Trajectory design results for 6U CubeSat EQUULEUS

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Abstract: EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) is a 6U CubeSat which is being developed by the University of Tokyo and the Japan Aerospace Exploration Agency (JAXA). EQUULEUS will be launched at the end of 2021 by NASA's Space Launch System rocket as a piggyback and transfer to an Earth-Moon L2 (EML2) quasi-Halo orbit via invariant manifolds and lunar flybys. We present EQUULEUS trajectory design method and its latest trajectory design results which are based on Nov. 2021 launch conditions.

超小型深宇宙探査機 EQUULEUS の軌道設計手法とその結果

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概要：EQUULEUS は東京大学と JAXA が中心となり開発している 6U サイズの CubeSat であり，2021 年度末に NASA の新型ロケット SLS の試験機 EM-1 の相乗り衛星として打ち上げられる予定である．地球-月のラグランジュ点への航行を通じ，超小型深宇宙探査機としては世界初となる太陽-地球-月圏での軌道操作技術を実証するとともに，地球磁気圏プラズマや月面に衝突する小隕石フラックスなどを観測することを目的としている．EQUULEUS のような超小型深宇宙探査機はリソースが制限され，電力，熱，通信，推力，燃料など多くの制約が生じる．シンポジウムでは，2021 年 11 月打ち上げの軌道条件を用いた EQUULEUS の軌道設計および解析結果について報告する．

I. Introduction

EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) is a 6U CubeSat which is being developed by the University of Tokyo and the Japan Aerospace Exploration Agency (JAXA).[1)] The spacecraft will be one of the 13 secondary payloads onboard NASA's Space Launch System rocket and transfer to an Earth-Moon L2 (EML2) quasi-Halo orbit via invariant manifolds and lunar flybys. There are three mission objectives for EQUULEUS: 1) demonstrate the orbital maneuvering capabilities of a nano-satellite in the cis-lunar environment, 2) observe the magnetosphere plasma, and 3) grasp the size and spatial distribution of solid objects in the cis-lunar region.[2)]

Compared to past missions to the Moon, EQUULEUS has two mission constraints that increase the complexity and challenges of its trajectory design. First are the CubeSats limited propulsion capabilities[3)], which force the trajectory design team to rely on lunisolar perturbations that are highly dependent on the spacecraft's initial conditions. Second are the actual launch conditions, which are provided by NASA and subject to last minute changes due to technical and/or political reasons.

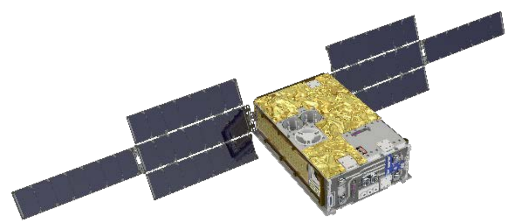


Figure 1: EQUULEUS

This paper presents 1) the trajectory design method for EQUULEUS, 2) Launch conditions, and 3) current trajectory design results.

II. Spacecraft specification and Trajectory design approach

A. Spacecraft specification

The specifications of the spacecraft are listed in Table 1. The propulsion performance is based on the ground test results. EQUULEUS's trajectory control consists of Delta-V Thruster (DVT) operation and unloading by RCT. Then, the actual / average thrust magnitude is lower than the thrust performance of DVT.

Table 1: EQUULEUS specifications

Mechanical& Structure	• 6U, with two wings of 4 SAPs(with gimbaling) • 10.5 kg (wet)
Propulsion	• Water Resistojet thrusters 1.73mN/63.6s x4 (RCT), 4.94mN/73.1s x2 (DVT)
Electrical Power System	• 50W@1AU, BOL,70degC • Li-ion, 31 Wh
Telecom	• X-band MGA x 1 • X-band LGA x 5 • Chip Scale Atomic Clock x 1
Attitude Control System	• Reaction Wheel x 3 • 3-axis MEMS Gyro • Sun Aspect Sensor x 4 • Star Tracker x 1

Table 2: Constraints for Eclipse

a) Power constraint

Eclipse fraction	Acceptable Time [hour]
100%	1.0
90%	1.5
80%	2.8
70%	8.9
60%	No limitation

b) Thermal constraint

Eclipse fraction	Acceptable Time [hour]
100%	1.0
80%	3.0
60%	6.0
40%	No limitation

B. Eclipse constraint

EQUULEUS trajectory is confronted with the eclipses from the Earth and the Moon. Table 2 shows the eclipse constraint for the power and thermal point of view. The optimized trajectories are checked using values in Table 2. If we cannot distinguish the constraint violation since the eclipse time is close to the borderline, we need to discuss with power and thermal subsystems.

