

Differential Optical Shadow Sensor CubeSat Mission

Andreas Zoellner, Sasha Buchman, John W. Conklin, Dan B. DeBra, Shally Saraf, Seiya Shimizu
Stanford University
Hansen Experimental Physics Laboratory, 452 Lomita Mall, Stanford, CA 94305; +1 650 336 3136
zoellner@stanford.edu

Hamoud Aljibreen
King Abdulaziz City for Science and Technology
P.O Box 6086, Riyadh 11442, Saudi Arabia

ABSTRACT

A CubeSat mission is proposed to demonstrate in orbit performance of the Differential Optical Shadow Sensor (DOSS), a high precision, compact, low-cost position sensor. The DOSS is used as displacement sensor in the Modular Gravitational Reference Sensor (MGRS). GRS technology enables advances in Earth science and precision distributed Earth-observing sensors, as well as space science, precise orbit determination and maintenance, and precision spacecraft formation flying. To reduce the overall mission risk for a proposed drag-free small satellite mission built around the MGRS, the DOSS is tested in a 2U CubeSat. The main mission objective is to raise the Technology Readiness Level for the sensor. The performance goal is a sensitivity of 1 nm at 1 mHz. This is over one order of magnitude improvement over the current setup which is largely limited by environmental noise. In order to achieve the low frequency stability, lock-in detection is used. The real-time signal processing required for drag-free control is demonstrated on a digital signal processor (DSP). This paper gives a system level overview of the proposed mission.

INTRODUCTION

Drag-free satellites¹ have application in various fields including Geodesy, Aeronomy, Autonomous orbit determination and Fundamental Physics. The goal of a drag-free satellite is to fly in an orbit that is purely gravitational, i.e. all other forces (atmospheric drag, solar radiation pressure etc.) are eliminated. In order to accomplish that, a test mass is free floating inside the satellite, shielded against all these disturbances. A control loop is established in order to track the movement of that test mass and make the satellite follow it using thrusters.

The system that performs these measurements is called a Gravitational Reference Sensor (GRS). One such sensor is the Modular Gravitational Reference Sensor (MGRS)² developed at Stanford. This sensor consists of a spherical test mass, an optical shadow sensor to sense the test mass displacement with nanometer sensitivity and a large dynamic range, a charge control system based on UV LEDs, a caging system to lock the test mass during launch, and a picometers laser interferometer displacement sensor for science measurements. Due to the modular approach parts of the sensor can be omitted for certain applications. For example, the interferometric sensor is not needed for most geodesy applications.

The performance of a drag-free satellite is usually measured in terms of the acceleration noise that the test mass sees. In order to be useful for future Geodesy missions, NASA specifies in its Science Instruments, Observatories, and Sensor Systems Roadmap that the acceleration noise should be lower than $10^{-12} \text{ m/s}^2\text{-Hz}^{1/2}$ for frequencies between 10 mHz and 1 Hz.

The drag-free missions flown to date are medium to large size satellites. Stanford is proposing a drag-free CubeSat³. A CubeSat is a small satellite with a standardized size as described in the CubeSat Specification⁴. It was originally developed at Stanford and Cal Poly beginning in 1999. To date many more than 50 CubeSats have been launched. Many of them were developed in university projects.

In order to reduce the overall risk of the proposed drag-free mission, two technology demonstration missions are planned to test the major components of the MGRS. The first one is the UV LED satellite⁵, scheduled to be launched in 2013. The second one, a technology demonstration of the shadow sensor, is described in this paper.

MISSION OVERVIEW

The Differential Optical Shadow Sensor (DOSS) CubeSat is a technology demonstration mission on a 2U

CubeSat to be launched as secondary payload into a low earth orbit (LEO). The goal of the mission is to raise the Technology Readiness Level (TRL) of the shadow sensor in order to fulfill the requirements of the planned drag-free CubeSat mission. The performance goal for the shadow sensor is a displacement sensitivity of $1 \text{ nm/Hz}^{1/2}$ for frequencies between 1 mHz and 1 Hz.

The DOSS CubeSat is designed to be a subset of the proposed drag-free mission. Therefore the requirements for the following subsystems are inherited from the drag-free mission: on board data processing and storage capabilities, power consumption, and weight and size of the shadow sensor subsystem. The test mass in this CubeSat is not free floating but mounted to a motor that spins it.

