Development of a CubeSat CLIMBing to the Van-Allen belt

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Abstract

Based on its successful CubeSat mission PEGASUS, the University of Applied Sciences Wiener Neustadt (FHWN) is preparing its new CubeSat mission called CLIMB. CLIMB is a 3U CubeSat that will be launched to a low, circular orbit of about 500 km. Using a Field Emission Electric Propulsion (FEEP) system commercialized by the company ENPULSION, the satellite will be lifted to an elliptical orbit with its apogee around 1000 km – well inside the inner Van Allen belt. During its 1.5 yearlong ascent and its operation in the Van Allen belt, the satellite will continuously monitor the space radiation with a RadFET dosimeter payload and the impact on CLIMB's subsystems. Comparisons with radiation testing on ground will allow the assessment of the capability of ground tests to predict effects of space radiation on CubeSat subsystems.

The operation of the propulsion system will raise the satellite's apogee on average 16 times a day. A comprehensive analysis has been conducted to assess its collision probability throughout its mission time. Using various tools, provided by ESA (CROC, MASTER and the DRAMA ARES python package), the collision probability for the entire mission duration (~3 years) was calculated to be 3.38×10^{-5}, i.e. a magnitude smaller than the requested probability of 10^{-4}.

The second payload of CLIMB is an anisotropic magnetoresistance (AMR) magnetometer with a, for CubeSats high, sensitivity of about 10 nT RMS. The first results of measurements with this COTS based magnetometer are presented as well as experimental assessments of the satellite's magnetic cleanliness.

The benign thermal conditions on CubeSats operating close to Earth are complicated by the relatively high-power propulsion system onboard CLIMB. Detailed numerical analysis (ANSYS, ESATAN) and experimental verifications resulted in the identification of possible methods to deal with up to 18 W of dissipated electric power. The main heat sources are the thruster and the battery unit, during thruster operation.

Keywords
Field Emission Electric Propulsion System, FEEP, Van-Allen Belt, Magnetometer, Magnetic cleanliness, DRAMA, Thermal analysis, ENPULSION, magnetic cleanliness, CLIMB

1. Introduction

After the successful PEGASUS mission, the University of Applied Sciences Wiener Neustadt (FHWN) is preparing its new CubeSat called CLIMB. By using a Field Emission Electric Propulsion (FEEP) system by the company ENPULSION, the satellite will be transferred to an elliptical orbit with its apogee in the inner Van Allen belt. During its about 1.5 yearlong ascent and its operation in the Van Allen belt, the satellite will continuously monitor the space radiation and its impact on CLIMB's subsystems.

2. Orbital planning and assessment

CLIMB will be launched into a circular orbit of 500 km altitude and is planned to raise its apogee up to 1000 km using the IFM thruster from the company ENPULSION. Due to the power budget of CLIMB and the properties of the IFM, a quasi-spiral orbit is not possible, and the thruster will be operated at almost every perigee. The apogee raising orbit also ensures a lower perigee for the final orbit, which results in an orbit lifetime below 25 years and ensures a proper deorbiting at EOL.

2.1. *Orbit raising*

CLIMB's orbit will be raised by several minutes of thruster operation almost every time CLIMB crosses the perigee. Comprehensive numerical simulations of the orbit manoeuvres have been conducted with the firing time, drag area variations, thrust variations, thrust misalignments and many other parameters as input variables. The values obtained for the total raising time varies from 350 days for 10 minutes firing duration up to 504 days for 8 minutes firing duration (Figure 1). The requirement of continuous realignment provides a real-life scenario; however, the NEPTUNE propagator does not provide the possibility to align the satellite in the direction of the Sun. For the assessment the extreme cases are considered, i.e. maximum and minimum possible cross-section as drag area. This results in a change of 9 days from minimum drag to the maximum drag area, which is small, compared to overall orbit raising time. Similarly, during the de-saturation of the reaction wheels with magneto-torquers the satellite needs to be aligned in a specific orientation depending on the magnetic field, which also will have an insignificant impact on satellite raising time. Assuming that one day in a week is required for desaturation, 52 days will be added in the overall raising time. The raising time rather depends on perturbations than on the satellite attitude. For example, a solar maximum will change the atmospheric density around the satellite and the drag value even though the drag area remains unchanged.

