Moon Mission Lifetime Analysis of a 2U CubeSat Equipped with Pulsed Plasma Thrusters; The Aoba-VELOX IV Mission Case

By Jose Rodrigo CORDOVA ALARCON,[1)] Necmi Cihan ÖRGER,[1)] Sangkyun KIM,[1)] Tran Quang VINH,[2)] Lim Wee SENG,[2)] Bui Tran DUY VU,[2)] and Mengu CHO[1)]

[1)]*Laboratory of Spacecraft Environment Interaction Engineering, Kyushu Institute of Technology, Japan*
[2)]*Nanyang Technology Institute, Singapore*

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Recent advances in low-power propulsion systems potentiate CubeSats orbit control capabilities for the extension of their mission lifetime and increase of orbit maneuver range, in order to reach an optimal operational orbit. In this paper, we focus on the analysis of mission lifetime extension capacity of a two-unit CubeSat whose propulsion system is based on pulsed plasma thrusters (PPT). Our analysis is based on the features of Aoba VELOX-IV (AV4), which is a two-unit CubeSat developed by Nanyang Technological University and Kyushu Institute of Technology. AV4 will serve as a platform for technology validation towards a future lunar mission for the observation of lunar horizon glow. Because we needed to derive the success criteria of the PPT future lunar mission with 60m/s as ΔV budget, we analyzed the mission lifetime and orbit maintenance capabilities through numerical simulations, which takes into account the LP165p Moon gravitational field model. Our analysis shows that the deployment of the satellite into different orbits within frozen orbits will not be suitable for a one-year term mission; however, initial orbits whose mission lifetime is below 1 year can be extended with the proposed orbit maintenance strategy.

Key Words: Aoba VELOX IV, Pulsed Plasma Thrusters, Orbit control, Mission lifetime, Lunar orbit

Nomenclature

$\boldsymbol{r}$	:	position vector
μ	:	standard gravitational parameter
∇U	:	partial derivative of the spherical harmonic gravity potential
$\boldsymbol{F}$	:	orbit disturbance force vector
α	:	in-plane thrust angle
e	:	eccentricity
υ	:	true anomaly
E	:	eccentric anomaly
ω	:	argument of periapsis
Ω	:	right ascension of ascending node
op	:	orbital parameter
W_{op}	:	weighting factor for each controlled orbital parameter

Subscripts

E	:	Earth
M	:	Moon
S	:	Sun
sc	:	spacecraft
J_2	:	second degree zonal harmonic coefficient
sp	:	solar radiation pressure
i	:	inertial reference frame

1. Introduction

With the growing interest in interplanetary missions and the concurrent technology development in hardened and miniaturized components which survive the outer space environment, CubeSats platforms have found an opportunity to cover a wide range of science and technology demonstration missions, including those who serves as compliment of measurements from the primary mission [1]. Even though CubeSats are limited by their attitude and orbit control capabilities, as well as their mission lifetime, orbit correction capability via Pulsed Plasma Thrusters (PPT) have shown to be suitable due to their high scalability, power input and performance at relatively low cost [2].

In recent years, several lunar missions have been proposed, followed by the augmented interest on the investigation of lunar environment and surface composition. CubeSats missions such as Lunar Flashlight, Lunar IceCube, LunaH-Map, SkyFire and OMOTENASHI are being developed to conduct exploration missions by analyzing the lunar surface and radiation environment [3]. In this regard, Aoba VELOX-4 (AV4) is being developed by Kyushu Institute of Technology and Nanyang Technology University (NTU), which will serve as technology demonstration platform for the development of a future lunar mission, whose main mission objective is envisaged to carried out investigation of the Lunar Horizon Glow (LHG) and provide evidence of the observations of Apollo missions.

Unexpected excess brightness appeared in several photographic sequences from Apollo missions, which was unrelated to the inner coronal and zodiacal light (CZL), but instead was associated with the lunar horizon. Glenar, D. A. analyzed the photographic sequences taken by Apollo mission and produced a quantitative picture of the exospheric dust distribution at the location and time of the Apollo 15 orbital sunset measurements, and conclude that there does not appear to be a correlation between the detection or non-detection of horizon glow and any particular solar UV or solar plasma condition [4]. In the other hand, Apollo 17 astronauts observed and sketched the CLZ and a LHG at 110 km altitude while approaching the orbital sunrise [5], but since Apollo era, LHG has not been observed. It is assumed that meteoroid impact plumes may play an important role in the generation of vast population of lunar dust, enough to produce a LHG [6]. Therefore, LHG may be a high varying phenomenon whose physical mechanism is still investigated.