Figure 1 shows the CAD model draft of the DOSS CubeSat with one side cut open. The motherboard and radio are located at the bottom. The electrical power system (EPS) is above the motherboard in the stack. Above the EPS is a circuit board that will hold the electronics for the motor controller and one that will have additional power circuits as described below. The main payload is the aluminum housing in the middle of the satellite with four sensor boards attached to its sides and one board with the payload processor on top. The housing is made partially transparent in the figure to show the spherical test mass in its center. The outside walls of the satellite are covered with solar panels. An antenna, harnesses and most fasteners are not shown in the model.

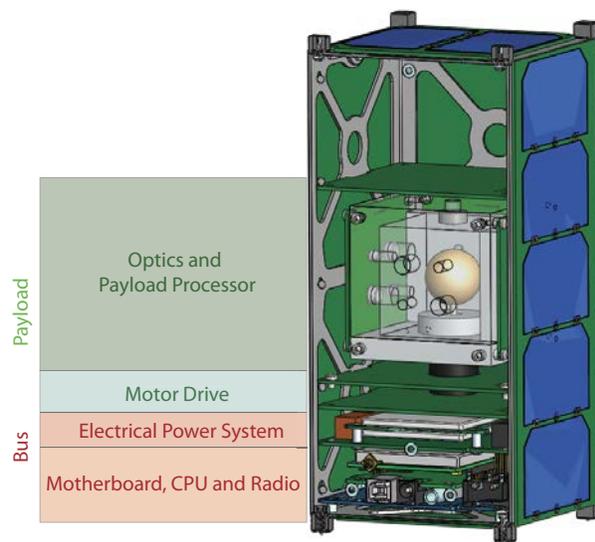


Figure 1 DOSS CubeSat

The ground station at Stanford University will be part of a network of ground stations for this mission.

Depending on availability other ground stations such as the one in the GENSO⁶ network can be used.

The mission lifetime is two months and includes an initial system checkout and sensor calibration, the main technology demonstration and a final data download phase. The mission is accompanied by a ground experiment for data validation.

THE DOSS CUBESAT PAYLOAD

Overview

The main payload is the differential optical shadow sensor. The use of a shadow sensor to measure a test mass displacement has been suggested^{7,8} even before the first drag-free satellite was flown but the technology at that time didn't allow for the optical system to be flown. A shadow sensor is also used in another gravitational science experiment, LIGO, to measure the suspension of the mirrors^{9, 10, 11}.

The basic idea of a shadow sensor is to have a light beam that is partially blocked by the device under test and a detector arranged such that part of it is in the light beam and part of it in the shadow. Any movement of the device under test leads to a change in the shadow position and therefore changes the measured differential intensity on the detector.

As there are almost no requirements for the wavelength to use for this sensor (other than not interfering with the UV LED charge control system of the MGRS at around 255 nm), a detector with maximum sensitivity can be chosen. InGaAs detectors for the near-infrared have a peak sensitivity of about 1 A/W, exceeding the typical sensitivity of Si detectors of about 0.72 A/W.

Light emitting diodes (LEDs) are widely available for the entire spectrum of visible and NIR wavelengths. Laser sources or superluminescent LEDs are possible light sources for this sensor and have been used before, but the mass and power budget for the CubeSat suggests the use of LEDs.

Figure 2 illustrates the arrangement of LEDs and photodetectors (PDs) in a plane perpendicular to the test mass spin axis. A total of two planes are used for a fully redundant three dimensional measurement.

The force F from the photons on the test mass for a single beam with total power $P = 1 \text{ mW}$ is $F = P/c = 3 \cdot 10^{-12} \text{ N}$, with c the speed of light. For a 1 in diameter Gold-Platinum proof mass of mass $m = 170 \text{ g}$ this leads to an acceleration of $a = F/m = 2 \cdot 10^{-11} \text{ m/s}^2$. As this acceleration is larger than the goal for the drag-free CubeSat, the locations of PDs and

LEDs are switched in the second plane in order to balance the momentum transferred by the photons.

