

## Nanosatellite Deorbit Motor

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### ABSTRACT

Existing and expected debris mitigation regulations require LEO spacecraft to deorbit within 25 years. Given typical spacecraft ballistic coefficients, this places an upper limit of perigee of around 600 km altitude for nanosatellites such as CubeSats. Also with operational nanosatellite constellations being deployed in the coming years there is an increased need to remove small spacecraft from LEO orbits much faster to ensure that defunct satellites can be replaced within the constellation with new satellites.

Practical deployable drag systems being developed as products can lower the ballistic coefficient sufficiently to allow perigee up to 800 km altitude, however this still rules out many launches above that altitude for CubeSats and MicroSats that ride as secondary payloads. There is also the problem that a drag system does not reduce total intersected time-area product, thus debris impact probability is not reduced even if the lifetime requirement is met.

This paper provides an overview of a recently developed deorbit system using a CubeSat sized solid rocket motor that was successfully tested in February 2013. The system is adopted from technology applied for European launch vehicle igniters, available at the development partners. It has sufficient propulsive capability to lower the perigee of a 3-unit CubeSat from a 1000 km altitude circular orbit to comply with the 25 year maximum orbit lifetime. Test results will be presented for the deorbit system, generating around 180 N thrust and 590 Ns total impulse at atmospheric pressure. Furthermore the challenges and solutions of implementing such a system inside a nanosatellite mission (both technical, programmatic and legal) will be addressed.

All thrusters have an off-axis thrust component that causes the spacecraft attitude to be unstable when thrust is applied. Analysis will be presented showing that sufficient gyroscopic stiffness is achieved at reasonable spin rates to maintain stability of a 3-unit CubeSat in a long-axis spin. Attitude control algorithms were tested in simulation to demonstrate that the spin rate and pointing accuracy can be achieved using only traditional CubeSat magnetic sensors and actuators.

### BACKGROUND

In response to recent concerns about orbital debris, international guidelines have been created recommending that satellites be removed from orbit within 25 years of launch<sup>1</sup>, which have been adopted as law in a number of countries<sup>2</sup>. This presents a challenge for the CubeSats community, which has been enabled by the availability of cost-effective and opportunistic launches as secondary payloads. As most nanosatellites

are only removed from orbit by the effect of drag, which reduces rapidly with altitude, the regulations effectively prohibit the use of certain classes of orbits. Unless mitigation methods can be found to comply with the orbit lifetime requirements, there will be fewer CubeSat launches available and costs will rise.

The risk of impacts between spacecraft and debris in a crowded constellation orbit has the potential to significantly undermine the reliability and thus the

feasibility of the constellation. This is especially true if the planned spacecraft density is high due to the use of large numbers of relatively cheap nanosatellites. Removing old or defunct satellites from a constellation allows replacement and renewal of the constellation without escalating the impact risk due to crowding.

### Expected CubeSat Orbit Decay

Achieving deorbit by passive means requires launching to an altitude from which the satellite orbit will decay and re-enter in a timely manner. The deorbit time is thus dependent on the spacecraft ballistic coefficient and the state of the Earth's atmosphere. CubeSats have a mass of 1 to 1.5 kg per 1-Unit volume, and a typical drag coefficient<sup>3</sup> of 2.0 results in approximate ballistic coefficients for a 1-unit CubeSat of between 50 and 75 kg/m<sup>2</sup> and for a 3-unit CubeSat of between 50 and 225 kg/m<sup>2</sup>. Applying standard methods for calculating orbital lifetime<sup>4</sup>, for this range of ballistic coefficients the 25 year orbital lifetime is not met for orbits with perigee above about 600 km altitude.

### Drag Sail Orbit Decay

Passive solutions to reduce the orbit lifetime include deployable sails, balloons and tethers that increase the cross-sectional area and hence reduce the ballistic coefficient. In order to meet the 25 year lifetime requirement at 1000 km altitude, a ballistic coefficient of around 0.5 kg/m<sup>2</sup> is required.