For a long-term lunar mission and hence, the increase of possible LHG observations, orbital analysis should be performed by considering the irregular gravity field of the Moon. Nowadays, better spherical harmonic resolutions of lunar gravity potential model are available after the measurements obtained by Clementine, Lunar Prospector Discovery, SELENE and GRAIL missions [7]. The lunar mission lifetime is related with the initial orbital ephemeris of the satellite, particularly the initial inclination, right ascension of the ascending node, argument of periapsis and altitude, where zonal and tesseral harmonics of Earth gravity field plays an important role because of its proximity with the Moon [8]. Frozen orbits can be considered as optimal orbits for a long-term lunar mission [9]; however, being a piggy-back from a main mission may restrict the placement of AV4 in such kind of orbits, so orbit maintenance maneuvers become essential for the increase of the mission lifetime.

To demonstrate the feasibility of the use of a CubeSat platform in a future lunar mission, the following AV4 mission success criteria should be accomplished in Earth orbit:

- Momentum dumping of 0.0001Nms angular momentum around short axis via PPT within 1 hour.
- Orbit maneuvering via PPT with ΔV =60m/s within 1 year.
- Capturing several images of the horizon as sequence while passing day side to night side.
- Capturing Earth night view image via low-light camera.

In this work, we performed the mission lifetime analysis by carrying out numerical simulations, considering the 60 m/s ΔV budgeted constrain and the motion of the spacecraft subjected to orbital disturbance due to the irregular gravity field of the Moon, the oblateness of the Earth, the gravity of the Sun and the solar radiation pressure. The candidate orbits to perform this mission is constrained to 100km altitude circular orbit and 20° to 70° as orbit inclination range. We show the scenarios were one year term lunar mission could be achieved with and without orbit maintenance maneuvers and how the frozen orbit region is extended with the budgeted ΔV.

Regarding orbit maintenance maneuvers strategy, optimal in-plane maneuvers are considered to be executed to extend the mission lifetime of the satellite. Because of the power consumption features of AV4 PPTs, we considered that these maneuvers should be performed in dayside to avoid critical discharge of the batteries.

The content of this work is organized as follows: Section 2 is dedicated to the AV4 mission objectives description and overview of the satellite bus; Section 3 refers to our mission lifetime analysis method; Section 4 shows the optimal in-plane orbit maneuver that was implementer for orbit maintenance maneuvers; Section 5 shows our simulation results and the closure of this work is done by our conclusion remarks.

2. Aoba VELOX 4 mission overview

AV4 project consists on the technology demonstration of AOCS capabilities based on 3-axis reaction wheels and pulsed plasma thrusters (PPT) developed by NTU, for orbit maintenance capabilities and attitude control maneuvers, as well as the usage of a COTS monochrome low-light camera for the observation of the LHG (Figure 1). AV4 is the second joint satellite program between Kyutech and NTU, which will be launched for an Epsilon rocket as a piggy-back by the Japanese space agency JAXA in 2018.

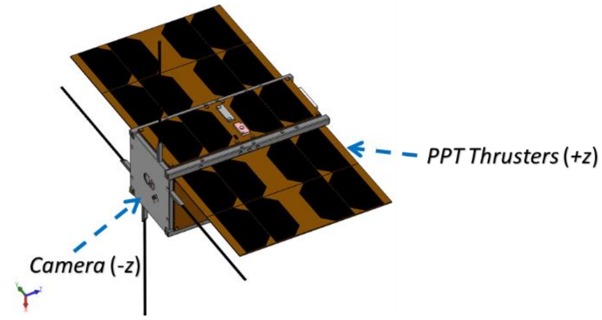

Fig. 1. Aoba VELOX-4 satellite 3D view.

