Orbit corrections in LEO satellites

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***Abstract*—Repeating Groundtrack Sun-synchronous orbits are critical for satellite missions, especially those involving Earth observation and remote sensing applications. This paper addresses the importance of maintaining a repeating groundtrack sun-synchronous orbit for small satellites deployed in Low Earth Orbit (LEO), specifically focusing on orbit correction strategies. A repeating groundtrack sun-synchronous orbit combines the characteristics of both a Sun-synchronous orbit and a repeat-ground track orbit. It is designed to maintain a consistent orientation towards the Sun while also repeating its groundtrack over a specific time interval. This paper focuses on perturbations effects on repeating Sun-synchronous orbits, which consist of maintaining Sun-synchronicity through orbit inclination and repeativity through the semi-major axis. Perturbations in these orbits can lead to changes in inclination, resulting in shifts in the local time of node crossing. Similarly, perturbations affecting the semi-major axis can cause drift in the groundtrack. Correcting these drifts is essential to preserve specific orbit characteristics. By analyzing these drifts, the study aim to identify orbit correction strategies that minimize drift time, ΔV usage and optimizing the efficiency and long-term stability of satellite missions.**

***Index Terms*—sun synchronous orbit, repeating ground track corrections.**

I. Introduction

LEO satellites operate at altitudes ranging from 500km to 2000km above the Earth's surface. These satellites are subject to various perturbations that can affect their orbits over time and impact the stability of satellite missions. These perturbations can arise from several sources, including atmospheric drag, Earth's oblateness, gravitational forces from the Moon and the Sun, and other celestial bodies. Mean local node-crossing time drift and repeating groundtrack shift drift are two important aspects to consider in maintaining a repeating groundtrack Sun-synchronous orbit.

A. Repeating ground track shift drift

It refers to the gradual displacement of a satellite's ground track over time. In Sun-synchronous orbits, the groundtrack should repeat after a specific time of interval. The main cause of this groundtrack drift at the equator is decay in the semi major axis caused by atmospheric drag, as well as drift in the orbital inclination due to the effect of the Suns and moon gravitational attraction. Atmospheric drag reduces the satellite's altitude, As a consequence, the nodal period, which is inversely proportional to the altitude, decreases as well. This change in nodal period affects the timing of groundtrack repetition, causing a shift in the groundtrack pattern over time. **Drag effect on semi major axis:** The drag effect on semi major axis is calculated as (1)

$$\frac{da}{dt} = -\rho \frac{C_D A}{m} {v_{rel}}^2 \sqrt{\frac{(1+e^2+2ecos(v)}{n\sqrt{1-e^2}}} \tag{1}$$

where, ρ is atmospheric density,
C_D is drag coefficient,
A is area of satellite,
m is mass of the satellite,
${v_{rel}}^2 = \frac{n^2a^2}{(1-e^2)} 1 + e^2 + 2ecos(v)$,
e, v and n are eccentricity,true anomaly and mean motion of satellite respectively. To mitigate the effects of groundtrack shift drift, orbit correction maneuvers are necessary. These maneuvers involve applying velocity changes (ΔV) to the satellite to raise its altitude. By periodically adjusting the orbit through these maneuvers, the decrease in the nodal period caused by atmospheric drag can be compensated, allowing the desired ground track repetition to be maintained

B. Mean local node-crossing time drift

Mean local node-crossing time drift refers to the deviation of a satellite's local node-crossing time from the desired value. In a Sun-synchronous orbit, the nodal drift rate is adjusted to approximately 0.9856 degrees per day to ensure that the satellite's angle with respect to the Sun remains constant. The secular rate of the Right Ascension of the Ascending Node (RAAN) in Sun-synchronous orbits is primarily influenced by the J2 perturbation, which arises from the Earth's oblateness. Changes in the orbit's inclination (i), semi-major axis (a), and eccentricity (e) can affect the secular rate of RAAN. However, changes in the inclination have a more significant impact on the secular rate of RAAN compared to changes in the other orbital elements. Therefore, maintaining the desired inclination is crucial for long-term orbit stability and the preservation of Sun-synchronous characteristics. By carefully considering and controlling the inclination during orbit design and maintenance maneuvers, the secular rate of RAAN can be managed, allowing for the precise maintenance of the Sun-synchronous characteristics of the orbit.