The effective area of a sail is half the total area, as the satellite is not expected to hold the large sail oriented in the velocity direction. A 3-unit Cubesat weighing 3.9kg thus requires an area of 7.8 m<sup>2</sup> in order to achieve timely deorbit from 1000 km. Proposed commercial drag sails for nanosatellites that are suitable for up to 6-unit CubeSats currently only provide a drag area between 0.5 and 4.0 square meters<sup>5,6,7</sup>.

Larger sails are under development for CubeSat flights, up to 25 square meters in area<sup>8</sup>. These are flown as primary payloads on technology demonstration missions and take up a volume of two CubeSat units (10 x 10 x 20 cm<sup>3</sup>), therefore they are less suitable for most nanosatellites smaller than a 6-unit CubeSat.

### Drag Sails Impact Probabilities

The impact probability ( $P_i$ ) of an object over its orbital lifetime is equal to the volume swept by the object over its lifetime ( $V$ ), multiplied by the particle density of debris ( $p_d$ ).

$$P_i = V \cdot p_d \quad (1)$$

If we assume the orbital velocity ( $v$ ) to be constant:

$$V = v \cdot A \cdot t \quad (2)$$

Where  $A$  = cross sectional area; and  $t$  = orbital lifetime. The orbital lifetime ( $t$ ) is inversely proportional to deceleration due to drag ( $a_d$ ):

$$t = \frac{K}{a_d} = \frac{K}{\frac{1}{m} \left( \frac{1}{2} \rho v^2 C_d A \right)} \quad (3)$$

Where  $K$  = a constant that depends on initial orbital parameters;  $m$  = mass;  $\rho$  = gas density; and  $C_d$  = drag coefficient. Combining these equations gives an expression for the impact probability:

$$P_i = \frac{2mKp_d}{\rho v C_d} \quad (4)$$

The derivation of these equations assumes  $C_d$ ,  $m$ ,  $\rho$ , and  $p_d$  to be constant for the purposes of comparison, which is considered a reasonable approximation for comparison of a CubeSat with and without a drag sail. This shows that the impact probability is not reduced by increasing the cross sectional area through use of a drag sail, and thus brings into question the validity of the 25 year lifetime requirement and the use of drag sails to reduce impact hazards.

### Deorbit By Chemical Propulsion

In addition to lowering the impact probability due to lower lifetime swept volume, a chemical propulsion deorbit system has the advantage of immediate confirmation of removal of spacecraft and/or debris from orbit or into an orbit that will quickly decay. It also provides the operational flexibility to lower the orbital altitude at either the beginning or the end of the mission.

In order to achieve the 25 year deorbit requirement, a nanosatellite in a 1000 km circular orbit must have perigee lowered to 400 km, requiring a delta-V of around 155 m/s. For a 3.9 kg CubeSat, this requires around 600 N.s total impulse to be exerted along the anti-velocity vector. Ideally such a system would be fit within the volume and mass envelope of one CubeSat unit (volume 10 x 10 x 10 cm<sup>3</sup> and mass 1300 grams).

### SYSTEM DESIGN

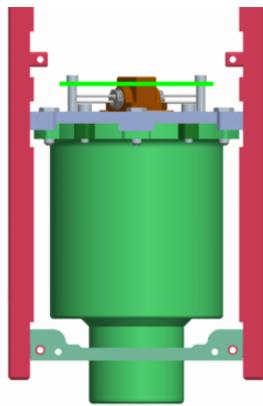
The Nanosatellite Kick Stage (NKS) is a suitably sized solid rocket motor developed by ISIS, APP and TNO. Adopted from technology applied for European launch vehicle igniters, the NKS uses an ammonium perchlorate formulation propellant with a specific impulse of around 240 seconds. Several performance characteristics were identified as desirable for a

nanosatellite thruster: maximum acceleration of 11 g; low heat transfer to the satellite structure; operation over a temperature range of -40 to +85 degrees Celsius; and low mass.

A small and safe igniter has been developed that does not need a safe and arm device. To prevent an undesired ignition, i.e. caused by EMC or by switching on the electronics, a significant power input is required to the igniter. Normally 0.1 J is sufficient to ignite a standard igniter. In this design around 50 J is needed, which gives a significant safety margin and is no problem to be supplied by a small battery.

