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Improving Orbit Prediction Accuracy with a Realistic Thrust Model for KARI LEO Satellite Flight Dynamics Operation

Youeyun Jung*, Jaedong Seong, Saehan Song, Okchul Jung

SSA Research Office, National Satellite Operation and Application Center, Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseong-gu, Daejeon, Republic of Korea 34133, yejung@kari.re.kr*, acestars@kari.re.kr, songsaehan@kari.re.kr, ocjung@kari.re.kr
* Corresponding Author

Abstract

Since LEO satellites currently operating in KARI are sun-synchronous orbits and do not require frequent maneuvering, maneuvers for maintaining altitude has performed by empirically adjusting the duration of thrust firing. To automate the orbit maneuver process and improving prediction accuracy of LEO satellites operating in KARI, a simple thrust model is formulated with the Tsiolkovsky rocket equation. To check the validity of the formulation, dV values calculated with the given duration from the results of previously performed maneuvers and estimated from orbit determination are compared. From the comparison results, it was confirmed that the dV value calculated from the duration is almost same compared to the value calculated from the orbit determination. Finally, the method of calculating the dV value and duration for the desired altitude increase is summarized.

Keywords: Flight Dynamics System, Low Earth Orbit, Orbit Maneuver, Thrust Modeling

Nomenclature

r_A	=	distance between Earth center and point *A*
μ	=	standard gravitational parameter
h	=	angular momentum
e_1	=	eccentricity of initial orbit
r_B	=	distance between Earth center and point *B*
v_{B_e}	=	speed at point *B* on the elliptical orbit
v_{B_c}	=	speed at point *B* on the circular orbit
Δv_B	=	velocity increment at point *B*
Δv	=	velocity increment
m_i	=	initial satellite mass before maneuver
m_f	=	final satellite mass after maneuver
F_{MAN}	=	thrust along maneuver direction
Q_{MAN}	=	mass flow rate
τ	=	duration of thrust firing
τ'	=	recalculated duration of thrust firing considering minimum firing duration
N_{count}	=	count number of pulse-width

Acronyms/Abbreviations

Compact Advanced Satellite 500 (CAS500), Geostationary Earth Orbit (GEO), Flight Dynamics System (FDS), KARI (Korea Aerospace Research Institute), Korean Multi-Purpose Satellite (KOMPSAT), Low Earth Orbit (LEO), Pulse-Width Modulation (PWM), Sun-Synchronous Orbit (SSO)

1. Introduction

The number of satellites orbiting the earth is rapidly increasing as activities in space diversify such as space internet, space tourism, and space mining as well as the rapid increase in demand for satellite information [1-3] (see Fig. 1). In particular, when operating more than thousands of satellites constellation such as SpaceX [4], maintaining their own orbits is an important factor.

Fig. 1. Variety of global space activities *

KARI has been developing and operating LEO satellites such as KOMPSAT and CAS500 series since 1994. Currently, KARI is operating 5 LEOs and 3 GEOs, and it is expected that the number of satellites to be operated will increase significantly according to the "3rd Basic Plan for Promotion of Space Development" of the Korean government (see Fig. 2). Therefore, the autonomy of the FDS for simultaneous operation of multiple satellites will become more important.

