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Article

Orbital and Positional Perturbation of Satellites Under Solar Radiation Pressure at Influence of Area-to-Mass Ratio and C_R Variability

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Abstract: Among the perturbing factors that act on an artificial satellite, one of the most important is surely direct solar radiation pressure, mainly for objects with a high area-to-mass ratio. Direct solar radiation pressure had a considerable effect on the evolution of far-away orbits. The larger A/m is, the more strongly orbital elements and spatial position will deviate over time. Including a proper model of radiation pressure, therefore, is essential in space mission design and orbit prediction for small satellites. Future studies suggest the inclusion of Earth's shadow and thermal emissions as ways to further enhance the accuracy of numerical models.

Keywords: Orbital Perturbation, Solar Radiation Pressure (SRP), Area-to-Mass Ratio (A/m), Reflectivity Coefficient C_R, Orbital Elements.

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1. Introduction

The main non-gravitational perturbations of satellites, especially those in high orbits or with a large area-to-mass ratio, are considered to be direct solar radiation pressure. Perturbations mean deviations from an idealized or unperturbed motion [1]. This force is a result of the continuous collision of solar photons with the satellite surface, where each collision transfers some momentum, yielding a small but continuous acceleration over time. Despite the tiny magnitude of this acceleration, its effect accumulated over a long period result in an appreciable deviation of orbital elements [2]. A sphericity of the central body, atmospheric drag and left, the presence of other attracting bodies, the impact of solar radiation pressure, thrust, magnetic fields, solid earth tides, ocean tides, Earth re-radiation, and relativistic effect are the usual perturbations for the orbit problem [3]. The effect of solar radiation pressure, therefore, forms an important aspect of study to improve the accuracy of orbit prediction, satellite attitude control, and space mission design. Its importance increases for small satellites, space debris, and distant satellites, where atmospheric drag is negligible, and radiation pressure becomes the dominant perturbing factor. In this paper, the variation of orbital elements of distant satellites due to direct solar radiation pressure is presented for different area-to-mass ratios (A/m) [4]. Numerical simulations that investigate the perturbation of orbital elements due to the semi-major axis, eccentricity, and orbital inclination were also included in the study [5]. Solar radiation pressure on an artificial satellite has been investigated to determine its effect on its motion by a number of authors including Brooks C.J. and Ryland F.C.E. [6].

Numerical simulation was used in the study to calculate how orbital elements like the semi-major axis, eccentricity, and orbital inclination-and the displacements of the satellite in position-d_{along}, d_{rad}, and d_{out}change with time. The obtained results help improve the understanding of long-term orbital evolution and its stability under the influence of solar perturbations. At higher elevations, the non-conservative perturbation of solar radiation pressure becomes significant. Accurately modeling and forecasting the solar cycles and variations is one of the more challenging parts of solar radiation analysis. first created expressions for the specific force (acceleration) and its measurement must be exams in order to analyze the overall impact of solar radiation [7]. The apparent size of the satellite facing the Sun is essential for precisely calculating the amount of acceleration because the incoming radiation from the Sun exerts a force on the satellite. Simply dividing the force by the incident area exposed to the Sun yields the pressure. Accurate orbit prediction, spacecraft attitude control, and mission design all depend on the study of SRP effects. It becomes increasingly important for small satellites, debris, and high-altitude spacecraft, where atmospheric drag is negligible, and radiation pressure becomes the dominant perturbing force.

The precise location of the Sun, the proper orbital attitude, the precise value of the solar-radiation pressure, and the effective, time-varying, cross-sectional area exposed to the incoming radiation all depend on the satellite's shape and composition. This means that the pressure distribution is extremely important. The proper and typically time-varying coefficients to model the satellite's reflectivity [8] and the solar radiation pressure or force that the sun exerts on the satellite, which is inversely proportional to the satellite's mass-that is, if the satellite is large and light, it is more affected. Because the satellite is made of materials with varying refectories', it is very difficult to modulate this kind of perturbation [8].