The NKS is mounted to a CubeSat by a single bracket at the top of the motor. Finite element analysis was used to verify the bracket can survive launch vehicle loads for a range of launchers and loading from the thruster itself. The single bracket allows easy assembly and disassembly after the rest of the satellite has been assembled. It also serves to minimize heat transfer to the nanosatellite structure from the hotter regions of the motor such as around the rocket nozzle and lower portion of the combustion chamber.

Figure 1 shows the NKS in a CubeSat structure. The mounting bracket is shown side-on across the top of the motor and connects to the CubeSat rails. Above that bracket (grey) are the igniter (brown) and control electronics (light green), and below the bracket is the body of the NKS (green). The lower rib between the CubeSat rails does not make contact with the thruster.

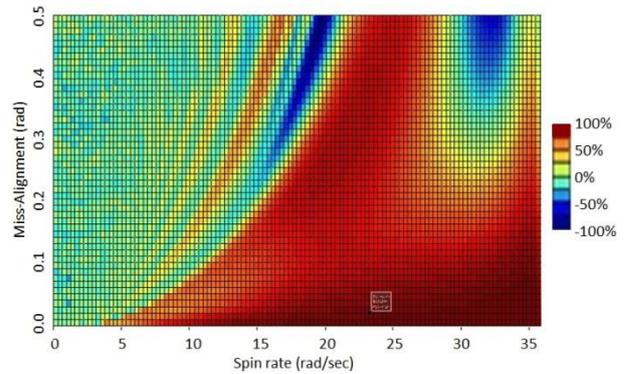


**Figure 1: CAD model of the Nanosatellite Kick Stage shown mounted in a CubeSat structure**

**ATTITUDE CONTROL**

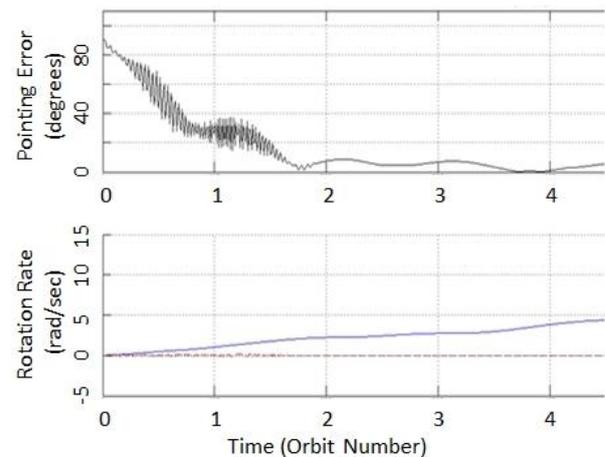
All thrusters have an off-axis thrust component that causes the spacecraft attitude to be unstable when thrust is applied. Spin stabilization was investigated for a 3-

unit CubeSat thrusting along the long-axis in the presence of significant thrust misalignment. The total on-axis impulse fraction for a range of thruster misalignment angles and satellite spin rates was simulated, yielding results as shown in Figure 2. For expected misalignment up to 0.2 radians, sufficient gyroscopic stiffness is achieved at a spin rate of 20 rad/sec for all operating temperatures.



**Figure 2: On-axis thrust percentage at +85°C**

To limit the impact on CubeSat requirements, it is desirable to point and spin up the 3-unit CubeSat used in this example by using standard off-the-shelf CubeSat magnetic sensors and actuators. Building on existing attitude control algorithms<sup>9</sup>, a successful control strategy was implemented in two steps; first aligning the spacecraft and then slowly increasing the spin rate.



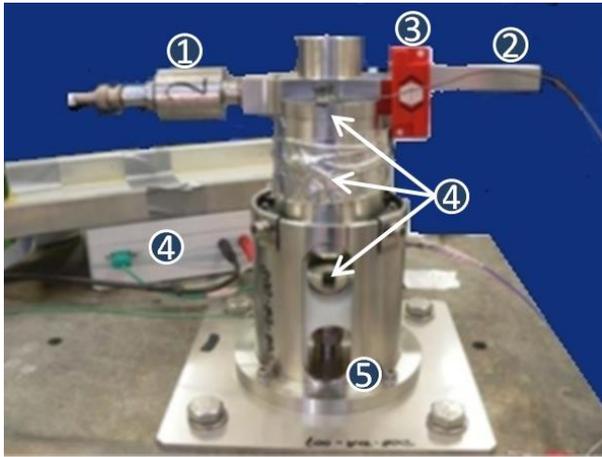
**Figure 3: Scenario 3**

It can be seen in Figure 3 that a pointing error of less than 5 degrees can be achieved. Only the first four orbits are plotted here in order to show details of the initial pointing maneuver.