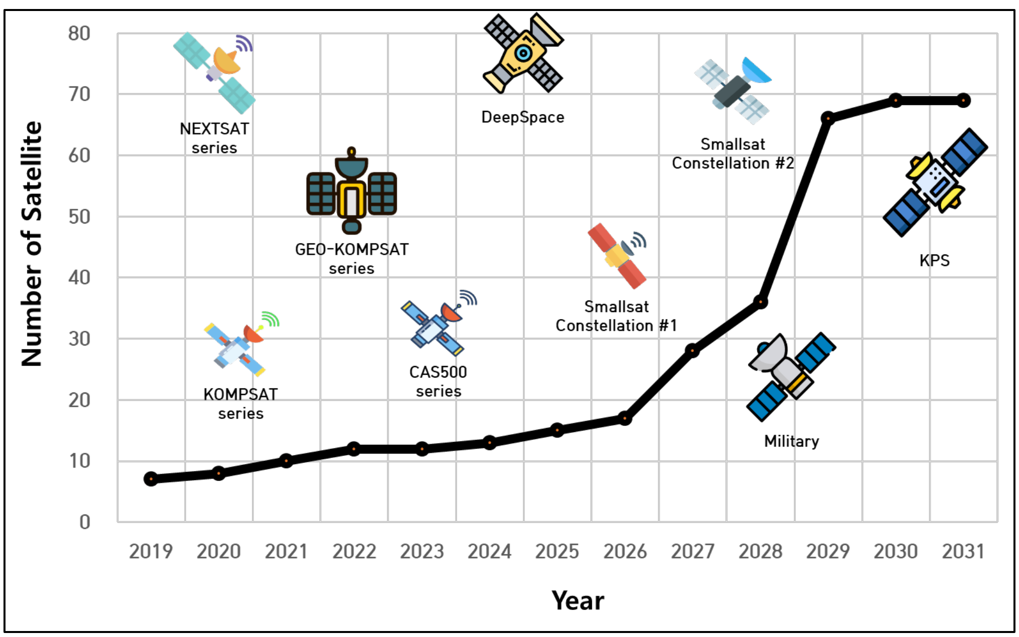

Fig. 2. Increasing trend in the number of planned national satellites

Since LEO satellites currently operated by KARI are in SSOs and do not require frequent maneuvering, the duration of thruster firing has been used empirically to adjust the altitude and inclination. However, in the case of a satellite with a relatively low altitude such as 500 km (for example, CAS500-1), it usually showed a tendency to rapidly decrease in altitude (see Fig. 3). Even during maneuvers, there were many cases where the altitude was less than expected.

* Background images originated by Economychosun, Virgin galactic, SpaceX, Blue origin, Deep Space Industries, and AstroSclae

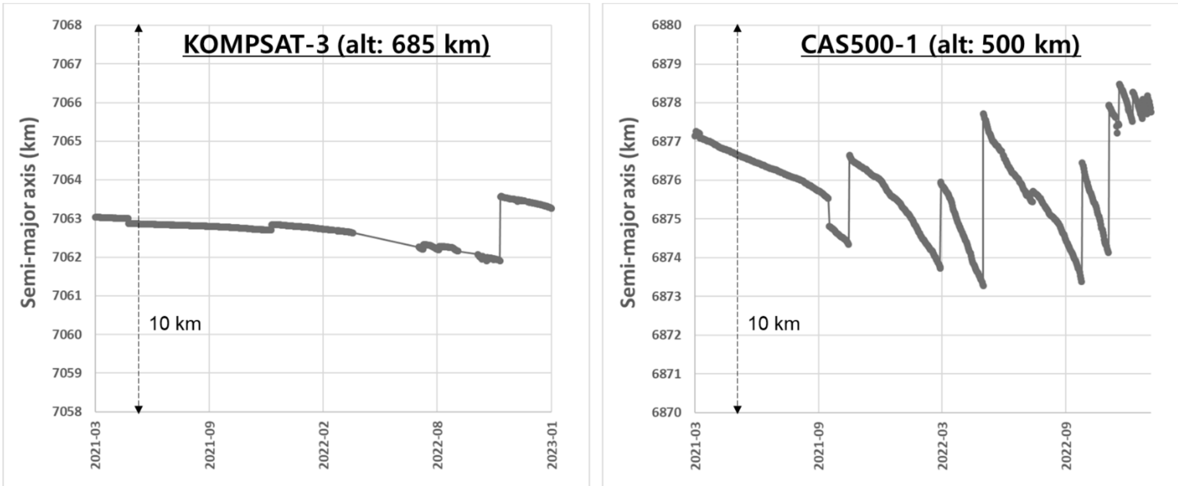

Fig. 3. Altitude change of KOMPSAT-3 (685km) and CAS500-1 (500km)

In order to support multiple mission operations, FDS maneuver planning shall be automated. Therefore, we plan to establish a procedure to automatically calculate the accurate duration of thrust firing for the desired altitude increase as follows. First, calculate the required Δv to transfer from the current altitude to the desired altitude by using classical orbital mechanics. Second, calculate the duration of thrust firing through the Tsiolkovsky rocket equation with the pre-calculated Δv. At this time, the thrust and specific impulse are obtained from the relationship between the thrust inlet pressure and the vacuum thrust/specific impulse in steady-state. Third, perform the orbit prediction taking into account the maneuver, and check the prediction accuracy by comparing the orbit determination results after the maneuver.