The primary drift in inclination in Sun-synchronous orbits is primarily caused by the third body gravitational effects rather than the J2 perturbation associated with Earth's oblateness. Gravitational influences from the Sun and the Moon on a satellite in a Sun-synchronous orbit causes drift in the satellite's inclination over time.

Third-body effect on inclination: The change in inclination caused by third-body gravitational force is calculated as,

$$\frac{di}{dt} = \frac{GM}{8n\sqrt{1 - e^2 d^2 (15e^2 \sin(incl)\cos(incl)\sin(2(w-\Omega)) - csc(incl)(15e^2\sin^2(incl)\cos(2(w-\Omega)) + (1+\frac{3e^2}{2})3\cos^2)(incl) - 1)}} \tag{2}$$

where GM=Third body gravitational constant
d= Distance from satellite to third body
e, incl, w, Ω are eccentricity, inclination, argument of perigee

and RAAN of satellite respectively. Where, periodic orbit-adjustment burns are necessary to maintain satellite's angle with respect to the sun remains constant within the specified tolerance. These burns involve adjusting the satellite's velocity (ΔV) to correct the inclination drift caused by the third body gravitational influence. By carefully controlling the timing and magnitude of these maneuvers, satellite operators can effectively manage the inclination drift and maintain the desired Sun-synchronous characteristics of the orbit.

II. Simulation

A. Maintaining Repeating ground track shift:

To develop an effective repeating ground track orbit-adjustment burn plan, the following steps are considered:

1) ***Perturbation Analysis****:* Analyze the perturbations affecting the semi-major axis $(\frac{da}{dt})$ and inclination $(\frac{di}{dt})$. These perturbations can include atmospheric drag, third-body effects (such as gravitational influences from the Moon and the Sun) and neglecting other small perturbations in the spacecrafts motion.

2) ***Analyze Required Corrections****:* with perturbation effects, calculate the drift time for maximum allowed ground track shift. Let $(\Delta\lambda_{rev})$ is the maximum allowed ground track shift, calculate the time (t-drift) for ground track shift drift of $\pm\Delta\lambda_{rev}(1)$, then determine the semi major axis change (Δ_a) for t-drift time. For a 500km sun synchronous orbit with 5 day repeativity, drift time for ground track shift with change in semi major axis for ground track shift of $\pm 5km$ with average flux(F 10.7 = 140 SFU and AP = 15) and area = $2m^2$, is shown in below figure 1.

3) ***Burn Planning****:* Once the required corrections are determined (Δa), determine the velocity changes (ΔV), the timing and frequency of the burns. The velocity change is calculated as:

$$\Delta V = \frac{n}{2}\Delta a \tag{3}$$

where, Δa= required semimajor axis change
n = mean motion of satellite.
As shown in figure 1, the drag perturbation causes semi major axis change of 0.3760 km for a 500 km orbit with ground track shift drift of $\pm$ 5km in 6 days (t-drift). If semi major axis is raised by 0.3760 km during launch, it takes t-drift time to drift to the nominal value. So after $2 * t$ drift time semimajor axis correction $(2\Delta a)$ is required to restrict the groundtrack shift drift of $\pm 5km$ as shown in figure 2.

For LEO satellites of range 300km to 1000km repeating sun synchronous orbit with average flux values(F10.7 = 140 SFU, AP = 15) and Area = $2m^2$, drift time for ground track shift of $\pm 1km$ to $\pm 5km$ and number of corrections required for a year and semimajor axis change and ΔV for correction of semimajor axis is shown in figure 3.

The semi-major axis drift in a satellite's orbit is primarily influenced by atmospheric drag, which depends on the density of the Earth's atmosphere. The density, in turn, is affected by various factors, including solar radiation. Consequently, the drag-induced semi-major axis drift can be influenced by the minimum and maximum flux values. For a 500km orbit, with minimum flux values (f10.7 = 70 SFU) and maximum flux values (f10.7 = 250 SFU) (3), density variation effect on semi major axis decay and ΔV for correction for ground track shift drift is shown in below figure 4.