AV4 mission will be supported by a ground station network (GND) placed in NTU Singapore, Kyutech and National Cheng Kung University (NCKU) Taiwan and Mongolia. GND will be synchronized via GPS clock and satellite positioning experiment will be performed. Orbital ephemeris will be sent to AV4 satellite to carry out orbit propagation and hence, the calculation of the reference frames used for orbit maintenance and attitude control calculations. The on-board computer possesses a TMS320F28075 micro-controller, wherein AOCS schemes, horizon detection algorithm and AV4 functional routines are embedded. AV4 is equipped with a PPT unit with four heads, its own processor unit and Teflon propellant per head, which provides an impulse bit of 1025s and 60 m/s ΔV budget average.

3. Moon orbit lifetime analysis

For our analysis, we developed a numerical simulation where we implemented the restricted three body problem with orbital disturbances (Figure 2) [10]:

$$\boldsymbol{r} = \nabla \boldsymbol{U}_{M,sc} + \mu_E \left(\frac{\boldsymbol{r}_{E,M}}{r^3_{E,M}} - \frac{\boldsymbol{r}_{E,sc}}{r^3_{E,sc}} \right) + \\ + \mu_S \left(\frac{\boldsymbol{r}_{S,M}}{r^3_{S,M}} - \frac{\boldsymbol{r}_{S,sc}}{r^3_{S,sc}} \right) + \boldsymbol{F}_{E,J_2} + \boldsymbol{F}_{sp} \qquad (1)$$

The LP165p lunar gravity model at 100 degree has been implemented from MATLAB aerospace toolkit. The Moon's gravity potential is determined by the position of the satellite in Moon-Centered-Moon-Fixed coordinate system, whose transformation matrix to Inertial Celestial Reference Frame (ICRF) is given in IAU/IAG 2000 Report [11]. Sun and Moon position algorithms were implemented by numerical methods based on series expansion [10,12]. The orbital disturbance due to the Earth J2 term is calculated based on the satellite position in Earth-centered inertial reference, derived from the gradient of the simplified Earth gravity potential [13]. To determine the sunrise and sunset in Moon, we model the geometry of the umbra as a simple cylindrical shape.

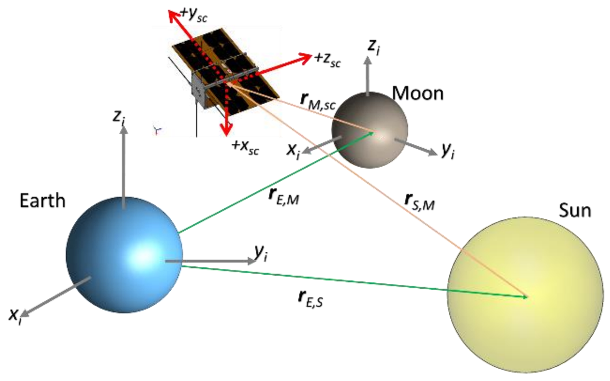

Fig. 2. Representation of the restricted three body problem.

Figure 3 shows the case of the lunar orbit lifetime considering several initial inclinations we targeted for the future lunar mission in a 100km altitude circular orbit. These results were obtained by considering the initial conditions showed in table 1.

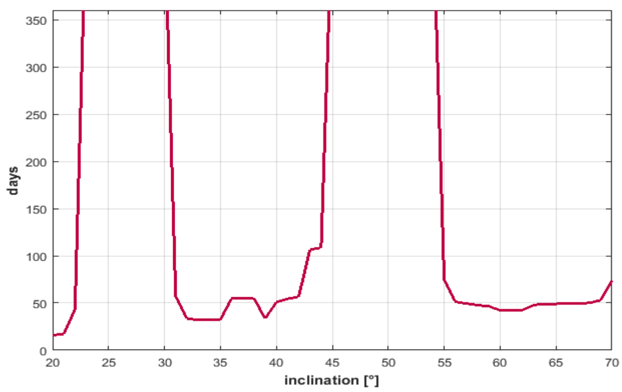

Fig. 3. Lunar mission lifetime profile in 100km altitude circular orbit.

Table 1. Initial conditions used for this study case.

