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A CubeSat Constellation to Investigate the Atmospheric Drag Environment

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ABSTRACT

The value of CubeSats to the scientific community depends on the availability and quality of suitable miniature scientific instruments. We introduce one such instrument capable of measuring total atmospheric density within the envelope of a 3U CubeSat. The Atmospheric Drag Environment Sensor (ADES), to be flown on a constellation of CubeSats, is a miniaturized version of accelerometer technologies that have been used to study the upper atmosphere since the dawn of the space age. ADES is designed to measure at the 10 nano-g level, while occupying a space of less than 10x10x10cm. The remainder of the 3U CubeSat will be dedicated to the attitude determination and control, power production and storage, telemetry, data processing and storage subsystems. The mission goals are as follows: (1) Provide global coverage of atmospheric density measurements, (2) Investigate storm-time features of the thermosphere over a large range of spatial and temporal scales, and (3) Provide the means for data assimilation into a first-principles model of the upper atmosphere. The benefit of this technology is not only its small size, mass and power requirements; but also the significant reduction in the cost of an accelerometer capable of measuring satellite drag. This technological breakthrough will facilitate the addition of a space weather sensor as a secondary payload to many existing LEO satellite mission with minimal impact on the main payloads and overall budget.

INTRODUCTION

Accelerometers have been used on LEO satellites to probe the neutral upper atmosphere since the dawn of the space age[1,2,3,4]. Most accelerometers designed for this purpose consist of a test mass and a cage that is capable of monitoring and restoring the distance between the two. Thus, the instrument senses any difference in acceleration between the satellite and the test mass. While the effects of gravity are not sensed, the main contributions of acceleration typically come from: aerodynamic drag and lift, radiation pressure emanating from the Sun and Earth, residual linear acceleration caused by any offset between the sensor and the center of mass of the satellite, structural vibrations of the satellite, and any attitude or orbit actuation (i.e. thrusters, momentum wheels, etc.).

Until recently, satellite accelerometers were only precise enough to operate around 250 km altitude, where the neutral density was large enough to overcome the instrument noise. In the past decade, several order of magnitude improvements have been made in the accuracy of such accelerometers. This has enabled drag studies at higher altitudes where the density is much lower and in turn, these missions can now last for nearly 10 years. For example, the CHAMP satellite[5] was launched in 2001 into a 410x460 km orbit that is scheduled to decay sometime this year. The GRACE satellites[6], both with accelerometers that were 10-times more precise than the accelerometer on CHAMP, were launched in 2002 into a 480x500 km orbit.

MOTIVATION

Air Force Space Command has a Precision Orbit Determination goal of making 72 hour forecasts of all satellite positions with errors that are less than a 5% increase from errors obtained during routine satellite position specification[7]. Orbital aerodynamic drag continues to be the largest uncertainty in determining trajectories of satellites operating in Earth’s upper atmosphere below about 600 km. The neutral density of the upper atmosphere (thermosphere) is the major factor determining orbital drag. Orbital drag accelerations for a satellite in the earth's atmosphere depend on neutral density, winds and the satellite properties that affect the drag coefficient.

Current assimilative operational models of the upper atmosphere now typically specify density and satellite drag to within 8% but during large geomagnetic storms, the three-hourly averaged data errors can easily exceed

15%. When forecasting three days into the future during even moderate geomagnetic conditions, typical errors are 65% at 400 km. The present clear consensus is that empirical models have reached the limit of possible improvement and physics-based models are lacking key data inputs to produce better results.

One of the main directives of the AFRL Orbital Drag Environment program is to provide physics based assimilative models for satellite drag and sufficient data in for these models to ingest. There is a critical need for comprehensive satellite drag measurements to address the current satellite drag forecast shortfall and to drive current and next-generation operational models. The objective is a capability to fly a constellation of capable instruments to:

a. Address missing physics in satellite drag models, and
b. Permit current empirical and forthcoming physics-based assimilative models to meet their potential.

MEMS NANO-G ACCELEROMETER

The Atmospheric Drag Environment Sensor is a MEMS accelerometer built on the principles of capacitive position sensing and electrostatic actuation of a test mass. An initial design concept can be seen in Figure 1. For reasons related to instrument calibration, discussed in the next subsection, it is necessary to rotate the test mass. To accomplish this, the instrument requires a motor, an optical link, and power coils to rotate, download data from, and power the rotating platform, respectively.