## TEST RESULTS

### Test Setup

Three firing tests were conducted of the NKS in an (almost) flight representative configuration, mounted in a vertical thrust stand as shown in Figure 5. The thrust stand and test motor were instrumented with several sensors that will not be present on flight units.



**Figure 4: NKS demonstrator on the thrust stand**

A pressure sensor (1) measures chamber pressure inside the rocket motor. The pressure sensor causes the mass to be asymmetric on the thrust stand, so a counterweight (2) is installed on the opposite side of the motor from the pressure sensor to balance the system.

A shock sensor (3) was set to trigger at 10 g in the vertical direction.

Temperature sensors (4) were placed at 5 positions: next to the nozzle, two locations on the cylinder wall, on the base and in the electronics box.

A load cell (5) measured the downwards force produced by the motor. The influence of gravity and bias drift on the sensor readout was removed through calibration immediately before and after the firing.

Video recordings were also taken with three different cameras from different angles. A screen shot of one of the videos is shown in Figure 5.

### Results

Three tests were performed, with the results shown in Table 1. The first two tests were performed on the same day, at ambient temperatures. Inside the preparation facility the temperature remained around 15 degrees all day.



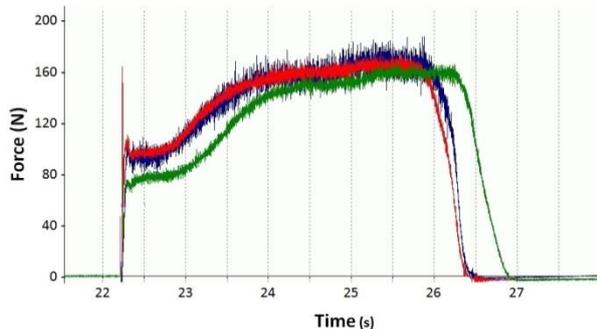
**Figure 5: NKS firing on thrust frame**

The third test was performed two weeks later, after conditioning the assembled motor at low temperature (-40 degrees Celsius) for 21 hours. The time between removing the demonstrator from the conditioning cabinet and the actual firing was between 6 and 7 minutes and the thermal properties of the casing provide sufficient certainty that the propellant grain was still very close to the conditioning temperature at the time of firing.

**Table 1: Test Results**

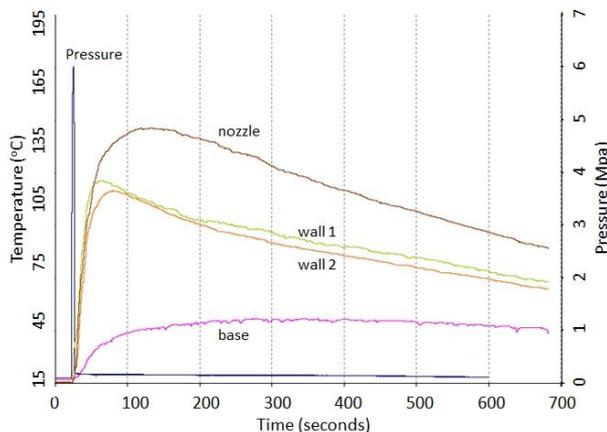
| Test # | Parameter     | Value          |
|--------|---------------|----------------|
| 1      | Temperature   | Ambient (15°C) |
|        | Total Impulse | 608 N.s        |
|        | Max Thrust    | 199 N          |
|        | Burn Time     | 4.2 sec        |
| 2      | Temperature   | Ambient (15°C) |
|        | Total Impulse | 604 N.s        |
|        | Max Thrust    | 186 N          |
|        | Burn Time     | 4.2 sec        |
| 3      | Temperature   | Cold (-40°C)   |
|        | Total Impulse | 607 N.s        |
|        | Max Thrust    | 178 N          |
|        | Burn Time     | 4.7 sec        |

The thrust profiles for each test are shown overlaid in Figure 6, in blue, red and green for the first, second and third tests respectively. These have been aligned on the time axis.