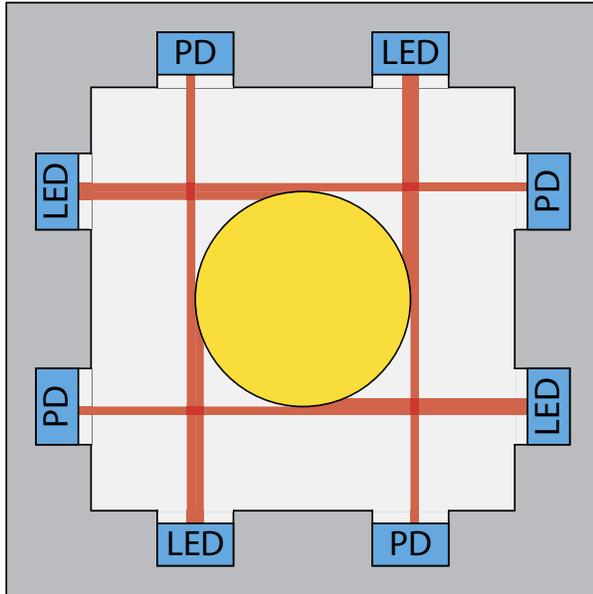


Figure 2 DOSS Measurement Principle

Figure 3 shows a block diagram of the main building blocks of the system electronics. The CubeSat Bus microcontroller is the spacecraft main computer and communicates with the payload computer, a digital signal processor (DSP) over a serial interface. The DSP generates a modulation signal with a software based direct digital synthesizer (DDS) which is used to control the LED Driver. This signal is also used as reference for the lock-in amplification. The current can be monitored with a sense resistor to calibrate and adjust the brightness of each LED individually. On the data acquisition side, the photodiode is followed by a low noise amplifier. The amplified signal is digitized and sent to the DSP to perform the lock-in amplification and provide a real-time position measurement to the main computer.

There are four identical electronic boards arranged around the test mass housing. Each contains two LEDs and two PDs together with the driver and amplifier circuits. The combination of the four differential signals allows measuring all three degrees of freedom with one additional cross check for redundancy.

In the following, each component is described in more detail.

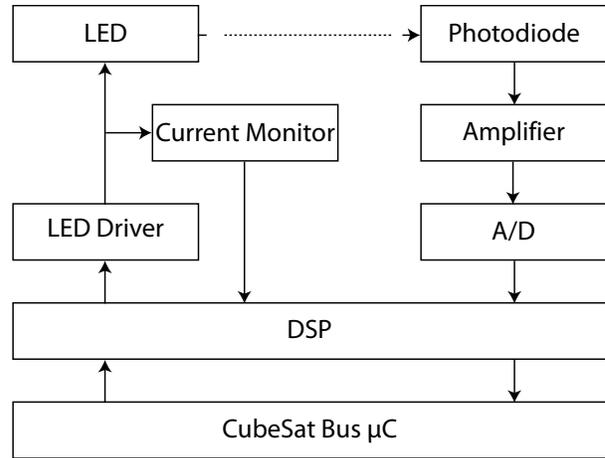


Figure 3 DOSS Block Diagram

LED Driver

The first component of the LED driver is a digital-to-analog converter (DAC) which receives the modulation signal from the DSP and sets the reference voltage for a subsequent amplifier stage. The amplifier stage is followed by a transistor that controls the current through the LED. A current monitor is included and wired to the analog input of the DSP for calibration purposes. The two LEDs on each side are connected in series and the reference voltage is the same for all boards. This way the relative intensity noise is kept low.

Photodiode Amplifier

The photodiode amplifier is designed for low noise and high dynamic range.

Assuming a detector diameter of 2 mm, the area of the illuminated part on the detector changes by $\delta A = 2 \cdot 10^{-12} m^2$ for a 1 nm movement of the test mass. Assuming further a beam power of 1 mW, the incident power change is $\delta P = 6.37 \cdot 10^{-10} W$. With a detector sensitivity of 1.05 A/W a current change of $\delta I = 6.68 \cdot 10^{-10} A/nm$ results. In order to scale this to the LSB of a 16 bit 5 V ADC (15 bits noise free), the current-to-voltage gain of a subsequent transimpedance amplifier needs to be at least $G = 2.28 \cdot 10^5 V/A$. This is done in two stages with a high-pass filter after the first stage to filter out the DC component of the signal that would otherwise overdrive the following stages.

Analog-to-Digital Converter

The Analog-to-Digital Converter (ADC) is designed such that it is not limiting the performance of the overall system, i.e. the measured and amplified signal for a 1 nm displacement is above the digitization noise. In order to resolve the entire range of 2 mm with a 1 nm

resolution, at least 21 bits would be necessary. Since the technology demonstration mission doesn't have a free floating sphere, the necessary dynamic range is smaller and a 16 bit ADC is chosen, limiting the dynamic range to about 60 μm . The drag-free CubeSat will require a higher dynamic range and the ADC subsystem needs to be modified for that.

Lock-in Amplifier

As commercial lock-in amplifiers are not suitable for the use in a CubeSat due to their size, weight and power consumption, another solution has to be found. The suggested design uses a digital signal processor (DSP) to perform the lock-in amplification^{12, 13} after the signal has been digitized by an A/D converter. The DSP is also used to generate the modulation signal with a direct digital synthesizer (DDS).