C. Trajectory design approach

EQUULEUS's trajectory is designed by patching the forward trajectory from the launch and the backward trajectory from the EML2. Figure 2 shows

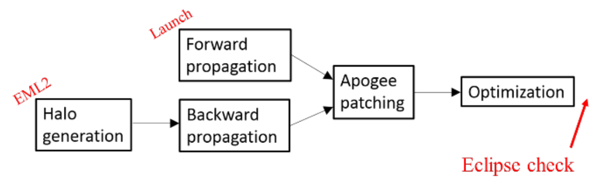


Figure 2: Overview of EQUULEUS trajectory design

the overview of EQUULEUS's trajectory design.

As for the forward trajectory, the arbitrary direction and magnitude of delta-V is added 36 hours after the deployment. This dV operation is called DV1 operation. After adding DV1, the trajectories are propagated and stored as the database.

The backward trajectory emanates from the science orbit. One candidate of science orbit is the Earth–Moon quasi-rectilinear halo in 4-to-1 resonance with the lunar synodic period[4)]. To guarantee an efficient escape from the quasi-periodic orbit, a small impulsive maneuver of magnitude is applied along the minimum stretching direction and the trajectories are integrated backward in time. The minimum stretching direction is the eigenvector associated to the minimum eigenvalue of the Cauchy–Green tensor. The backward trajectories are also stored to make the database.

The trajectories of two databases described above are compared to generate a set of first guesses for the optimization. Based on databases, a list of apogees is made, and close encounters in both the phase space and the epoch are searched for. Then, first guess trajectories are generated.

To minimize the sum of deterministic maneuvers in the first guess trajectories, a direct multiple-shooting technique is developed and implemented in jTOP[5)], an in-house trajectory optimization software that handles finite-dimensional nonlinear programming problems (NLP). Satisfaction of continuity constraints is enforced between successive arcs in time, position, and velocity where no impulsive maneuver occurs. The problem is then solved with SNOPT[6)], a general-purpose system for large-scale constrained optimization that efficiently implements a sequential quadratic programming (SQP) algorithm.

After the optimization, we check the eclipse. There is a possibility that the EQUULEUS trajectory has some eclipses, and they are not acceptable due to the constraint violation shown in the previous section.

III. Analysis object & Simulation conditions

Figure 3 describes the time of flight (ToF) and altitude at the moon closest approach (ballistic case) for Nov. 2021 launch. One launch period is about 2 weeks. For the most of initial conditions, ToF is around 5.1 days. The ToF for last several days becomes large. The altitude at the closest approach is not so deviated. EQUULEUS needs to increase this altitude to stay at the cislunar space since the inserted trajectory escapes from the Earth-Moon system without the delta-V operation.

IV. Results

Figure 4 shows the ToF and total dv for all optimization results. The open, middle, and close conditions for each launch window are used for the trajectory generation. The marker color changes if the launch conditions are different. The minimum ToF to transfer to science orbit is about 150 days. The minimum deterministic total dv is about 10 m/s.

Figure 5 shows the eclipse time for the Earth and the Moon for each trajectory. Some trajectories have large eclipse time, which violates the requirement. Since some of them occur just after the first lunar flyby, it is difficult to avoid them by small DV1. Figure 6 is an example of trajectory design results.

The results of the trajectory design is summarized in Table 3. As for the DV1, Total DV, and ToF, large values are distinguished by the red color. Further investigation is necessary to find better solution. The last column means the eclipse feasibility. The green color satisfies the eclipse constraints, but the red color doesn't satisfy. The yellow means the necessity to confirm the detail like the eclipse profile. As shown in this table, the avoidance of eclipses is critical for the EQUULEUS trajectory design.