Parameter	Value
Moon reference radius	1738km
eccentricity	0
Argument of periapsis	0°
Right ascension of ascending node	0°
Epoch	2016-03-30 12:00:00
LP165p degree	100
Satellite mass	2.4kg

The end of the lunar mission is established when the satellite reaches an altitude of 0km. From figure 3, it can be noticed the stable regions where the lunar mission lifetime can reach up to one year (from 25° to 30° and 45° to 54° inclination orbit). An example of a long-term lunar orbit mission is shown in figure 4, where initial inclination is 46°. The eccentricity varies below 0.04 and therefore, altitude does not reach the Moon surface. In the other hand, figure 5 shows an example of an unstable orbit where initial inclination is 44°. After several days, the eccentricity increases in such a way that satellite periapsis approaches to the Moon reference radius and chances of collision with the Moon surface increases. For this reason, orbit maintenance maneuvers capabilities become important to increase the satellite mission lifetime and the expectancy of its mission objectives achievement.

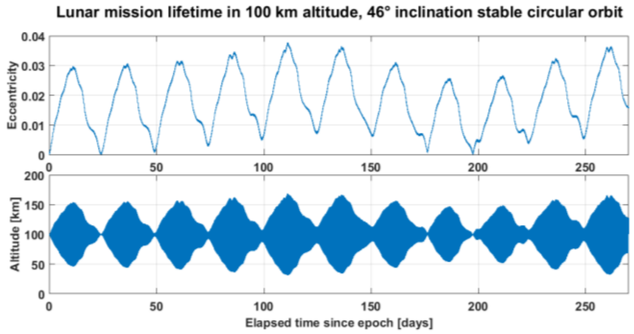

Fig. 4. Evolution of the eccentricity and lunar altitude within a stable orbit.

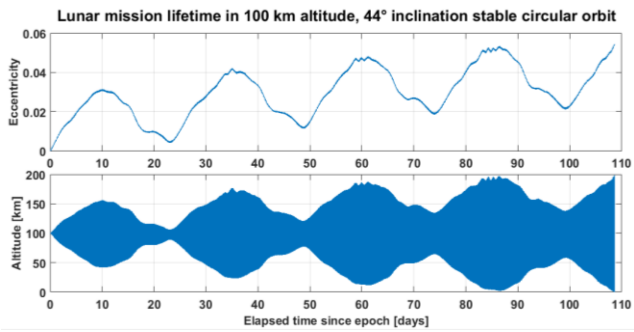

Fig. 5. Evolution of the eccentricity and lunar altitude within an unstable orbit.

4. Orbital in-plane maneuvers strategy

We consider optimal in-plane orbit maneuvers [14] to mitigate the effect on the eccentricity and periapsis due to the irregularity of the Moon's gravity field and keep the altitude of the satellite below 110km to observe the LHG. The thrust angle calculation is shown in table 2, according to the left-handed rule reference frame shown in Figure 6.

Table 2. Thrust angle calculations.

Orbital parameter	In-plane thrusting angle
Semi-major axis	$\alpha = \tan^{-1}\left(\frac{e \sin \upsilon}{1 + e \cos \upsilon}\right)$
Eccentricity	$\alpha = \tan^{-1}\left(\frac{\sin \upsilon}{\cos \upsilon + \cos E}\right)$

The force direction in inertial reference frame is calculated according with the equation (2) for each orbital ephemeris correction, applying an adaptive ratio R_f which serves as priority weighting factor. An additional weight W was used to provide additional weighting factor based on successive iterations that we conducted through our simulation scheme as described in equation (1).

$$\boldsymbol{F}_{PPT,i} = \boldsymbol{R}_z(\Omega)\boldsymbol{R}_x(i)\boldsymbol{R}_z(\omega) \sum\nolimits_{op} \boldsymbol{W}_{op}\boldsymbol{R}_f \boldsymbol{F}_{op} \quad (2)$$

$$F_{op} = \begin{bmatrix} \cos(\pi/2 - \alpha) \\ \sin(\pi/2 - \alpha) \\ 0 \end{bmatrix}, R_f = \frac{op_r - op}{op_r - op_o}$$

