ANALYSIS OF ELECTRIC PROPULSION SYSTEMS FOR DRAG COMPENSATION OF SMALL SATELLITES IN LOW EARTH ORBIT

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WHAT TO EXPECT?

➢ Overview
➢ Motivation
➢ Existing Research and Technology
➢ Preliminary Numerical Analysis
➢ Main Findings
➢ Extended Application
➢ Concluding Remarks
➢ Future Work
OVERVIEW

The drag experienced by small satellites is examined at an altitude range of 100 to 300 km. This range was chosen as it represents the perfect zone for Earth observation and reconnaissance missions. The higher atmospheric density makes it ideal for testing Atmosphere Breathing Electric Propulsion (ABEP) systems.

The analysis performed in this study aims to identify if Electric Propulsion and Atmosphere Breathing Electric Propulsion systems can be used to increase the usefulness of small satellites in Very Low Earth Orbits and find the trade-off altitude between the two.
MOTIVATION

INCLUDES THE BENEFITS ASSOCIATED WITH USING SMALL SATELLITES AT LOW ALTITUDES
MOTIVATION: WHY THIS ALTITUDE?

Ground Resolution

One important parameter for observational satellites is the linear (ground) resolution.

\[ X' = \frac{2.44h \lambda}{D} \]

The ground resolution refers to the detail that can be mapped to a single pixel. Lower values mean that more detail can be captured.

Debris Density

- Image Credit: [1]
MOTIVATION: WHY SMALL SATELLITES?

“95% of performance of large satellites can be reached with small satellites at 5% of the cost”

- Surrey University IAA Simposium 2001 [2]

Projections from the House of Commons show that between 2015 and 2019 more than 500 small satellites will be launched with an estimated market value of $7.4 billion [4].
MOTIVATION: ELECTRIC PROPULSION?

- Image Credit: NASA

• Very fuel efficient systems.
• High safety factor.
• Has the potential to achieve very high $I_{sp}$ and $\Delta V$.
• Thrust values within the required range.
• Can be made very small.
• Wide range of available options.
EXISTING RESEARCH AND TECHNOLOGY

AN OUTLINE OF THE CURRENT RESEARCH AND AVAILABLE TECHNOLOGIES IN THIS AREA
EXISTING RESEARCH AND TECHNOLOGY: SMART-1 SATELLITE

- The first small satellite to leave Earth’s sphere of influence, using solar electric propulsion.
- Hall Effect Thruster with 82.5 kg of Xenon gas. Thruster lifetime of over 4600 hours.
- The mission was extended due to the “... ultimate capabilities of the EP subsystem...” [5].

- Image Credit: [5]
EXISTING RESEARCH AND TECHNOLOGY: GOCE SATELLITE

• Very low orbit altitude, at about 250 – 270 km.

• Ion propulsion primarily used for drag compensation.

• Exceeded its design life of 20 months by additional 36 months.

• Perfect platform for testing Atmosphere Breathing Electric Propulsion.
EXISTING RESEARCH AND TECHNOLOGY: SIMILAR RESEARCH

Drag Compensation

• Very scarce.
• Primarily focused on LEO and altitudes above 300 and 400 km.
• Small satellites, such as CubeSats are rarely considered.
• Only one detailed paper found.

EP and ABEP Systems

• Plenty of research in multiple science journals.
• Comprehensive analysis of different types of electric micro-propulsion systems.
• ABEP research gives no information on the scalability of the system.
• No comparison between EP and ABEP.
NUMERICAL ANALYSIS

PRESENTS THE ATMOSPHERE MODELS, ORBITAL PROPAGATORS AND THRUSTERS USED
NUMERICAL ANALYSIS: ATMOSPHERE MODELS

- The analysis uses the NRLMSISE-00 atmosphere model.
- Drag forces between 0.5 N and 20 \( \mu \)N were observed for a 1U CubeSat.
- Small variations were found to exist due to satellite position and time of day.
- Space weather effects are significantly reduced at lower altitudes.
NUMERICAL ANALYSIS: ORBITAL PROPAGATOR

- Orbital Propagator based on Gauss’s Planetary Equations.
- Accounts for 5 perturbing forces.
- Able to monitor the change of orbital parameters throughout the simulation.
- Thrust profiles from EP and ABEP systems are easy to implement.