I. Conclusion

The trajectory design method and current results for EQUULEUS are presented in the paper. The actual launch conditions whose date is Nov. 2021 are used although the launch date has been postponed.

The current trajectory design results for EQUULEUS have a problem of the Earth and Moon eclipse which sometimes violates the eclipse constraint. The future work to this problem is to investigate feasible solutions for the extension of the search range, the change of quasi-periodic orbits, relaxation of the constraints, and so on. The nominal quasi-periodic orbit is 4:1 southern synodic resonant halo orbit (SRHO). The other candidates are 4:1 northern SRHO and 5:2 northern and southern SRHO.

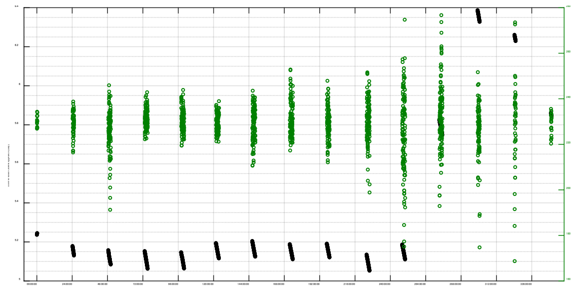
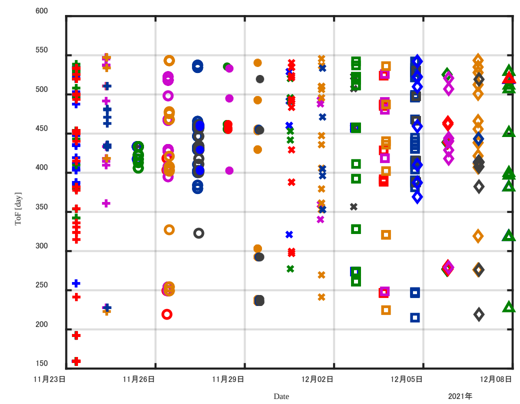
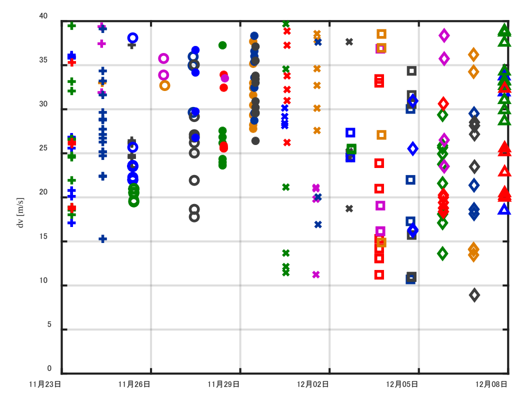