This paper largely consists of two parts. Chapter 2 explains the formulations mentioned in the procedure above, and Chapter 3 shows the verification results with actual maneuvering data and the simulation results for the example scenario.

2. Formulations

2.1 Δv Calculation

Based on the Hohmann transfer, Δv is calculated by assuming transition from an elliptical orbit with a very small eccentricity to a circular orbit with a major axis that is as long as the desired altitude from the center of the earth. (see Fig. 4)

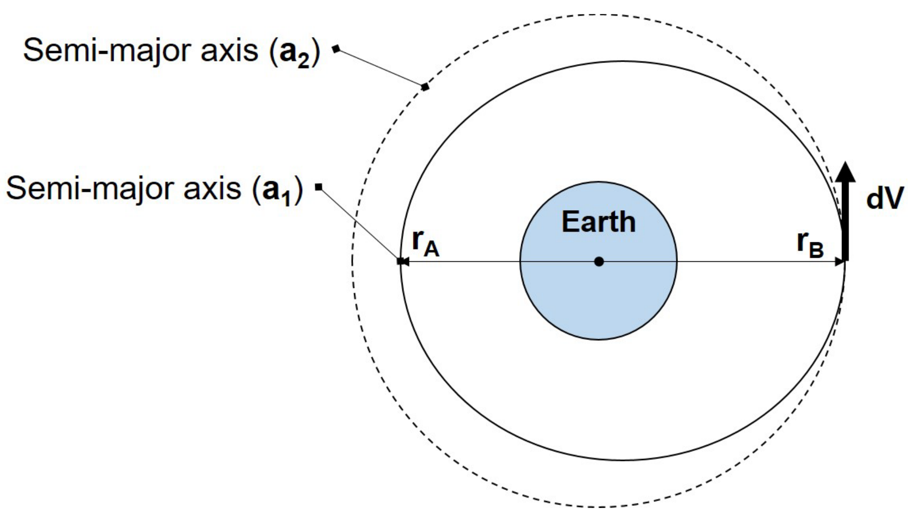

Fig. 4. Orbit transfer between two orbits

The formulation for calculating the Δv starts from the angular momentum equation as

$$r_A = \frac{h_2^2}{\mu(1+e_1 \cos\theta)} \tag{1}$$

Since the angle θ is zero and the semi-major axis of both orbit (a_1 and a_2) and the eccentricity e_1 is given as

$$e_1 = \frac{r_B - r_A}{r_B + r_A} \tag{2}$$

where $r_A = 2a_1 - a_2$ and $r_B = a_2$. Thus, the angular momentum h_2 can be obtained as

$$h_2 = \sqrt{\mu r_A (1 + e_1)} \tag{3}$$

Then, the speed at B on the elliptical orbit and circular orbit are respectively shown as

$$v_{B_e} = h_2 / r_B \qquad v_{B_c} = \sqrt{\mu / a_2} \tag{4}$$

Therefore, the required velocity increment at B is now obtained from (4):

$$\Delta v_B = v_{B_c} - v_{B_e} \tag{5}$$

2.2 Duration of Thrust Firing Calculation

To calculate the duration of thrust firing, the Tsiolkovsky rocket equation (See eq. 5) is used

$$\Delta v = v_e \ln \frac{m_i}{m_f} \tag{6}$$

The exhaust velocity can be derived in two ways such as

$$v_e = I_{sp} g_E = F_{MAN} / Q_{MAN} \tag{7}$$

where F_{MAN} can be obtained from the form of thrust set of each dedicated satellite such as number of thrusters or each thruster's tilt angle (e.g. 4 tilted thrusters with 14 degree). If the exhaust velocity is constant during the maneuver due to the short duration, then the final satellite mass can be expressed as

$$m_f = m_i - Q_{MAN} \tau \tag{8}$$

With eq. (6), (7) and (8), the duration of the thrust firing can be calculated as

$$\tau = \frac{m_i v_e}{F_{MAN}} \left[1 - e^{-\Delta v / v_e} \right] \tag{9}$$

Due to the characteristics of the PWM-controlled thrusters, the duration has to be recalculated refer to the count number of pulse-width. Therefore, the duration of the thrust firing will be recalculated as

$$\tau' = N_{count} t_{count} \tag{10}$$

where $N_{count} = round(\tau / t_{count})$.