B. Maintaining Local time crossing of orbit:

To develop an orbit-adjustment burn plan to maintain the local time of a satellite, consider the following steps:

1) ***Perturbation Analysis****:* The RAAN is influenced by perturbations such as the Earth's oblateness (J2 perturbation) and third-body gravitational influences causes change in inclination($(\frac{di}{dt})$) and neglecting all other small perturbations. Analyze the change in orbital elements that effects local time mainly change inclination caused by third body effect. Define the desired local time drift limit $(\Delta\Omega)$, this can be based on mission requirements or the specific objectives of the satellite mission.

2) ***Calculate Required Corrections****:* Let $(\Delta\Omega)$ is the maximum allowed mean local node-crossing time drift. With perturbation effects, calculate the drift time (t-drift) for local node crossing time drift of $\pm\Delta\Omega$ with inclination change (Δi) (1). For a 500km sun synchronous orbit, drift time for $\pm 10mins$ local time drift with inclination change is shown in below figure 5.

3) ***Burn Planning****:* Develop a burn plan to execute the required orbit-adjustment maneuvers. Calculate velocity change (ΔV) for required inclination correction, the timing and frequency of the burns.

$$\Delta V = 2v_{initial}\sin(\frac{\Delta i}{2}) \tag{4}$$

where, $v_{initial}$ =initial velocity of satellite, Δi = required inclination change for correction. As shown in figure 5, the third body gravitational effects causes inclination change of 0.0946° for local node crossing time drift limit of $\pm$ 10 minutes in 996.64 days (t-drift). The inclination is biased by 0.0758° to a favorable side during launch; it drifts to the nominal value after t-drift value. So after 2*t drift inclination $(2\Delta i)$ correction is required to restrict local time crossing drift of $\pm 10mins$ as is shown in figure 6.

For a repeating sun synchronous LEO satellites of range 300km to 1000km, drift time for local time drift of $\pm$ 5 minitues to $\pm$ 15minutes with inclination change and ΔV for correction of inclination is shown in figure 7.