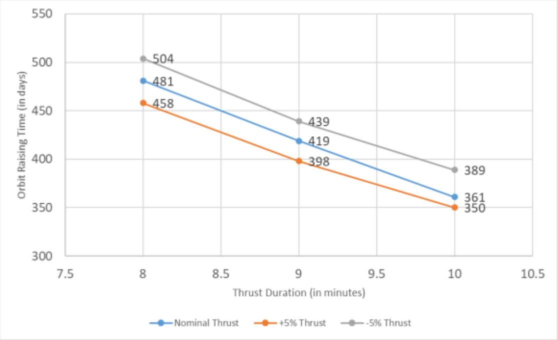

Figure 1: Orbit raising time for different thruster firing durations.

2.2. *Annual collision probability levels*

ESA's MASTER tool was used for the population estimation. It considers a condensed population of all man-made objects and the meteoroids with predicted orbits until 2027. The results show that the population density increases with increasing inclination with a maximum between the altitudes of 700 km and 900 km. This is also verified from the UCS satellite database. The population data served as input for an initial assessment of conjunctions and collisions with ESA's DRAMA ARES Python package. The orbits are raised in segments of 10 days and for each segment the collision probabilities are calculated. The values are then averaged over the whole mission duration to obtain the collision probability and the number of required avoidance manoeuvres. The overall collision probability results in 3.38 x 10^{-5}. This involves a requirement of 0.2 avoidance manoeuvres to achieve the probability of 10^{-4} and two manoeuvres to achieve the probability level of 10^{-6} (Figure 2). According to industrial standards, 10^{-4} is considered as safe. Hence, these initial values demonstrate that the CLIMB mission will not require any collision avoidance manoeuvre during its complete mission lifetime. However, these values do not consider the screening volume as suggested by 18SPCS, which is considered below.

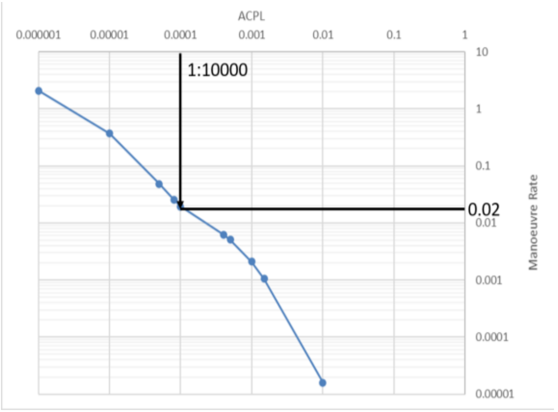

Figure 2: Number of manoeuvres required based on annual collision probability level.

2.3. Conjunction assessment

The conjunction assessment considers a firing duration of 8 minutes and an inclination of 70 degrees. The initial data are evaluated for a screening volume of 50 km × 50 km × 50 km, which is subsequently filtered down to the screening volumes suggested by the 18 SPCS. For filtering the data, two screening volumes are considered, first ‘Basic’, which is generally used for a non-manoeuvrable satellite with a size of 1 km × 1 km × 1 km, and an ‘Advanced’ screening volume for manoeuvrable satellites, with a size of 2 km × 44 km × 51 km. The identification of the worst-case conjunction events is based on the overall miss-distance and subsequently on each orthogonal component to determine the validity of the conjunction event. The data confirms that there are no single event conjunctions, which need to be avoided, as predicted in the initial results by DRAMA. However, there are many conjunctions events depending on the chosen screening volume, which requires a careful planning of thrust operation in order to avoid the occurrence of conjunction events.