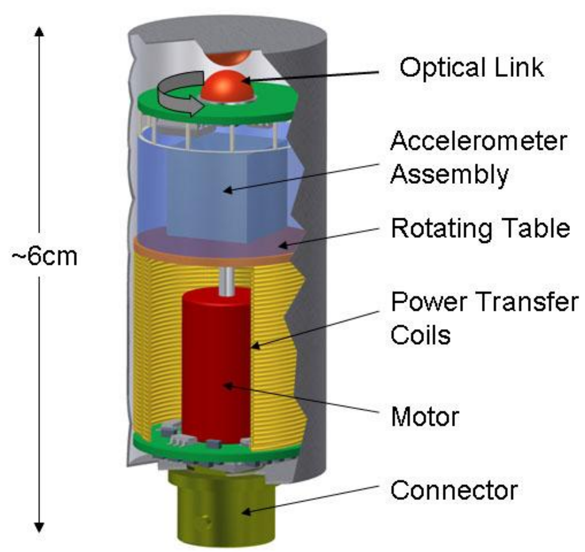

Figure 1: ADES design concept

On-Orbit Instrument Calibration

Nearly all satellite drag accelerometers require careful calibration in order to mitigate the slow (on the order of a day) instrument drift. The calibration is usually applied to the raw accelerations using the following formula:

$$A_{corrected} = Scale*A_{raw} + Bias$$

with the variation in the Bias term usually dominating the total calibration. For satellites in eccentric orbits, these factors can be estimated by using the accelerations measured near apogee as a baseline. For satellites in near-circular orbits such and CHAMP and GRACE, precision orbit determination is usually employed to compare the accelerometer-measured acceleration with the GPS-observed accelerations over the span of a day. Calibration of ADES will also be required. In fact, due to the sensitive nature of MEMS devices, recalibration is expected to be required much more frequently, possibly on the order of 10 minutes. To mitigate this potential error source, the test mass will be rotated at a nominal rate of 1 Hz through the ram and cross-track directions. Comparing the in-track with the anti-in-track measurement will allow us to compute the bias factor. The scale factor will be estimated as needed by temporarily increasing the rotation rate to around 1.2 Hz and comparing with data taken at the nominal 1 Hz rotation rate. Utilizing the rotation of the test mass, the single axis accelerometer is transformed to a dual axis accelerometer in which both axes are automatically cross-calibrated. With all conventional accelerometers, errors introduced by the the cross-calibration of individual axes has made it nearly impossible to deduce cross-track winds from accelerometer measurements.

Targeted Performance and Physical Characteristics

This device is designed to operate within the size, weight, power and mission constraints of a 3U CubeSat. Table 1 shows the size, mass, power and performance characteristics of ADES compared to the STAR Accelerometer.

Table 1: Performance and physical characteristics comparison between the ADES (design targets) and STAR accelerometers

	ADES	STAR
Accuracy	10 nano-g	1 nano-g
Precision	10 nano-g	0.3 nano-g
Size	<10x10x10 cm	22.6x19.6x18.2 cm
Mass	0.5 kg	11.4 kg
Power	1 W	9.5 W

The targeted precision of the accelerometer is 10 nano-g, as shown in Table 1. Also shown is the precision of the STAR accelerometer, designed by Onera. While ADES has a much lower level of precision, the overall size, mass and power requirements will allow it to be integrated into a 3U satellite which will have a large inverse ballistic coefficient $B^{-1} = C_D*A/M$. A 3U CubeSat of standard size and mass will experience an estimated 2.5 times as much acceleration as a satellite capable of supporting the STAR instrument, such as the GRACE satellites. Figure 2 shows the approximate acceleration of a 3U CubeSat that can be expected from aerodynamic drag, given by the MSIS model[8], as a function of height and solar activity. The intersection of the 10 nano-g noise level indicates the extent of the regions in which ADES will be useful. Ideally, this instrument will operate on satellites having perigees of less than 300 km height.