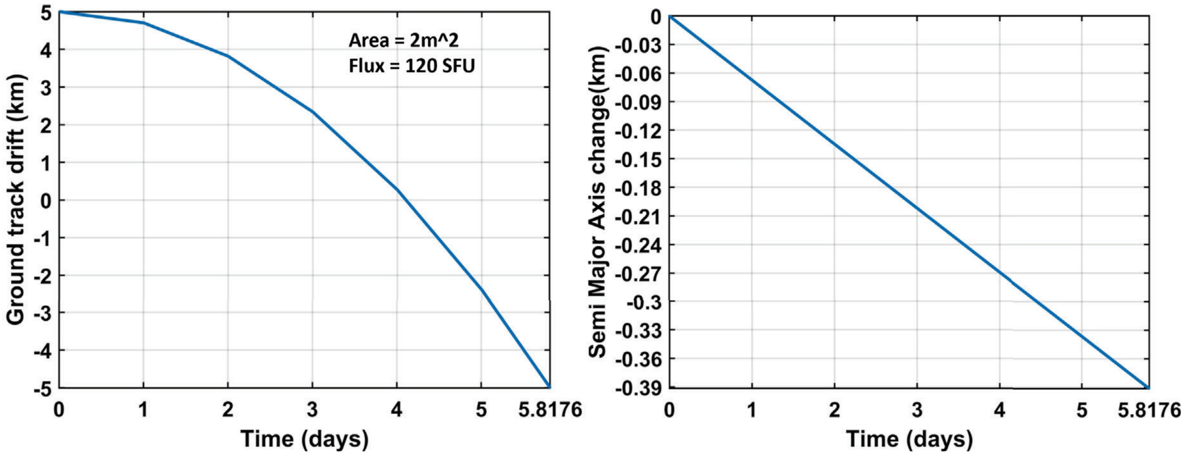

Fig. 1: Ground track shift drift vs. semi major axis change

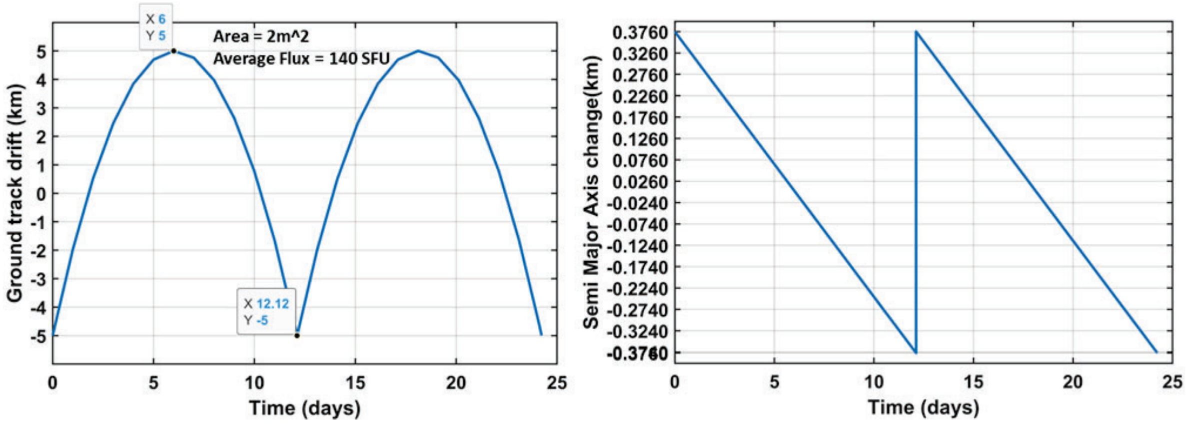

Fig. 2: After Initial bias of semimajor axis Groundtrack drift with semi major axis drift

CONCLUSIONS

Maintaining a repeating Sun-synchronous orbit is essential for satellite missions, but perturbations can affect the orbit inclination and semi-major axis, leading to a deviation from the desired orbit characteristics. To optimize the correction process, it is beneficial to analyze the changes in inclination and semi-major axis