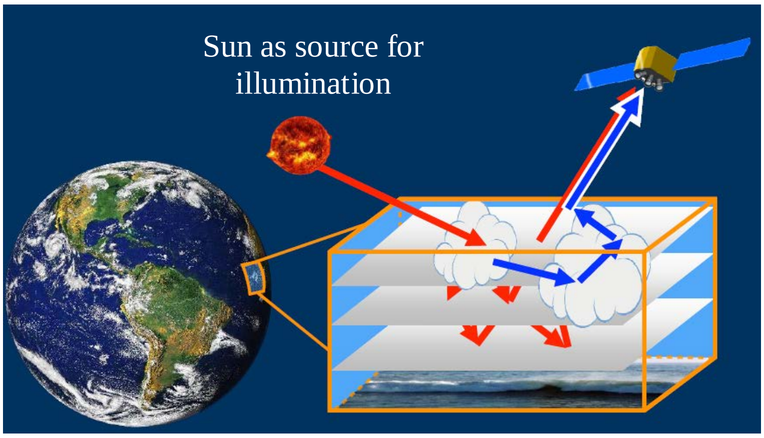

Fig.2: Illuminated by the Sun, the backscattered light from different cloud layers is detected by the satellites from different directions. Sensor data fusion algorithms generate 3D-images by postprocessing of data from the satellite formation.

4. SMALL SATELLITE FORMATIONS

The performance and lifetime capabilities of the class of pico- and nano-satellites (in the 1kg to 10 kg range) dramatically improved in the recent years. In particular, high precision attitude control by miniature reaction wheels as well as orbit control by electric propulsion systems provide all essential functions for joint measurements by satellites cooperating in a formation. This offers innovative application potential for distributed sensor networks in Earth observation, such as CloudCT.

4.1 Satellite Design

Terrestrial requirements for miniature and power-efficient electronics, in particular in the automotive sector and for cellular phones, lead to significant technology progress. The "new space" approach takes advantage of these impressive commercial developments. Nevertheless, the deficits of miniaturization are higher noise levels and, in particular in the context of space applications, higher susceptibility for radiation effects. Here software for filtering and for FDIR (fault detection, identification and recovery) receives a significant role as technology enabler for usage in space [[3], [15]. Such concepts have already been applied on the satellite UWE-3 (launched 2013), which exhibited this way seamless operations since launch, today already for 5.5 years, despite encountered frequent SEUs (single event upsets) and latch-ups caused by radiation in a polar orbit in 600 km altitude. Thus at a mass of just 3 kg in CloudCT a related satellite capable of formation flying is designed (cf. Fig. 3).

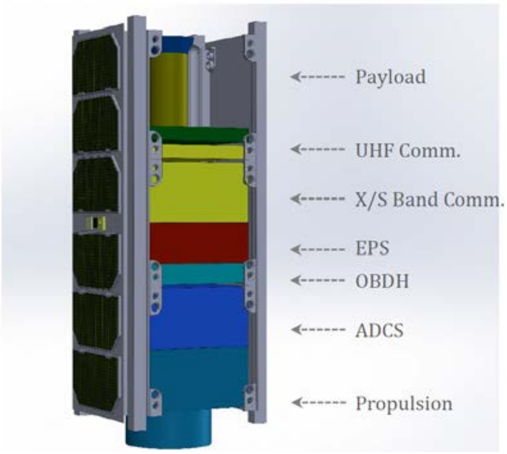

Fig. 3: CAD model of the ClouCT spacecraft

For coordinated joint observations of clouds, precision attitude control to observe same target areas from different perspectives. Due to recent miniature reaction wheels (cf. Fig.4), appropriate 3-axes attitude control systems can be composed in order to achieve the necessary pointing accuracies at the level of pico-satellites.

Fig.4: The miniature reaction wheel (from S^4/Wittenstein) with low nominal power consumption.

4.2 Orbit Design

The orbits in this multi-satellite system are designed in such a way that the average disturbance per revolution is similar for all spacecraft. In case of two satellites, this is realized by a helix orbit, where an identical semi-mayor axis in combination with a small eccentricity and a difference in the argument of perigee $\Delta\omega$ of 180° leads to one rotation of the two satellites around each other during one orbit revolution (see Fig. 5). This principle used earlier in the Tandem-X or CAN-X4/5 missions can be extended to multi-satellite missions to so-called cartwheel configurations. Here the satellites are subsequently placed on the reference orbit or rotate around a virtual center on the reference orbit.

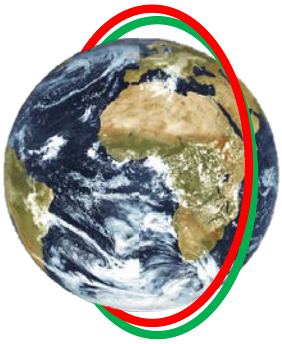

Fig.5: Helix orbit

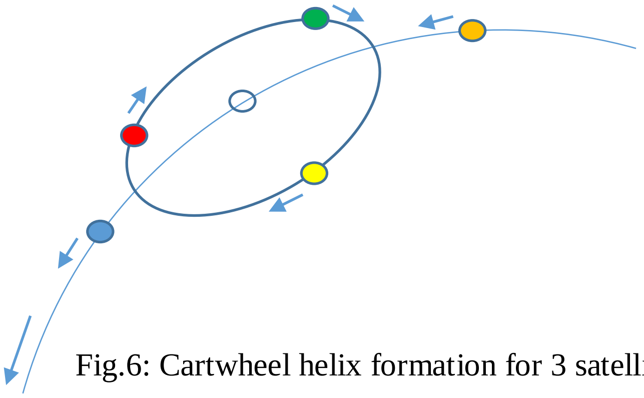

Fig.6: Cartwheel helix formation for 3 satellites

4.3 Satellite Formations

To realize the novel tomography approach, distributed control algorithms coordinate the multi-satellite system in a formation on basis on relative navigation sensor measurements. While in a classical constellation each satellite is individually controlled from ground control, in a formation the satellites self-organize via inter-satellite links. In addition, advanced in-orbit autonomy, distributed computing, and networked control contribute to efficient self-organization. The formation initialization after deployment from the launcher adaptor in the delivery rockets upper stage, as well as the drift compensation by orbit perturbations of the different satellites are realized by an electric propulsion system. New challenges refer also to ground testing of formation characteristics: The crucial inter-satellite links and coordinated attitude control for observations in the formation are tested by high precision turntables.

Fig.7: The high precision, high dynamics turntables to characterize in hardware-in-the-loop-tests intersatellite links and coordinated pointing control in observations.

5. CONCLUSIONS

Clouds have a key role in Earth's energy balance and its water cycle, as even small errors in assessing clouds' properties can lead to major inaccuracies in climate predictions. By combining interdisciplinary synergies from spacecraft engineering, imaging and cloud physics, innovative Earth observation methods are developed to characterize the clouds' external and internal properties in 3 dimensions. The computed tomography approach in CloudCT takes images simultaneously from many directions around the clouds to generate by sensor data fusion methods related 3D-images. This new data will serve to train cloud resolving models to better capture warm cloud properties and climate sensitivities. The appropriate satellite technology base is provided by a networked self-organizing formation of small and agile satellites, employing an electric propulsion system and a precision 3-axes attitudes control system composed of miniature reaction wheels to coordinate the proper observation geometry. This interdisciplinary approach in the CloudCT mission aims to investigate approaches for improvements in longer term climate predictions.

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