(a) 0.001 Eccentricity at 300 km Perigee, Equatorial Orbit.  
(b) GRACE Mission Parameters, Near Polar Orbit.
NUMERICAL ANALYSIS: ELECTRIC PROPULSION

- Three different types of thrusters, represent a wider range of electric micro-propulsion systems.
- Less efficient but simpler Pulsed Plasma Thruster [6].
- Medium range Ion thruster [7].
- Highly efficient but bigger Field Emission Electric Propulsion [8].
NUMERICAL ANALYSIS:
ATMOSPHERE BREATHING ELECTRIC PROPULSION

INLET:
Utilises the in situ resources for propellant

PROPELLANT TANK:
Storage of the atmospheric gases

COMPRESSOR:
To increase the gas pressure

PAYLOAD BAY:
Internal subsystems of the satellite

PROPULSION SYSTEM:
Providing the required thrust
NUMERICAL ANALYSIS: ABEP INTAKE

Long Annular Intake

- Intake in front of the satellite, simpler design.
- Long duct allows the forming of a compression zone.
- Duct straws prevent potential backflow.
- DSMC analysis shows collection efficiencies ranging from 17 to 23 % [12].

Bypass Annular Intake

- Bypass intake with the satellite core in the middle.
- Long duct allows the forming of a compression zone.
- 45 degree conical diffusion region.
- DSMC analysis shows collection efficiencies ranging from 40 to 50 % [12].
NUMERICAL ANALYSIS: ABEP INTAKE

Small Satellite Considerations

• Intake area ratio \( \frac{A_{in}}{A_{out}} \).
• Relationship between mass flow rate and intake area ratio.
• Compression of atmospheric gases.
• Particle interference and backflow.
• Type of intake.
NUMERICAL ANALYSIS: ABEP THRUSTER

- Inductive Plasma Thruster (IPG6-S) [13].
- Less influenced by atmospheric composition.
- Higher thrust allows for lower orbital altitudes.
- No need for plasma neutralisation.
- Required power varies from 2 to 10 kW and maximum efficiency is between 50 and 60 %.
MAIN FINDINGS

PRESENTS THE MAJOR FINDINGS FROM THE ANALYSIS
MAIN FINDINGS: CONTROL ORBITAL DECAY

- The satellite is assumed to have greater packing density.
- More conservative propellant mass was chosen.
- The satellite is at a standard polar orbit.
- Orbital decay varies between 56 days (300 km) and 4 hours (100 km).
MAIN FINDINGS:
EP DRAG COMPENSATION 1U

- Both the PPT and RIT can achieve full drag compensation with minimal power requirements.
- The FEEP system chosen is too big for a 1U satellite.
- The power requirement doubles for every 50 km of altitude decrease.
- Increase of lifetime is significant enough for the propulsion system to be considered.

<table>
<thead>
<tr>
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<th>PPT 300 km</th>
<th>PPT 250 km</th>
<th>RIT-μX 300 km</th>
<th>RIT-μX 250 km</th>
<th>RIT-μX 200 km</th>
<th>IFM Nano</th>
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<td>7.5</td>
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<td>2-3</td>
<td>5-7</td>
<td>7-10</td>
<td>25</td>
<td>Na</td>
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<tr>
<td>Lifetime [Days]</td>
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<td>62</td>
<td>344</td>
<td>75</td>
<td>17</td>
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<td>Extension [Days]</td>
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<td>48</td>
<td>288</td>
<td>61</td>
<td>15</td>
<td>Na</td>
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</table>
MAIN FINDINGS:
EP DRAG COMPENSATION 2U

- Thrust for drag compensation is increased by 2 to 4 times.
- The increased size allows for the implementation of bigger propulsion systems.
- The greater thrust produced by the FEEP system allows for a 2U CubeSat to operate at 200 km.
- The same missions can be performed with bigger satellites, giving additional space for instrumentation and propellant.

