Assessment of Orbit Maintenance Strategies for Small Satellites

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Objectives: To explore and validate how various orbit maintenance strategies for small satellites can be optimized for ΔV usage, by varying the tolerance bands as the independent variable.

Needs: A computationally efficient and accurate model for the rate of orbit decay, and a model small satellite in LEO as test parameters.

Summary: Three methods were proposed: one of forced-Keplerian orbits using constant thrust, one via Hohmann transfers, and one via cyclical direct burns. Results show potential for minimizing ΔV usage, and also reveal and interesting connection as tolerance bands tend to infinitesimally small values.

0. THE ORBITAL DECAY MODEL

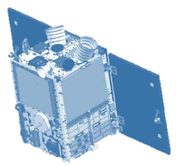


Fig 1: Model satellite and orbit parameters used in the simulation

VELOX-CI Satellite Information
Payload: Radio Occultation Unit
615 X 608 X 848 mm³
Mass = 123 kg
Semi major axis = 6928.14 km
Altitude = 545 km
Inclination = 15 degrees
RAAN, ARP, True Anomaly = 0

Decay Data from Model	2.444 km
Decay Data from GPS	2.566 km

Fig 2: Decay data comparisons with proposed model

Model Satellite & Parameters:	VELOX-CI
Orbit Characteristics:	Circular orbit, near-equatorial
Orbit Decay Validation Period:	16/12/2015 to 11/11/2016

Rate of Orbit Decay Model: (Derivations in Proceedings)

$$\frac{dR}{dt} = \frac{\alpha_o(R) \cdot T(R)}{\pi}$$

- R = Orbital radius from Earth
- T = Instantaneous orbit period
- α_0 = Sum of decay forces

- Orbit decay model was validated against 331 days (16/12/15 to 11/11/16) of GPS data.
- From Fig 2, decay rate model is very close to the actual GPS data, short by about 4.75%.
- Regardless, achieving model accuracy is not the primary objective – focus is on ascertaining the best orbit maintenance strategies rather than perfecting an orbital decay model.
- We then use this decay model for simulating orbit maintenance.
- Orbit maintenance simulations were then run for 5-years using the decay-rate model derived above.

I. METHOD OF FORCED KEPLERIAN ORBITS

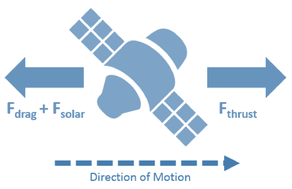


Fig 3: Force diagram for forced Keplerian orbits

$$F_{thrust} = -m(\alpha_{drag} + \alpha_{solar}) = 5.715\ \mu N$$

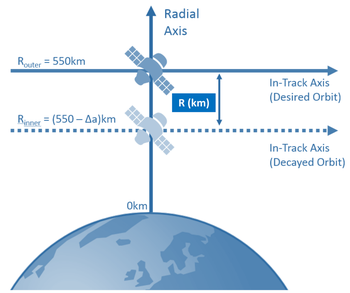
$$P_{loss} = F_{thrust} \times Velocity = -0.0434W$$

$$U_{loss} = \int_0^t (P_{loss})dt = -6.84MJ$$

$$\Delta V_{total} = \int_0^t (\alpha_{drag} + \alpha_{solar})dt = 7.332m/s$$

- Keplerian orbit – idealised trajectory of motion between two bodies in space due to gravity.
- Forced Keplerian orbit – constant thrust manoeuvre acting in the opposite direction of decay forces.
- Unfeasible in practice because:
  1) Impractical for the satellite to calculate out and exert the precise thrust force needed to counteract decay forces in the opposing direction accurately throughout mission.
  2) Desired thrust values are too small even for FEEPs and cold gas micro-thrusters.
- Therefore, for now we will consider the forced Keplerian orbit as an idealised method for us to benchmark the performance of other orbit maintenance strategies against.

II. METHOD OF HOHMANN TRANSFERS



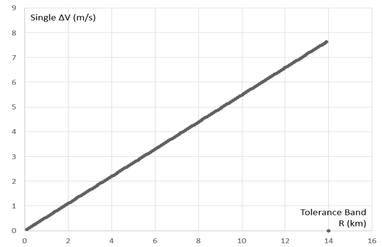


Fig 4: Single ΔV of single Hohmann transfer, against radial axis tolerance band (km)

- **R** is the radial-axis tolerance band, varied as the independent variable, where the satellite thrusts once it crosses this band.
- Hohmann Transfer: A fuel efficient orbit manoeuvre that transfers a satellite from one circular orbit to another circular orbit.
- Total ΔV consumed for entire manoeuvre comprises the scalar sum of two separate burns: one for entering the Hohmann transfer orbit at periapsis, and one to leave the transfer orbit at the apoapsis.
- Full derivations are found in proceedings.