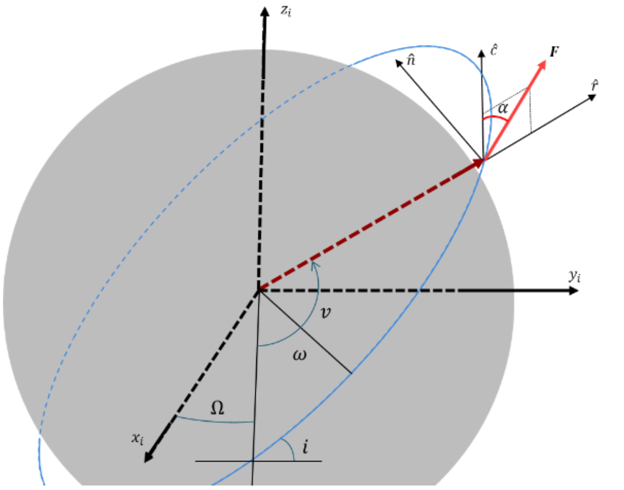

Fig. 6. Geometry of the reference frame used to compute the thrust direction ***F***.

5. Mission lifetime extension by using PPTs

To show the expected orbit maintenance capability of AV4 AOCS towards a future lunar mission, we performed numerical simulations based on the hardware specifications of AV4 PPTs mentioned in section 2 and the proposed orbit maintenance strategy in section 4. The initial conditions for each simulation is shown in table 2. Once reaching the threshold levels for each orbital ephemeris shown in table 3, the satellite orbital maneuver is deactivated for each controlled orbital parameter. Once reaching 60m/s ΔV, the control orbit strategy is disabled and the simulation runs are stopped when satellite reaches 0km altitude or achieving 1 year orbit lifetime.

Table 3. Selection of *W* values

Weight	value
Wa	0.5 if $(a-a_{ref}) > 50$km, 0 if $(a-a_{ref}) < 5$km
We	1 if $(e-e_{ref}) > 0.015$, 0 if $(e-e_{ref}) < 0.01$

Figure 7 shows the results of our simulations considering orbit maintenance maneuvers. The yellow area represents the extension of the mission lifetime and the blue area is related with the nominal lunar mission lifetime. These results show that:

- An increase of mission lifetime was successfully achieved in initial inclinations above 55°, from 50 days as average to up to 75 days.
- The stable lunar orbit range was increased from 23° - 30° to 21° to 30°, and from 45° - 54° to 43° - 54°.
- From 30° - 42° inclination range, apparently orbit maintenance strategy would not be effective due to the high orbit disturbance caused by the irregular Moon gravity field.
- An apparent reduction of mission lifetime resulted by applying the same orbit maintenance strategy in the range of 39° - 42°.

5.1 Discussion

Figure 8 shows the particular case of the 43° initial inclination, where the mission lifetime was extended resulting in a long-term lunar mission. The ΔV produced by the PPT unit was enough to achieve this goal; however, satellite reaches altitudes above 200km in certain periods of time, differing occasionally with the conditions of LHG observations from Apollo missions. Figure 9 shows similar results, where satellite can extend its mission lifetime in a 65° initial inclination from 49 days to 103 days and satellite reaches a high eccentricity orbit. In both cases, PPT unit was being utilized during the satellite mission. Nonetheless, satellite may carry out diverse tasks that imply attitude maneuvering for the observation of the LHG or any other required task.

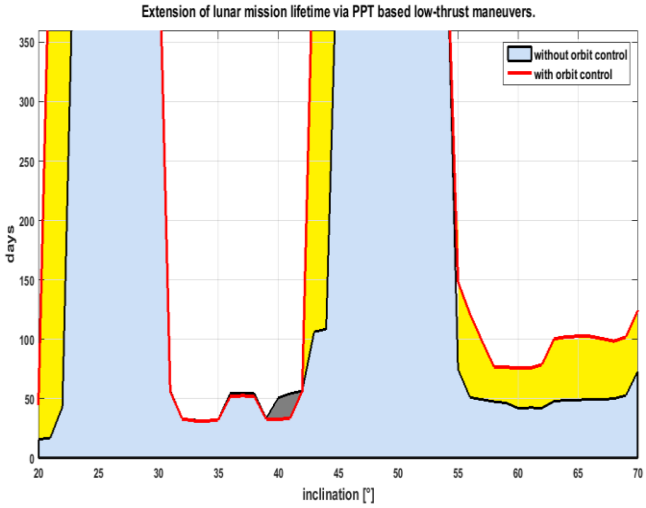

Fig. 7. Simulation results considering a range of initial inclinations for a lunar orbit mission and the extension of the mission lifetime.

