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# An Ultra-Low-Gravity Centrifuge in Low-Earth Orbit

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## Abstract

Near-Earth small bodies such as 162173 Ryugu and 101955 Bennu produce gravity fields around 4 orders of magnitude below that of Earth and their surfaces do not correspond to equipotential surfaces. Still, we observe familiar geologic textures and landforms that are the result of the granular physical processes that take place on their surfaces. However, the nature of these landforms, their origins, and how these surfaces react to interrogation by probes, landers, rovers and penetrators remain largely unknown.

We present the concept of a simple CubeSat-hosted laboratory that consists of a centrifuging chamber of grains in low-Earth orbit as a test-bed to observe granular dynamics in low-gravity environments. We describe the first flight demonstration, where small meteorite fragments will pile up to create a patch of real regolith under realistic asteroid conditions, paving the way for subsequent missions where landing and mobility technology can be flight-proven in the operational environment, generated in low-Earth orbit.

## 1. Introduction

Much has been learned about small-body geology [1], but for most practical purposes it remains poorly understood. Interacting with its surface therefore presents a risk. Even seemingly straightforward operations present great uncertainty: how does low-gravity regolith respond when interrogated by sampler heads, landing feet, astronaut boots, rover wheels, or excavation tools? Can a spacecraft be anchored to embedded rocks? Are landforms stable, or will exploration or excavation activities disturb them catastrophically?

We are developing AOSAT-1 as a way to quantify how granular materials behave in low-gravity environments [2]. A better understanding is essential to addressing these practical questions of how to appropriately interact with these environments. It also tells us how to interpret what we see in the context of Solar System evolution. How does cohesion affect the interactions between discrete grains? As gravity decreases, some type of cohesion will take over as the dominant force between grains [3] and will greatly influence outcomes from various stresses both quantitatively and qualitatively [4,3,5]. It has also been shown that packing can strongly affect these interactions [6]. In practice, how does packing and porosity influence the response of grains in these environments?

## 2. Setup

The AOSAT-1 centrifuge chamber will be dedicated to the study of physical phenomena in low gravity. Inserted into low-Earth orbit and filled with granular material, a first, 3-U (10 × 10 × 34 cm) CubeSat, AOSAT-1 (**Fig. 1**), will be launched in 2019 and sent into controlled rotations, simulating the gravitational environment of interest. This will compliment the impending first sample acquisition attempt at Ryugu, which is to take place before solar conjunction this winter [7], as well as future sample acquisition attempts at Ryugu and Bennu [7,8], by helping to explain the regolith response that will be observed.

## 3. Design

The science payload of AOSAT-1 features internal sensors and optical cameras aimed at a regolith chamber, returning image data for analysis on Earth. Tunable vibrators provide additional experiments, and have the practical benefit of shaking granules off the viewing glass. The spaceflight components (roughly 1U, or 10 × 10 × 10 cm) are positioned at one end of the chassis, and the lab chamber at the other. This positions the center of mass near the 'top' of the chamber (**Fig. 1**), facilitating the separation of engineering requirements: for the spacecraft to function and return data, and for the lab chamber to run experiments and produce data. Experiments include formation of a stable pile at the angle of repose, reversal of torque to create an avalanche, and vibrators to fluidize the regolith. Experiments are conducted in a spun state, lasting minutes to hours; communications with the ground are conducted afterwards, in a de-spun state, tracking the ground station for several orbits. Centrifuge conditions are attained using a single reaction wheel that is capable of spinning the spacecraft about one of its short axes up to several rotations-per-minute (rpm). The wheel is sized to apply the required torque without saturation. Electromagnetic rods (magnetorquers) are used to stabilize off-axis motions during spin-up. We model this torque in combination with flywheel action and irregular spacecraft mass distribution, to show the dynamical stability of AOSAT-1 (**Fig. 2**). Oscillations damp quickly, so that 1 rpm rotation is stabilized within 15 s, assuming a worst-case mass distribution (the entire regolith pile offset at a far corner of the chamber). We find that after shifts in the regolith mass distribution, AOSAT-1 will stabilize in its experimental mode in minutes [9]. After each experiment, the magnetorquers are used to stop the rotation so that the spacecraft can point and communicate with Earth.

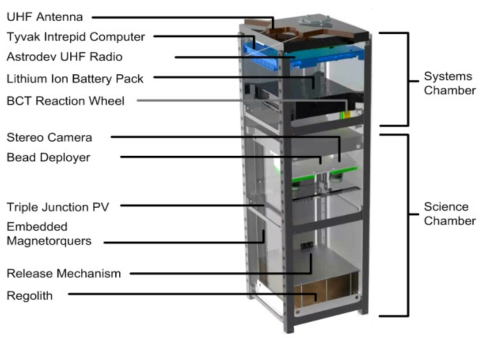


Figure 1: AOSAT-1. The mission will demonstrate an on-orbit centrifuge laboratory to simulate small-body gravity conditions.

## 4. AOSAT-1 Science

JAXA's Hayabusa-2 mission [7] and NASA's OSIRIS-REx mission [8] are set to perform the most robust to-date experiments involving regolith surfaces in sub-milligravity environments, using sampler heads, and, in the case of Hayabusa-2, a small hypersonic impactor. These missions will obtain images, thermal data, and other measurements indicating the force response. With AOSAT-1, watching simple, but informative granular dynamics play out in a low-gravity environment, without the ops- and risk-related constraints on data-acquisition time, will compliment and help to explain the sample-acquisition data from these small-body sampling missions.

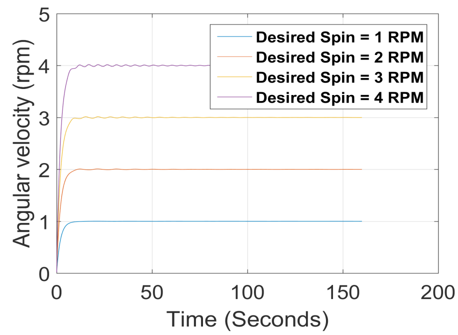


Figure 2: Dynamical stability calculation of AOSAT-1 assuming a worst-case regolith distribution scenario. A single reaction wheel creates a wobble stabilized by magnetorquers.

We will exploit the benefits that come with having a long-term, sustained experiment, including the ability to observe the dynamics inside the chamber continuously for long periods—important given the low velocities and weak forces.

Numerical modeling of granular material will be performed using PKDGRAV [10–13]. This will be of great value in quantifying the material parameters, including static, kinetic, rolling, and twisting frictions [13,14], as well as cohesive properties [5]. These material models can then be applied in large-scale simulations involving small bodies, both for studies of evolutionary processes [15] and for simulating the interrogation of the surface by spacecraft mechanisms [16].

## References

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