The vacuum thrust and specific impulse in steady-state can be obtained by the relationships between the propellant inlet pressure and them, which are given by the dedicated thruster model (see Fig. 5.)

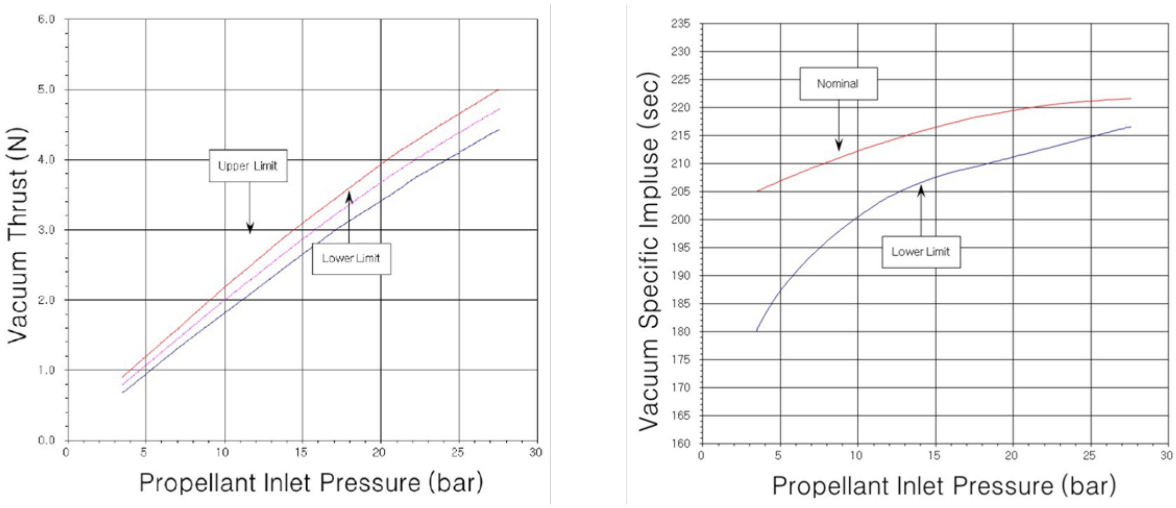

Fig. 5. Example of relationships between propellant inlet pressure and vacuum thrust/specific impulse

3. Results

3.1 Verification of formulation

To verify the formulation, each Δv calculated by the classical orbital mechanics, the Tsiolkovsky rocket equation with the designated duration of thrust firing, and estimated by orbit determination using GPS measurement are compared for the past three maneuvers. Details of past three maneuvers are shown in Table 1.

Table 1. Date and duration of past three maneuvers

No.	Date	Duration (sec)
Case 1	2022/12/20	30
Case 2	2023/01/03	20
Case 3	2023/01/10	20

Results of calculated Δv are shown in Table 2.

Table 2. Comparison of $\boldsymbol{\Delta v}$ from each calculation

No.	Δv Classical (m/s)	Δv Tsiolkovsky (m/s)	Δv OD* (m/s)
Case 1	0.4480	0.4490	0.4480
Case 2	0.2980	0.2976	0.2987
Case 3	0.2978	0.2976	0.2971

* OD: Orbit Determination

As shown in Table 2, the Δv values of the classical approach and orbit determination are almost identical. The reason is that the dV of the classical approach uses the mean semi-major axis from the orbit determination results. Similarly, the Δv values derived by Tsiolkovsky equation are also similar with others.

3.2 Simulation results of example scenario

The initial and target conditions for the simulation is given as Table 3.

Table 3. Initial and target condition for the simulation

Parameter	Initial	Target
Mean Semi-major axis (km)	6868.75	6870.75
Mass (kg)	500	-
Propellant inlet pressure (bar)	10	-

With the conditions and t_{count} is assumed as 5 msec, the velocity increment, thrust along the in-track direction, specific impulse, and finally the duration of thrust firing can be calculated as Table 4.