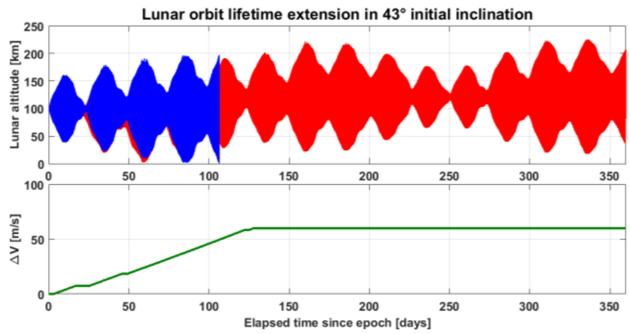

Fig. 8. Mission lifetime extension profile by considering a 43° initial inclination.

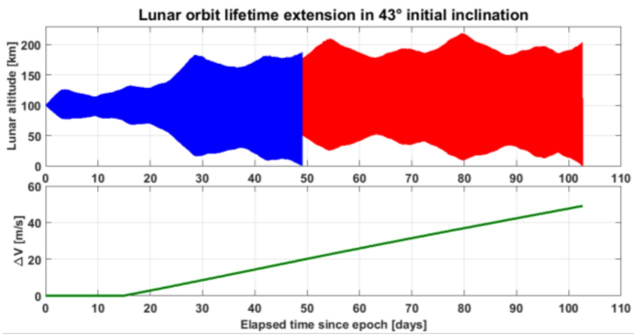

Fig. 9. Mission lifetime extension profile by considering a 65° initial inclination.

Figure 10 shows the lunar altitude of the satellite and ΔV usage considering 40° inclination as initial condition, where the mission lifetime decreased. By comparing the natural orbit lifetime of the satellite (red line) and the resulting lifetime after executing the control maneuvers (blue line), the orbit control strategy was successfully performed during 20 days after epoch, observing an oscillation reduction of the lunar altitude. However, the resulting altitude in the 20th day after epoch is slightly lower than the unactuated one and consequently, the orbital disturbances caused a faster decrement of lunar altitude. To overcome this issue, the target semimajor-axis can be increased to mitigate this effect.

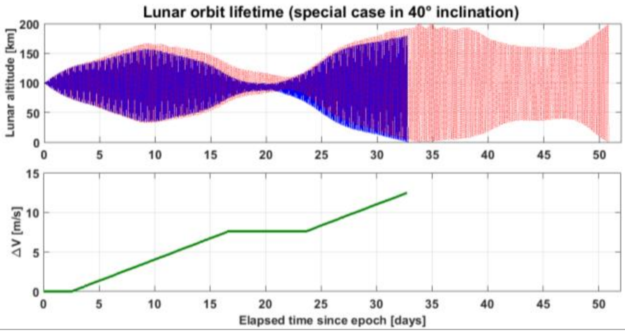

Fig. 10. Special case when lifetime reduction resulted by implementing the proposed orbit control strategy.

6. Conclusion

In this work, we presented the orbit maintenance capability of AV4 PPT unit for its use in a future lunar mission through numerical simulations, aiming to the observation of the LHG. Because of the irregular gravity field of the Moon, numerical simulations were performed to determine the adequate orbit regions where a long-term lunar mission can be achieved. Considering that 100km circular stable orbit regions are constrained to few initial inclination orbits, AV4 PPT unit is envisaged to be utilized in a future lunar mission to overcome this limitation. We analyzed the possibility to extend the stable lunar orbit region, as well as extend the mission lifetime in other orbits whose initial inclination is results in a short-term mission. By performing orbit correction maneuvers with the current features of the PPT unit and implementing an optimal in-plane orbital maneuvers during the sun phase, our simulations shows that the mission lifetime extension can be achieved successfully in the 55° - 70° initial inclination region by additional 25 days as minimum. Moreover, our simulations show that the stable orbit region where extended by +2° inclination angle. Even when we show the possibility to extend the mission lifetime by using our PPT unit, the final lunar orbit achieves a high eccentricity value after the execution of orbit maintenance maneuvers. Nonetheless, the opportunities to observe the LHG can be increased. In this regard, further research is being carried out in our institution to analyze the optimal conditions for the detection of the LHG, its physical mechanisms that cause them and its correlation with the satellite location while it is orbiting the Moon.

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