3. Thermal experiments and simulations

The thermal validation of CLIMB is essential to ensure a proper operation of all subcomponents of the satellite throughout the mission and up to the EOL. As CLIMB will undergo large temperature changes as well as temperature cycling, the thermal design of the CubeSat must balance the distribution and radiation of excess heat, while keeping the satellite in a proper temperature range.

3.1. Critical components

The most thermally critical components of CLIMB are the thruster, the batteries, and, to a lesser extent, the electronic circuit boards. The estimated (conservative) heat dissipation of the thruster implemented in CLIMB is around 4 W in cruise mode and 13.5 W in propulsion mode. The set of eight batteries is estimated to dissipate 2.36 W of heat in cruise mode and 6.32 W in propulsion mode, due to discharging.

Figure 3: Thermal vacuum testing of CLIMB’s thermal model with ENPULSION’s NANO thruster.

3.2. Validation of thermal model

CLIMB’s experimental thermal model was constructed to simulate the heat generation characteristics of the real components of the CubeSat. To validate the accuracy of the thruster’s thermal model, TVC tests were done with the model as well as on the thruster (Figure 3), and the temperatures measured on various positions were compared.

3.3. Experimental results

Table 1 summarises the temperatures measured on exemplary components in both the IFM thruster test and the thermal model test. Though the temperature deviation between both models is acceptable at 20℃, it increases significantly as the environment temperature decreases. The largest difference between temperatures of corresponding components was 13℃, measured at the interface located at the base of the thruster and with an environment temperature of -20℃.

	Temperature (°C)					
Subsystem	**Cruise mode @20°C**			**Cruise mode @-20°C**		
	IFM Test	Thermal Test	Temperature Difference	IFM Test	Thermal Test	Temperature Difference
Environment	22.4	22.15	0.25	-17.3	-18.14	0.84
Y- Side Panel	44	39.74	4.26	19.1	10.05	9.05
X- Side Panel	43.6	37.89	5.71	18.9	8.23	10.67
Y+ Thruster Interface	47	41.84	5.16	22.5	12.87	9.63
X- Thruster Interface	43.9	45.49	-1.59	30.6	16.68	13.92
Copper Plate	46.6	46.67	-0.07	21.1	17.68	3.42
Converter PCB	60.6	58.69	1.91	37.5	33.16	4.34

Table 1: Comparison of CLIMB thermal test and IFM test component temperatures in cruise mode.

Alongside the validation of the thermal model, TVC tests were used to assess the thermal performance of the CLIMB model. This shows that at an environment temperature of -20℃, component temperatures remain within an acceptable operable range of 8℃ at the X- side panel up to 33℃ at the converter PCB. However, higher environment temperatures require attention – the batteries and battery converter models experienced significantly elevated temperatures at an environment temperature of 20℃, reaching up to 60℃ under cruise conditions and up to 100℃ in thrust mode (Figure 4). These temperatures well exceed the operable limit of the batteries, highlighting the need for further optimization of CLIMB's thermal design or of the thermal model validation.

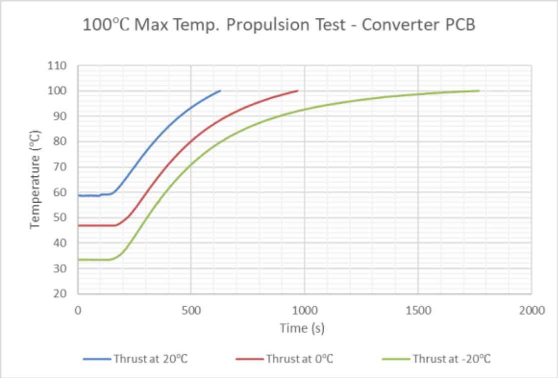

Figure 4: Power converter PCB temperature in thrust mode, up to 100℃.