and account for them during the satellite's launch. By launching the satellite with biased inclination and semi-major axis, the correction time can be optimized. Specifically, increasing the correction time to double the drift time allows for more efficient orbit corrections. By implementing this optimization strategy, satellite operators can reduce the frequency of orbit correction maneuvers and minimizes the fuel consumption and extends the satellite's operational lifespan.

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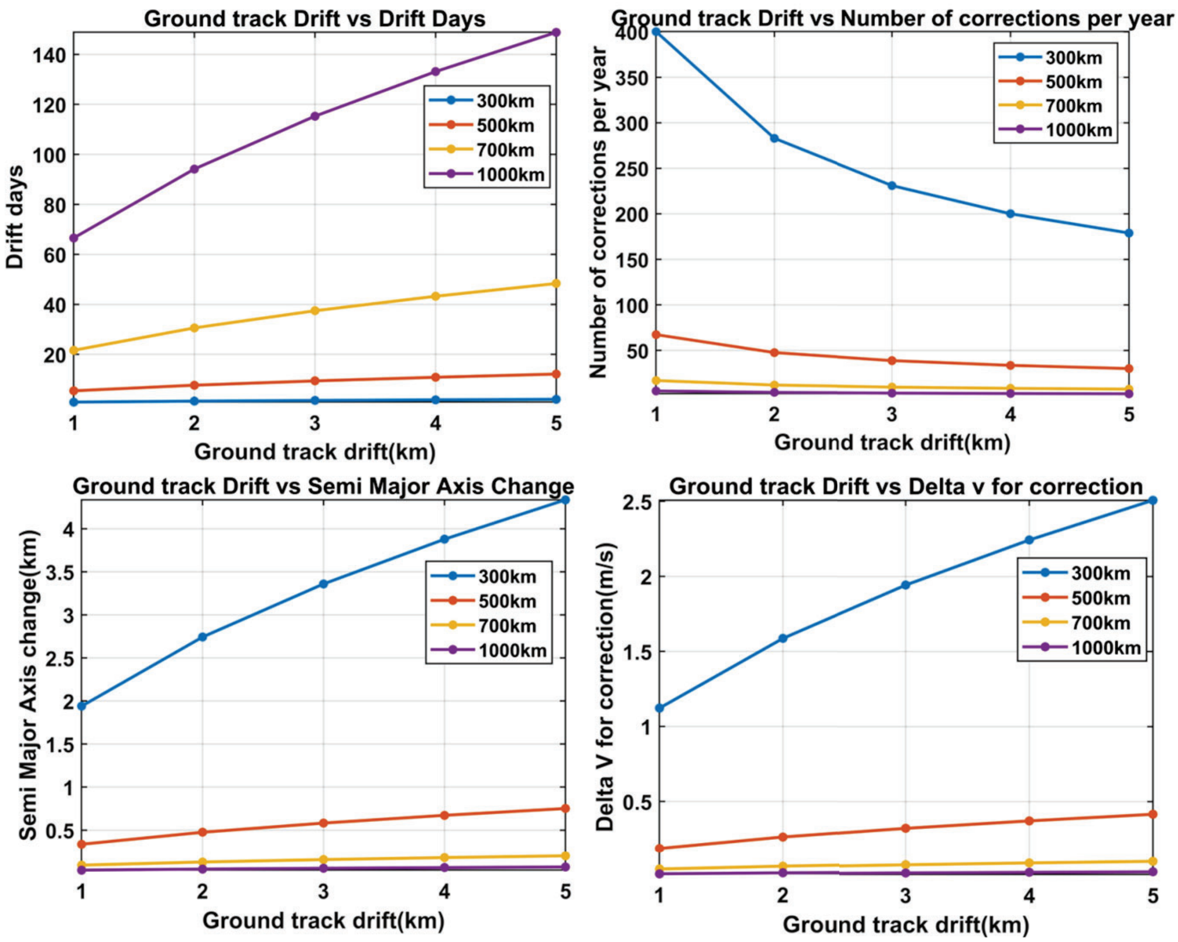