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<tr>
<td>Thrust [μN]</td>
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<tr>
<td>Power [W]</td>
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<td>Lifetime [Days]</td>
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<tr>
<td>Extension [Days]</td>
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<td>79</td>
<td>23</td>
<td>124</td>
</tr>
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</table>
MAIN FINDINGS:
EP DRAG COMPENSATION 3U

• Greater propellant fraction is required for increased orbital lifetime.
• At about 220 km the thrust requirements are in the mN range.
• More flexible thruster arrangement.
• Drag reduction can be achieved by changing the satellite geometry.
**MAIN FINDINGS:**

**EP DRAG COMPENSATION SUMMARY**

- Reduction in orbital decay is greater at lower altitudes.
- Assuming 150 g of propellant, a 2U CubeSat, equipped with the IFM Nano, can raise its orbit by 1200 km or change inclination by about 4 degrees.
- Thruster lifetime would be of great importance at lower altitudes.
MAIN FINDINGS:
ABEP DRAG COMPENSATION

• More conservative area ratio, due to CubeSat limitations.

• Higher collection efficiency, to compensate for the lower area ratio.

• The thrust produced by the IPT system is a function of several parameters:

\[ T = \dot{m}(h)V_e = \rho(h)V_{rel}(h)A_f \eta_c V_e \]

• Exhaust velocity is a function of the plasma enthalpy:

\[ V_e = \sqrt{2h_{cal}} \]

• Full drag compensation is achieved by the satellite.
MAIN FINDINGS:
ABEP DRAG COMPENSATION

- Full drag compensation at 180 and 250 km.
- Full drag compensation down to 120 km altitude.
- An increase of 42,000% is seen at 180 km of altitude (200h lifetime).
- Trade-off zone between EP and ABEP is seen in the 250 – 200 km range.
TECHNOLOGY EXTENSION
PRESENTS POSSIBLE INTERPLANETARY APPLICATIONS
INTERPLANETARY APPLICATIONS: MARS

- Technology can be applied to Lower Martian Atmosphere.
- Atmospheric density at 100 km similar to that of Earth at 300 km of altitude.
- Increased opportunities for Mars Observation Missions.
- The ABEP technology presented can be applied to the CO2 rich atmosphere.
- Satellites around Mars can provide essential communication for future exploration and colonisation missions.

- Image Credit: NASA
INTERPLANETARY APPLICATIONS:
JOVIAN AND SATURNIAN SYSTEMS

- Increased interest in the Saturnian and Jovian systems.
- EP systems can be used for attitude correction and expensive manoeuvres around the Moons.
- The atmosphere composition of Jupiter and Saturn makes them suitable for ABEP systems.
- Satellites can be dispatched to points of interest.
- Small CubeSats can be grouped in clusters and swarms and provide increased coverage.

- Image Credit: NASA
CONCLUDING REMARKS

• Substantial increase of orbital lifetime by implementing Electric Propulsion (6-700%).
• Greater lifetime increase is observed at Very Low Earth Orbits.
• Increased operational capabilities by allowing orbit raising and inclination change.
• Potential implementation of ABEP systems into small satellites.
• Established trade-off zone between EP and ABEP of about 200 to 250 km.
• Interplanetary application of the technology is possible.
FUTURE WORK

• Implementation of variable thruster modelling.
• Modelling of gas surface interaction and its incorporation in the propagator.
• Use of experimental data from rarefied wind tunnel tests.
• Development of a hyperthermal atomic oxygen wind tunnel to reproduce flow conditions experienced in VLEO.
• Characterisation of gas surface interactions to identify materials which can be used to reduce satellite drag.
REFERENCES


THANK YOU FOR YOUR TIME!

ANY QUESTIONS?