**Figure 6: Thrust profile for all three tests**

Motor surface temperatures during and after the first demonstration test are shown in Figure 7. The maximum temperature of 149 degrees Celsius occurred next to the nozzle, approximately 120 seconds after ignition. The temperature of the control electronics is not shown on the table and had little change from the ambient temperature in the test area.



**Figure 7: Temperature at various points on the motor surface**

Shock sensors did not trigger in any of the tests.

## DISCUSSION

### Discussion of results

The test results showed remarkably consistent performance, with <1% variation in total impulse. The maximum acceleration for a 3-unit CubeSat of mass 3.9 kg would be 5.2 g, well below the limit of 11 g. Additionally, no shocks greater than 10g were present.

The heat transfer to the satellite structure appears to be quite manageable as the vast majority of the heat released from burning the propellant leaves the system in the exhaust. Maximum temperatures at the base, where the bracket would mount the motor to the CubeSat structure, were below 50 degrees Celsius in all

tests. Radiative transfer from the wall or nozzle areas is expected not to raise the temperature of the CubeSat structure by more than a few tens of degrees, and multi-layer insulation can be added if this is considered problematic.

Successful operation has been demonstrated at temperatures of ambient (+15) and -40 degrees Celsius. Additional tests are planned at the maximum operating temperature of +85 degrees Celsius.

The mass of the flight system is expected to be 1.18 kg, slightly below the requirement.

### Technical Challenges

Formation of debris particles is a particular problem for solid rocket motor exhaust, especially when metal powder is used to increase the burn temperature and thus specific impulse. Combustion of the metal is often incomplete, resulting in the formation of metal droplets in the exhaust. The propellant formulation used in the firing tests was an available formulation and contained metal fuel. One goal for optimizing the concept design of the deorbit module will be to reduce the risk of particles in the exhaust while maintaining sufficient specific impulse.

Proving the reliability of a solid rocket motor requires a larger number of tests to arrive at a sufficient statistical confidence. This is particularly important for ignition and thrust performance in space conditions.

Safety must be considered paramount in all solid rocket motor testing as the potential for damage to equipment and personnel is significant for any unproven design. The associated procedures and equipment have both financial and schedule costs. Developing a solid rocket motor is not to be taken lightly, however once the safety and reliability have been proven the motor can be handled, installed and operated with confidence inside the envelope design.

### Programmatic Challenges

Following reliability testing, it is necessary to satisfy with launch providers that there is no risk to the launch vehicle. This process can be time-consuming, and must be commenced early in the spacecraft development program. It is expected that the NKS will achieve a type-acceptance from various launch providers, making it easier for each spacecraft developer to gain launch approval.

Using a solid rocket motor of this size exceeds the CubeSat specification<sup>10</sup> requirement 2.1.5 for total stored chemical energy. This may cause further programmatic challenges if working with launch

providers that wish to see strict adherence to this standard.

### **Legal Challenges**

The foreseen solid propellant is a class 1 material (explosive). In order to be able to transport the NKS loaded with the solid propellant, the NKS has to be approved for transport by a competent authority. APP (and TNO) have experience with the application for transport approval of solid rocket motors. Based on suitable propellant data and the motor design the competent authority will issue a transport classification. An Ammonium Perchlorate based propellant as foreseen to be used in the NKS will probably result in a class 1.3 transport classification.

Solid propellants and solid rocket motors furthermore need to comply with the specific import and export regulations for military or dual use goods.

### **CONCLUSION**

Solid rocket motors have been shown to be an effective means for meeting existing and expected debris mitigation regulations as well as reducing the impact probability. A motor has been developed that is suitable for deorbiting a 3-unit CubeSat from a 1000 km orbit. Spin-stabilization has been shown as a viable control scheme, and can be implemented using the most common type of CubeSat magnetic attitude sensors and actuators.

### **Acknowledgments**

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