Figure 3: Time of Flight and Altitude for the Moon closest approach

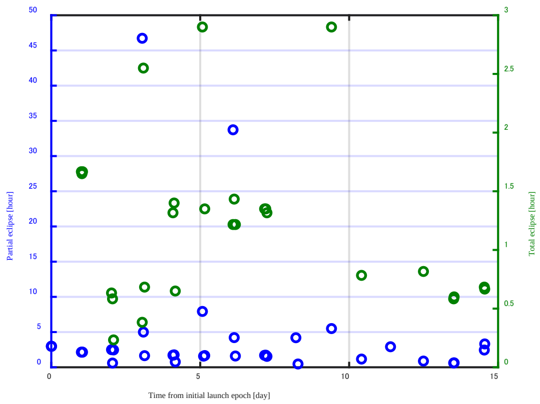


a) Time of flight

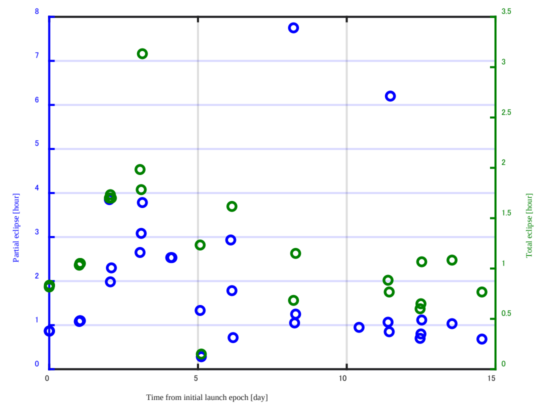


b) Transfer cost

Figure 4: Time of flight and Transfer cost for 2021 Nov. launch

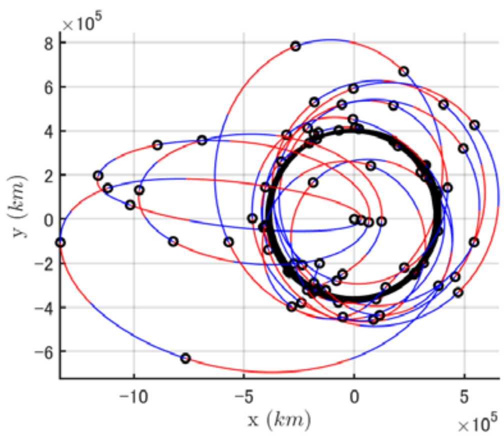


a) Eclipse time for Earth

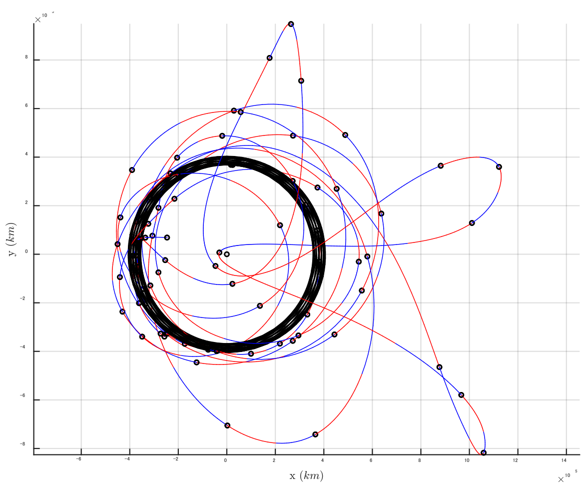


b) Eclipse time for Moon

Figure 5: Eclipse analysis results for each launch condition



a) ECLIPJ2000, Earth centered



b) Sun-Earth rotating frame

Figure 6: Trajectory for longest ToF case (index:16)

Table 3: Summary for Trajectory design

a) Index:1-24

index (time)	DV1 [m/s]	Total DV [m/	ToF [day]	Eclipse Feas
1	10.74	17.80	481.5	1
2	10.67	16.83	481.5	1
3	9.68	15.29	481.5	1
4	10.76	24.53	433.4	0.5
5	10.76	21.96	433.4	0
6	10.32	19.49	433.4	0
7	13.30	18.81	421.2	0
8	14.63	33.88	403.6	0
9	16.38	22.42	421.1	0
10	14.10	20.25	429.9	0
11	15.31	17.79	457.9	0
12	15.66	26.77	404.0	0
13	14.84	23.63	455.9	0
14	15.02	25.56	455.1	0
15	11.21	33.51	402.8	1
16	11.29	16.95	540.4	0
17	9.43	28.73	235.3	0.5
18	10.68	26.41	454.7	0
19	10.03	28.15	460.3	0
20	9.40	11.46	491.6	0
21	17.34	26.23	521.5	0
22	10.85	24.42	356.7	0
23	10.98	23.78	356.6	0
24	12.57	25.46	457.6	0

b) index:25-45

index (time)	DV1 [m/s]	Total DV [m/	ToF [day]	Eclipse Feas
25	8.19	8.87	387.7	1
26	6.72	17.35	381.8	1
27	9.42	15.85	336.0	0
28	7.98	11.23	359.5	1
29	10.48	27.59	353.1	1
30	10.84	20.05	470.8	0
31	4.92	11.22	246.7	1
32	4.92	11.22	246.7	1
33	13.07	14.87	487.3	0.5
34	9.58	10.69	496.3	0.5
35	9.00	10.97	387.9	1
36	9.47	16.19	522.4	1
37	8.63	13.62	525.4	1
38	8.97	18.38	280.0	1
39	13.51	23.52	418.1	0.5
40	8.32	13.47	276.2	1
41	8.73	17.76	276.2	1
42	7.66	8.92	382.4	0.5
43	8.00	18.51	518.6	1
44	8.80	28.65	381.4	1
45	7.56	19.97	519.9	1

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