$$\Delta V_{total} = \left(|V_{tA} - V_{iA}| + |V_{fB} - V_{tB}|\right)$$

- V_{iA} = initial velocity before entering transfer orbit
- V_{tA} = initial velocity after entering transfer orbit
- V_{tB} = final velocity before leaving transfer orbit
- V_{fB} = final velocity after leaving transfer orbit

- The duration of flight is given by:

$$T = \frac{P}{2} = \frac{1}{2} \cdot \sqrt{\frac{4\pi^2 a^3}{GM_E}}$$

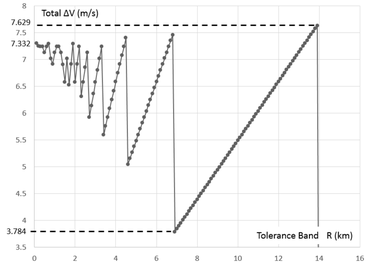
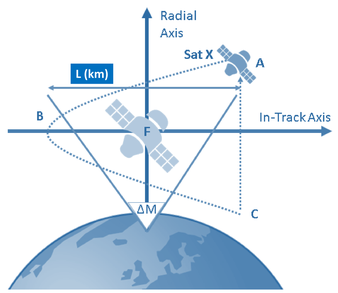


Fig 5: Total ΔV of all Hohmann transfers used in 5-year long mission, against radial axis tolerance band (km)

When the altitude falls below the tolerance band, the simulation boosts the altitude back to 545km and calculate the required ΔV per boost. Total ΔV is then summed up for the entire duration of the mission. The radial tolerance band will then be varied (independent variable), and the algorithm repeats.

III. METHOD OF CYCLICAL DIRECT BURNS



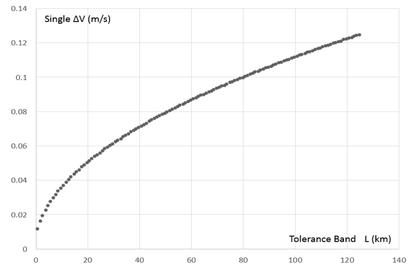


Fig 6: Single ΔV of single direct burn, against the in-track axis tolerance band (km)

L is the in-track-axis tolerance band; the independent variable, where the satellite thrusts once it crosses this band. Assuming the position of satellite X against reference F in Keplerian orbit in this algorithm:

1) At Point A, X is at higher altitude, and lags behind F. At the same time, the altitude decays due to drag and solar forces. This causes X to move from Point A to B.
2) At Point B, X's linear velocity matches F. However, it only stays at Point B for an instant, as decay is continuous. X drops in altitude and leads F with higher linear velocity, until it reaches Point C, where A and C both have the same in-track axis position.
3) At Point C, our satellite performs an impulsive thrust with a ΔV equivalent to the equation on RHS, until it boosts altitude back to Point A. The cycle repeats.

- The ΔV per manoeuvre can be approximated:

$$\Delta V \approx -2n\sqrt{\frac{LK}{3n}}$$

L = in-track tolerance (variable)
K = rate of decay from model
n = mean motion of X

- With the time-of-flight being: $T_M = 4\sqrt{\frac{L}{3nK}}$

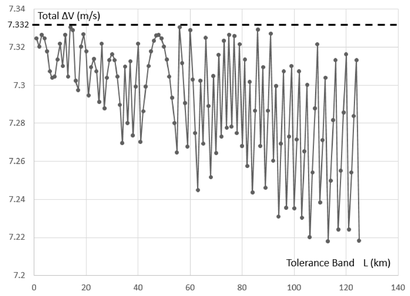


Fig 7: Total ΔV of all cumulative, cyclical direct burns, used in 5-year long mission, against in-track axis tolerance band (km)

You may find full derivation of this in the proceedings. Finally, this algorithm will be repeated again for various in-track thresholds L, where we will tabulate out all the possible total Delta-V's that are unique to each in-track threshold that we set. We would then analyse the data.

IV. RESULTS AND DISCUSSIONS

M1: Forced Keplerian Orbits	Total ΔV = 7.332 m/s. Interestingly, as the tolerance bands → 0 for Methods 2 & 3, the ΔV → 7.332 m/s for all 3 methods, indicating an almost "DC-like" thrust.
M2: Hohmann Transfers	Total ΔV diverges from 7.332 m/s as the radial axis tolerance band widens. Potential to find global minima for ΔV. Cost savings are substantial, but ground track isn't maintained.
M3: Cyclical Direct Burns	Total ΔV diverges from 7.332 m/s as in-track axis tolerance band widens. ΔV = 7.332 m/s forms an asymptotic upper. Satellite ground track is maintained.
Summary of Conclusion	Overall, there is potential for minimizing ΔV usage for M2 & M3 in a given mission duration by varying the tolerance bands. One should adopt a cyclical direct-burns approach to maintain orbit if ground track maintenance is a priority.

V. KEY REFERENCES

Acknowledgments to the project mentors of DSO National Laboratories, and the Satellite Research Centre (SaRC) in Nanyang Technological University (NTU), for providing the GPS data needed to validate our orbital decay model.

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