3.4. Numerical simulation

To support the experimental efforts, a numerical model of the experimental thermal model was established in ANSYS. The simulation results were validated with the experimental results and showed a deviation of only < ±5 °C. The ANSYS model was exploited to simulate a larger variety of temperature ranges, as well as to assess the impact of different material properties with the objective of identifying potential design improvements. Based on the ANSYS thermal model, a further model was established in ESATAN. ESATAN offers the opportunity to implement orbital parameters and therefore perform dynamic tests with unknown temperature cycles which is a more detailed simulation of inflight conditions - something which is not possible with ANSYS. The input parameters were correlated to those of the ANSYS model and the results similar to the ANSYS model and therefore also to the experimental result. Overall, this further validates the thermal results.

4. Magnetic cleanliness

As CubeSats continue to become more versatile, the number of use cases and (professional) missions increase steadily. Measurements of magnetic fields in space are one example, as the NASA ARCS mission impressively demonstrates [1]. For such applications not only the magnetometers need to be improved, but also the satellite platform and its magnetic cleanliness. Therefore, a numerical assessment as well as experiments were conducted to better understand the magnetic properties of the satellite and its impact on the measurements.

4.1. Simulation of the magnetic flux

The theory behind the simulation is based on current loops, which are conducting rings with a certain area and an electrical current. The Biot-Savart law serves to calculate the magnetic induction (Eq. 1). It results in the magnetic induction corresponding to the elemental ring segment $d\vec{L}$ and current I and the magnetic moment $\vec{\mu}$ measured in Am², using Eq. 2. In that equation, A is the area of the current ring, and $\hat{n}$ is a unitary vector normal to the ring. [2]

$$d\vec{B} = \frac{\mu_0 I}{4\pi}\frac{d\vec{L}\times\vec{r}}{r^3} \tag{1}$$

$$\vec{\mu} = IA\hat{n} \tag{2}$$

The simulations are based on the MATLAB function from Levron [3], which itself is based on the numerical technique from Haus [4]. The provided function computes the magnetic field B by a given geometry, represented as point coordinates. Each space between two consecutive points is treated as a straight conductor, also called current stick [3].

4.2. Modelling the satellite

The use of current loops to model the whole satellite turned out to be the wrong way. If the loops of the PSU are considered, all loops are closed at the battery unit and therefore several current loops overlap at the same location. This would result in an overestimated magnetic field strength. Secondly, the batteries are connected in parallel, which excludes one closed loop as the current path splits. For those reasons, another approach was chosen, which assumes current sticks only and the loops are not mandatory to be closed. The modelling process uses any PCB design tool, compatible with "DXF"-files. Those are opened in CATIA to manipulate them and end up with a point cloud representing all current sticks. This is exported to MATLAB for the magnetic field calculations using VBA scripts.

4.3. Simulation results

The simulation in MATLAB has been done with a resolution of 5 mm and an additional surrounding field extending 0.5 m in each direction, to especially evaluate the magnetometer position on the boom. Figure 5 shows the magnetic field of current paths on the PCBs on an x-y-plane in the centre of the satellite, at about 15 cm height. The red rectangle marks the satellite’s shape. The solar panels generate an increased magnetic field in their vicinity.

Further refinements of the model and the computation will be done by considering soft and hard magnet materials and will be followed by a comparison with measurements.

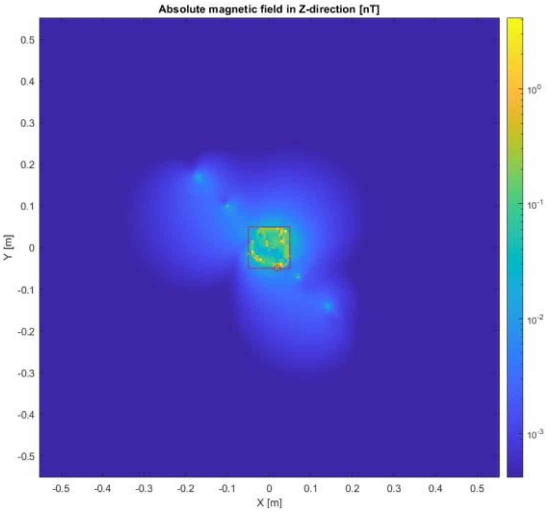

Figure 5: MATLAB plot of the CLIMB simulation showing the absolute magnetic field values in the satellite’s centred x-y-plane.