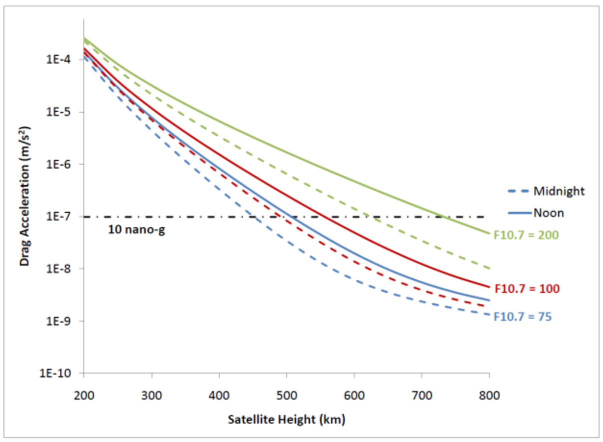

Figure 2: Aerodynamic drag acceleration vs. satellite height over a range of local times and solar fluxes

The rotation rate of the test mass restricts the data sampling to 1 Hz, or about 7.6 km in spatial resolution. Depending on the overall performance of the instrument, more averaging may be required to lower the instrument noise, further increasing the spatial resolution.

Test Assembly

An end-to-end test assembly has been constructed to demonstrate the rotating MEMS accelerometer concept and to test the performance of individual components. Figure 3 shows a picture and cut-away section of the prototype, with approximate dimensions of 19x5.5x5.5 cm. The test device has successfully demonstrated the following aspects of the instrument:

1. Capacitive sensing electronics with feedback electrostatic actuation of a test mass.
2. Power transmission from the stationary platform to the rotating platform through the power transfer coils.
3. Data transfer from the rotating platform to the stationary platform via the optical link.
4. Rotation of the instrument, including vibration characteristics of the motor.

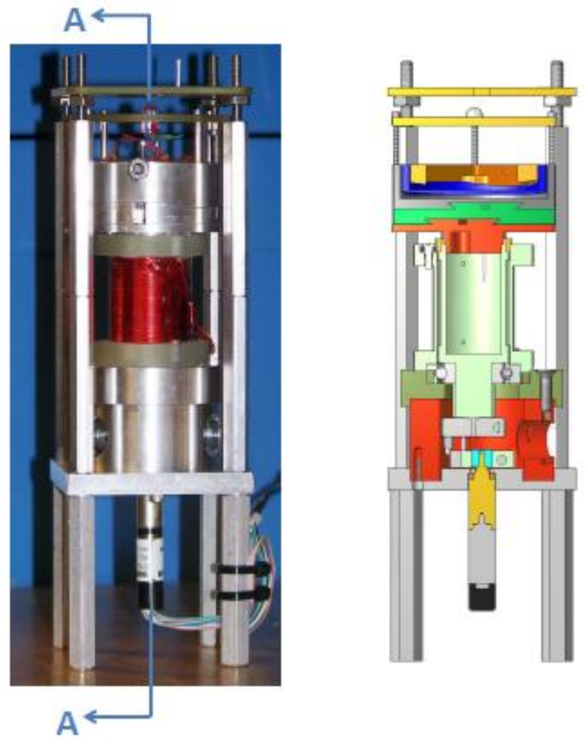

Figure 3: Bench-top prototype and testing apparatus for the accelerometer and rotating platform (middle), Section AA (approximate) of the accelerometer and rotating platform assembly (right)

CUBESAT IMPLEMENTATION

The ADES instrument is designed to operate under all of the constraints of a 3U CubeSat. In this section, we present an example design concept for a CubeSat mission that incorporates ADES with two additional scientific instruments and the other necessary support hardware. Initial studies have been conducted to support the feasibility of such a mission.

Orbit

For this mission, we desire to have global coverage. In addition, atmospheric density variations are extremely strong near the geomagnetic poles due to the increased Joule heating and ion-neutral coupling in these regions.

To satisfy both of these mission goals, we require an inclination in the range 75-105°.

Three additional parameters constrain the height requirements of the mission: (1) the sensitivity of ADES allows operation only below 400 km, (2) the desired lifetime is at least 1 year and less than 5 years, and (3) available launch opportunities. Given these parameters, we will target an orbit with perigee = 275 ± 125 km and apogee = 800 ± 200 km.