Table 4. Calculation results

Parameter	Value
Δv (m/s)	1.1090
F_{MAN} (N)	6.6384
I_{sp} (sec)	201.19
τ (sec)	83.506
τ' (sec)	83.505

The validation for the result is conducted by using high precision orbit propagator and astrogator tools in Ansys STK(Satellite Tool Kit).

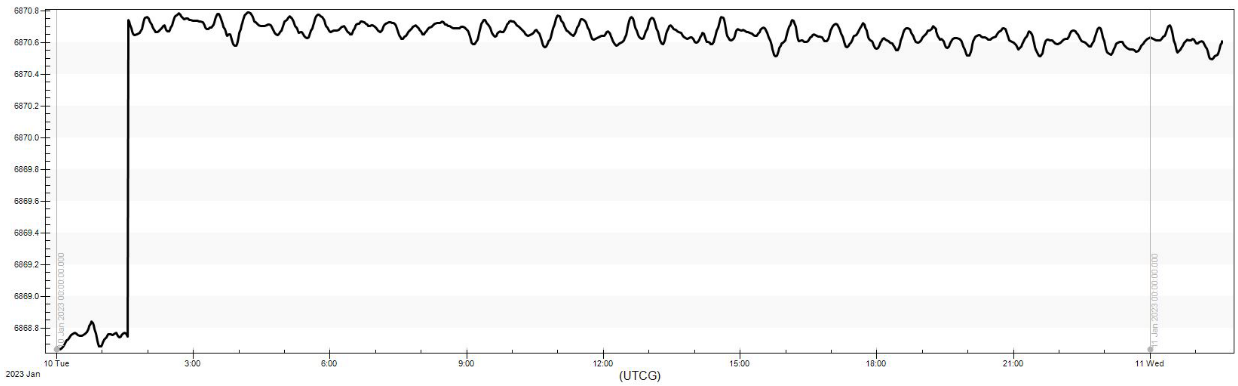

Fig. 6 Mean semi-major axis change after the maneuver

As shown in Fig. 6., the mean semi-major axis increases from 6868.754 km to 6870.746 km. The mean eccentricity, as shown in Fig. 7., decreases from 0.0001834 to 0.0001064.

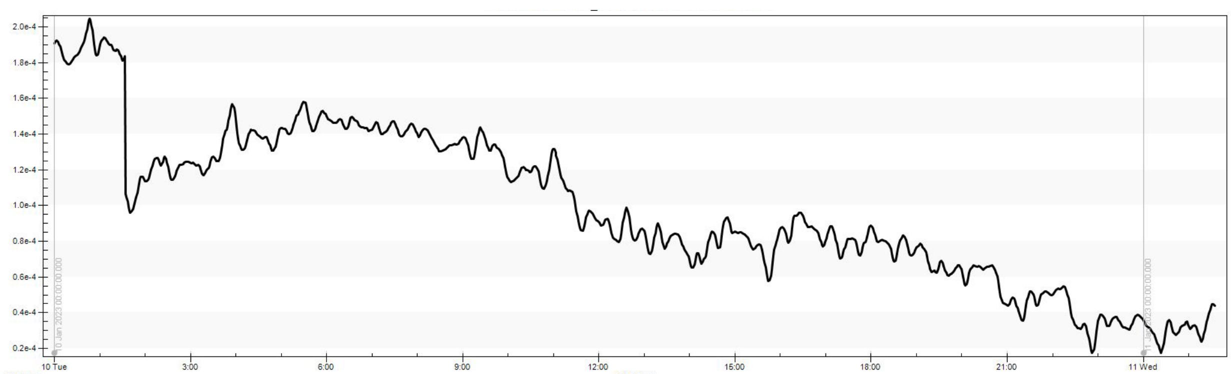

Fig. 7 Mean eccentricity change after the maneuver

4. Conclusions

This paper presents a simple maneuvering procedure to maintain LEO satellite's altitude for its mission by using classical orbital mechanics, the relationship between propellant inlet pressure and thrust/specific impulse, and the Tsiolkovsky equation. The duration of thrust firing can be calculated starting with the current and target altitude. The simulation results for the example scenario show the semi-major axis properly increases and the eccentricity decreases with the calculated dV.

References

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