The result of the calculations in the DSP is a real-time position of the test mass in three dimensions. This information can then be used to perform the drag-free control. Depending on computation power of the DSP, the drag-free control algorithm can be part of the DSP code and directly drive attitude control and thruster units.

Motor Controller

A vacuum compatible brushless motor is used to spin the test mass. The integrated hall sensors are used to control the rotation speed.

The motor controller is not part of the above block diagram as it won't be part of the drag-free mission. The motor controller board is connected to the CubeSat bus and communicates directly with the main board over several digital I/O lines and I²C.

Power Supply

The payload has its own power supply circuits as the CubeSat Bus has only a 5 V and a 3.3 V regulated line as well as the raw battery voltage. The payload circuits also require positive and negative 12 V supplies for the amplifier circuits and a negative 5 V supply for diode biasing. Boost regulators are used for the 12 V supplies. These lines are then filtered with a finesse voltage regulator¹⁴.

Housing and Test Mass

The entire sensor is to be mounted to a housing surrounding the test mass. This housing is required to be rigid as movements of the LEDs or photodiodes can't be distinguished from a movement of the test mass. The housing is machined out of aluminum. In the drag-free satellite the housing has a hole in one wall for the plunger of the test mass caging system. In the

DOSS CubeSat this space is used to mount the motor such that the spherical test mass on its shaft is centered in the housing.

Unlike the successor mission, this CubeSat won't have a free floating test mass. The material requirement for the test mass calling for a low magnetic susceptibility is relaxed and instead of a gold platinum alloy, a cheaper stainless steel sphere can be used. The surface roughness and the coating will be the same as for the drag-free satellite to achieve the same optical properties.

When a free floating sphere is spinning, it does so around its center of mass. Due to imperfections in the manufacturing of a real sphere, there is an offset between the center of mass and the geometric center. This leads to a wobbling of the sphere surface. One potential test mass design has parts of the sphere hollowed out in order to adjust the ratio of the moments of inertia such that the polhode frequency is shifted out of the science band¹.

The offset between the motor spin axis and the geometric center of the test mass is designed to be of the same order of magnitude as the mass center offset of a free floating sphere. The dynamic range of the shadow sensor is well above that distance in order to separate this effect from a lateral movement of the satellite with respect to the test mass.

Additional Sensors

The DOSS CubeSat will have additional sensors to better characterize the environmental effects on the on-orbit performance. These include temperature sensors at various places inside and outside the housing to compare the finite element simulations performed in COMSOL with real data.

THE CUBESAT BUS

The bus for the DOSS CubeSat is based on the CubeSat Kit from Pumpkin Inc. This kit includes a skeleton structure made from aluminum as well as a motherboard, a development board, and the real time operating system Salvos. The microcontroller on the boards is from the Texas Instruments MSP430 series. The selection was made in order to be able to use a unified development environment for both the bus software as well as the payload software on the DSP.

The communications subsystem including a transceiver and antennas is based on other successfully flown CubeSat missions with commercially available off-the-shelf (COTS) parts. The DOSS CubeSat will use amateur radio frequencies for a status beacon and data and command transfer. As there is no attitude control,

an omnidirectional antenna is used. This setup differs a bit from the follow-on mission which requires a higher data rate in order to transfer enough science data during the drag-free operation.

A COTS electrical and power systems (EPS) and battery module with a capacity of 10 W·h is included in the baseline design. It is controlled by the bus controller over I²C and connects directly to the CubeSat Kit bus. The CubeSat will be covered with solar panels on all sides for power generation.

MASS AND POWER BUDGET

The average power consumption is summarized in Table 1. It shows a total average power consumption of less than 1.3 W which is lower than the expected average power generation from the solar cells.

The mass budget is also shown in Table 1. The numbers are based on measurements where available, CAD model calculations, and estimates. The total mass of 1.609 kg is well below the maximum allowed mass for the CubeSat Specification.

Table 1: Mass and Power Budget

Component	Mass (g)	Power (W)
Chassis	253	-
Motherboard	88	0.066
Modem	52	0.4
EPS/Battery	169	0.1
Test Mass	66	-
Housing	551	-
Payload Mainboard	80	0.3
DOSS	150	0.4
Solar Panels	250	-
Total	1609	1.266

CONCLUSION

The large number of COTS parts available for CubeSats allows a rapid and cost efficient development of a technology demonstration mission for the Differential Optical Shadow Sensor. This mission will reduce the risk for the follow-on mission which is going to be a drag-free CubeSat.

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