Satellite Attitude

In order for the accelerometer to produce data of good quality, the orientation of the satellite must be 3-axis stabilized. Additionally, in order for ADES to measure drag in the ram direction, the rotating axis of the instrument must remain perpendicular to the velocity vector of the satellite. For most CubeSats, this is a difficult requirement to fulfill. Typical choices for attitude control include momentum wheels and magnetorquers. Due to the sensitivity of ADES to mechanical vibration, momentum wheels have been eliminated. Magnetorquers also require less space and power when compared to momentum wheels. However, the trade-off is reduced controllability of the satellite.

Table 2: Scientific instrument and subsystem mass and power requirements

Instrument/Subsystem	Mass (g)	Power (W)
Command and Data Handling	70	1.0
Attitude Determination and Control	250	1.0
Telemetry, Tracking, and Command	260	1.0
Electrical Power System	1200	0.25
Structures	250	
Thermal Control	100	0.25
Harness and Cables	100	
GPS	75	1.7
ADES	500	1.0
PLP	300	0.5
Particle Detector	200	0.5
Total:	**3305**	**7.2**

The choice of magnetorquers over momentum wheels creates the need for a fairly stable satellite attitude configuration. Several possible scenarios have been explored. In the first scenario, the instrument rotation axis is fixed to the long axis of the 3U CubeSat, which is nominally aligned to the cross-track direction. The CubeSat slowly spins about its long axis to maintain its pointing with respect to the Earth. The momentum bias from the instrument's rotating platform is in the direction of the CubeSat's rotation, and therefore stabilizes the attitude. The second scenario is a variation on 3-axis stabilization. The instrument's rotation axis is again fixed to the long axis of the 3U CubeSat, but is now nominally aligned to the nadir/zenith direction. The CubeSat spins about its long axis in the opposite direction to the instrument's rotating platform to cancel the biased momentum. The CubeSat also spins slowly about the cross-track axis with the frequency of one orbit to maintain its pointing with respect to the earth. In this configuration, the gravity gradient naturally acts as a stabilizing force.

The first scenario is the more stable of the two; However, the optimum alignment of the accelerometer is achieved in the second scenario (i.e. the accelerometer senses the in-track and cross-track directions instead of the in-track and nadir direction) which allows for the calculation of cross-track winds. These two scenarios will be further explored to find the optimum configuration both in terms of controller power and ADES pointing requirements.

Satellite Components

Most vital CubeSat components are available off-the-shelf. Table 2 shows a list of required components, along with a mass and power budget. The total mass fits in the envelope of a 3U CubeSat (<4kg). The total power required, on the other hand, is greater than conventional 3U body-fixed solar panels can provide (on the order of 4-5 W assuming the above orbit and attitude configuration). Figure 4 shows one method to obtain more than 4-5 W. With the orbit and attitude constraints mentioned, this solar panel configuration is capable of producing on the order of 9-11 W. After launch, solar panels are deployed to a fixed angle for the duration of the mission.

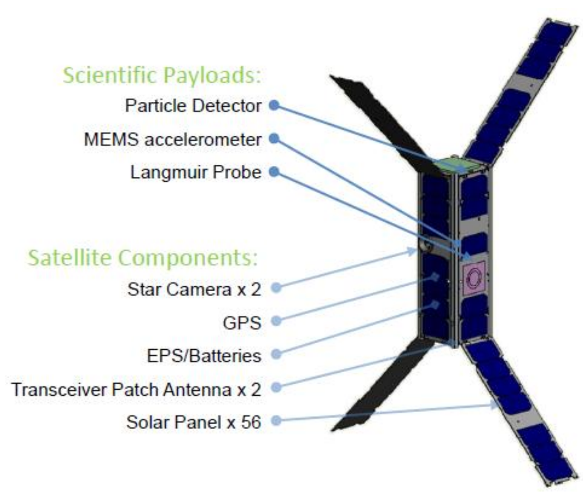

Figure 4: CubeSat design concept showing scientific payloads and support hardware/sensors

SUMMARY AND CONCLUSIONS

A MEMS accelerometer is being developed for satellite drag experiments on small satellites, including 3U CubeSats, with support from AFRL. Many of the main technical obstacles related to the instrument design have been overcome. Initial studies show that the device can be readily integrated with a suite of valuable scientific instrument on a 3U CubeSat.

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