5. Magnetometer Instrument

The Magnetometer Instrument of CLIMB will be used for scientific measurements of the magnetic field in the Van Allen Belt. The subsystem will be divided into an internal instrument control unit and a boom. The height of the boom and deploying mechanism is required to be lower than 5 mm as it will be mounted on the outer surface of the side panels. The boom shall not introduce low eigenfrequencies during launch and therefore the length has to be fine-tuned with regard to its width and thickness and material properties during the last stage of development.

5.1. Engineering model of the Magnetoboom

An Atmega128 is used for reading out the data of the sensors and forwarding it to the On-Board- Computer (OBC). The main magnetic field sensors used on the boom are Honeywell HMC1022 and HMC1021Z to provide measurements with an accuracy of ±10 nT (RMS) and a dynamic range of ±500 µT. The secondary sensors are Memsic MMC5983MA with a lower resolution. They are equally distributed on the boom for a differential field measurement that will serve as housekeeping data corrective values for the HMC measurement. The Serial Peripheral Interface (SPI) of the instrument controller is used to communicate with all connected sensors. Honeywell sensors give a differential output that is translated by the LTC 2440 ΔΣ 24-BitAnalog to Digital Converter (ADC). After acquiring the magnetic field data, it will be transferred to the OBC via Two Wire Interface (TWI). The PCB tracks on the boom are designed to twist themselves through the copper layers as Dong Gun Kam, et. al. [5][6] recommend to reduce cross talking between sensor tracks and magnetic interference by power supply tracks.

5.2. Testing procedures

The simulation of the expected magnetic field of Earth with the Systems Tool Kit (STK) from AGI results in an estimated field strength of about. ±50 µT. These fields are applied via a custom made Helmholtz cage. Additionally, in cooperation with IABG, external fields were applied in the company's magnetic field simulation facility. The components survivability and thermal drifts of the magnetic field sensors will be evaluated in a thermal vacuum chamber.

5.3. Testing results

The axial applied fields during tests at IABG were at ±30, ±50 and ±60 µT. The results of the secondary sensors show that apart from a zero-point calibration, all fields were sensed correctly (figure 6). The subsystem software needs to be adapted to convert the output into CLIMB's coordinate system.

The preliminary results of the main sensors showed a higher noise level than expected and thus need to be optimised via additional passive components on the engineering model. It was shown that the subsystem circuit itself is functional and can be forwarded to thermal vacuum tests.

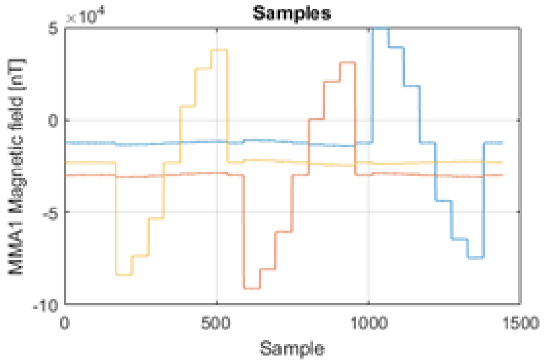

Figure 6: Test result of secondary sensors at magnetic field simulation facility.

6. Summary and Conclusion

The results of this paper show that CLIMB is able to withstand the extreme thermal environmental conditions during its trip to the Van-Allen belt. All simulated and measured temperatures are within the acceptable range. Simulations of the orbit raising time have shown that CLIMB is able to lift the apogee to the desired altitude within 1 to 1.5 years, with the necessary time mainly depending on the thrusting duration during each orbit. Most importantly, it was shown that the threat of collisions is negligible and, although possible, no collision avoidance manoeuvre is required throughout the mission time. A new magnetic boom is designed for the CLIMB mission, allowing very accurate magnetic field measurements. Simulations of the magnetic field generated by the satellite itself, have shown a negligible impact on the magnetic field measurements. Those simulation results were recently compared to measurements taken in the large magnetic field facility of IABG.

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