Fig. 3: Ground track drift, Semi major axis change, ΔV and no.of corrections per year

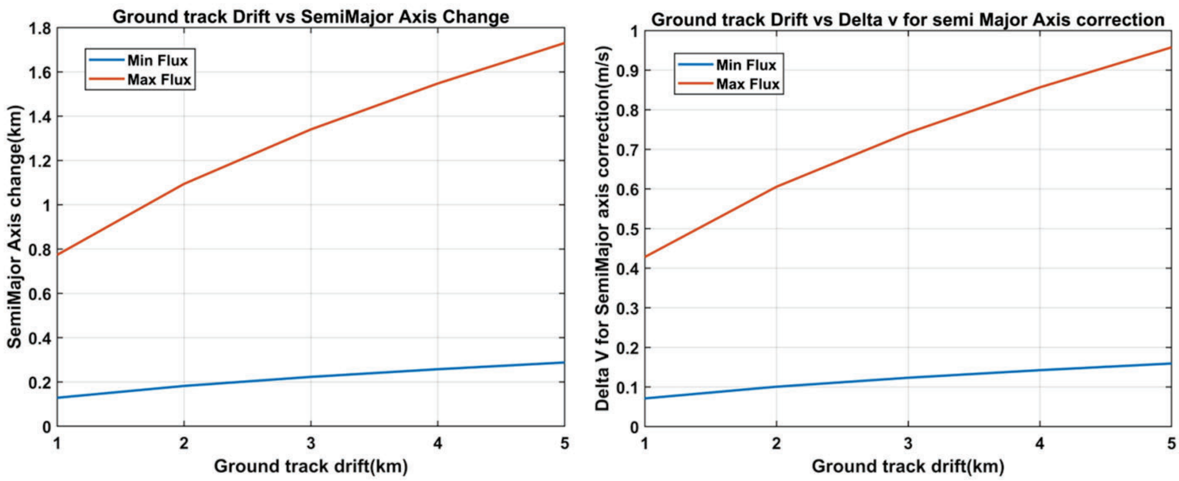

Fig. 4: semimajor axis change and ΔV for correction

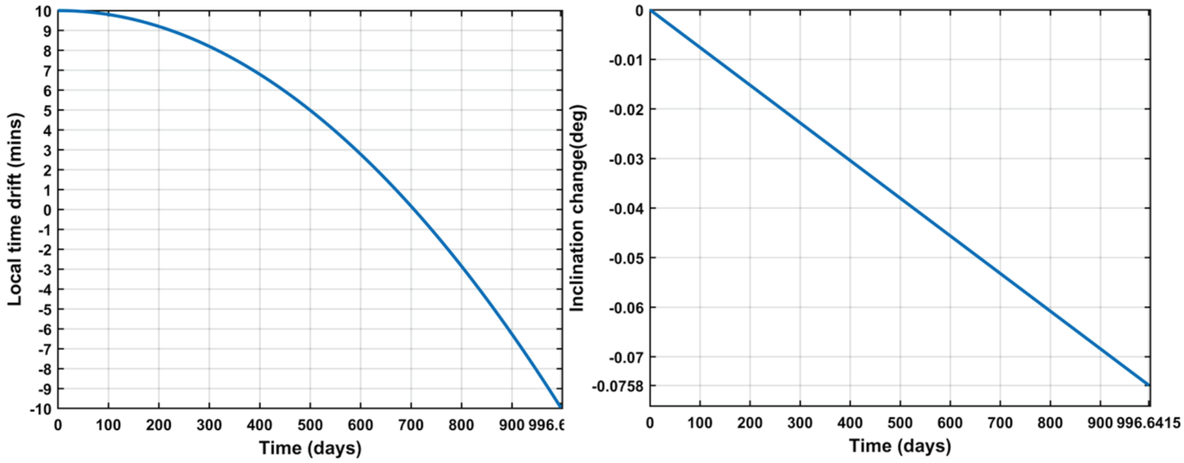

Fig. 5: Inclination change vs Local time drift

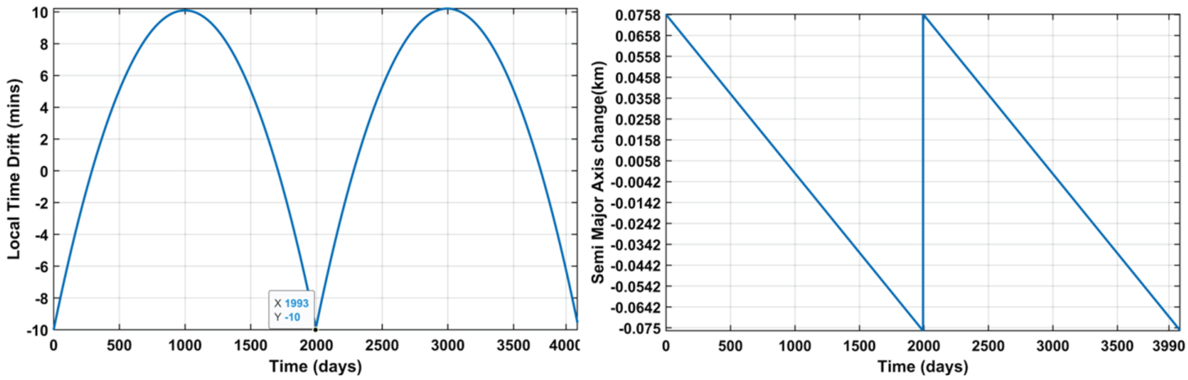

Fig. 6: After initial inclination bias local crossing time drift with inclination change

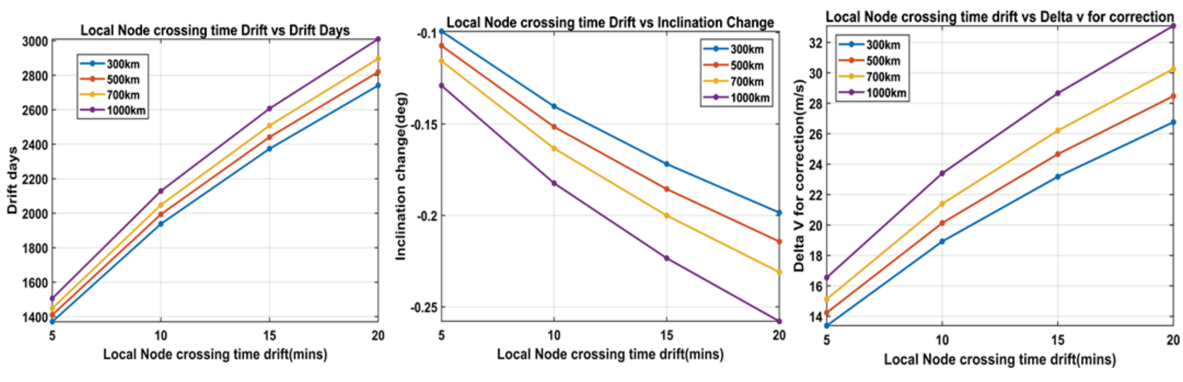

Fig. 7: Local crossing time drift with inclination change and ΔV correction

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