This study examines the effect of direct solar radiation pressure on the variations of orbital elements for distant satellites under different area-to-mass ratios (A/m). Numerical simulations are performed in order to study the influence of solar radiation pressure as a function of time with respect to the positional deviations along the d_{along}, d_{rad}, and d_{out} directions and with respect to orbital parameters such as the semi-major axis, eccentricity, and inclination. The resulting findings provide insight into the stability of orbits and long-term evolution due to solar perturbations. One of the key non-gravitational perturbations that determine the long-term evolution of orbital elements is represented by solar radiation pressure (SRP) . According to previous studies, satellites' area-to-mass ratio (A/m) might change over time and affect SRP effects significantly [9][10]. As part of their analytical investigation into the effects of Earth tides on satellite orbits, both Izzet et al. and Kocsis showed that these tidal forces cause significant perturbations in orbital elements. Hamwdi furthered the mentioned above studies investigating the effect of a satellite's orbital inclination on tidal-induced disturbances. It was found that these disturbances could cause quite noticeable changes in the semi-major axis of a satellite's orbit and that the magnitude of these changes largely depends on orbital inclinationLater, Izzet et al. analyzed the related orbital effects under similar conditions. For the first time, extended this study potential is studied in this manuscript on satellite orbits at different anomalies, supplying grist as to how the gravitational anomalies of Earth may affect orbital dynamics. In the present work, we investigate how solar radiation pressure acts on LEO satellites in comparison to these gravitational effects. This study, by investigating the Earth's potential perturbation on satellite orbits at various inclinations, offers insights into the ways in which Earth's gravitational anomalies may affect orbital dynamics. The present work focuses on the interaction of SRP with the Low-Earth orbit satellites, in contrast to these gravitational effects. Quantification of SRP-induced perturbations and their comparison with gravitational effects will be performed by considering the satellite's area-to-mass ratio and reflectivity in the present study. This will provide a comprehensive understanding of the variables affecting satellite orbital behavior [11] [12] [13]. varying area-to-mass ratios and reflectivity coefficients parallels other dynamical disturbances affecting celestial motion. Satellite deviations caused by atmospheric irregularities and Earth's gravity field distortions resemble the perturbations of small planets under the gravitational effects of massive outer planets. The dynamical systems, in both cases, are modeled through differential equations whose solutions most often rely on spectral or analytical techniques to describe periodic variations [14]. Moreover, the requirement for correct disturbance modeling to enhance orbital maneuver planning for minimal fuel-cost transfer trajectories by sequential mathematical methods is in good agreement with long-term perturbative effects shown in minor planet dynamics, including their possible climatic implications on Earth [15] [16]. Both studies converge by elaborating on how changing material or physical parameters—the satellite area-to-mass ratio and CR, or modified V2O5–MgO Na2B4O7—significantly impacts the stability of the overall system under external forces in both application contexts [17].

2. Materials and Methods

Solar Radiation Pressure

The transfer of momentum from sunlight to a satellite's surfaces, for most orbital analyses, is achieved by directing the solar radiation pressure acceleration along the Sun–satellite line and is proportional to the area-to-mass ratio A/m. Therefore, approximating the satellite as a cannonball (spherical and directionally symmetric) is considered a suitable first-order model, with the radiation coefficient C_R. In vector form (observing the inverse-square law and the shadow factor S∈ [0,1])

$$a_{SRP}(t) = -P_0 C_R \frac{A}{m} \frac{r_{\odot s}}{\left|\left|r\_r_{\odot s}\right|\right|} \left(\frac{1\,AU}{\left|\left|\,r\_r_{\odot s}\right|\right|}\right)^2 S(r_{\odot s}) \cdots\cdots (1)$$

where $r_{\odot s}$ is the vector from the Sun to the satellite and $P_0 \approx 4.56 \times 10^{-6}\,Nm^{-2}$ is the nominal solar pressure at 1 AU. For high-fidelity or long-duration propagations, it is advised to explicitly include the inverse-square term and an eclipse/shadow model.

Each photon with frequency f and wavelength (λ=cf), where c is the speed of light in a vacuum, carries linear momentum and energy (E=hf), according to quantum mechanics theory.

To relate SRP to changes in Keplerian elements, project a_{SRP} onto the local orbital frame (radial R, transverse/along-track T, normal/cross-track N):

$$R = a_{SRP}\,.\hat{r},\quad T = a_{SRP}\,.\hat{t},\quad N = a_{SRP}\,.\hat{n}.$$

The explicit functions of (R, T, N), true anomaly v, semilatus p, and other orbital quantities, Gauss' planetary equations provide the instantaneous rates $\dot{a}, \dot{e}, i, \dot{\Omega}, \dot{\omega}, \dot{M}$. For instance, in compact form, the semimajor axis and eccentricity rates read

$$\frac{da}{at} = \frac{2}{n\sqrt{1-e^2}}\sqrt{\frac{a}{\mu}}(e \sin v\, R + \frac{p}{r}T) \cdots\cdots (2)$$

$$\frac{de}{at} = \frac{\sqrt{1-e^2}}{na}\left(\sin v\, R + (\sin v\, R + \left(\cos v\, \frac{e + \cos v}{1 + e\cos v}\right)T\right) \cdots\cdots (3)$$

The standard Gauss expressions follow with $di/dt, d\Omega/dt, and\ d\omega/dt$. where the time history of the orbital elements is obtained either through numerical integration of these coupled equations or through direct Cartesian propagation, which includes a_{SRP}; both methods are commonly used in the literature.

Procedure for Computing RTN Positional Displacements

A state-difference approach was used to assess the positional displacements in the local orbital frame, specifically the radial d(rad), along-track d(along), and cross-track d(out) components. This technique offers a clear and straightforward way to measure how much solar radiation pressure affects orbital motion.

1. Reference propagation:

By numerically integrating the satellite's equations of motion, either with or without the solar radiation pressure (SRP) perturbation, a reference trajectory, $r_{eft}(t)$ was produced.

2. Perturbed propagation:
3. Using the chosen values of the radiation coefficientC_R and area-to-mass ratio A/m, a second trajectory $\boldsymbol{r}_{Pert}(t)$ was produced while SRP was in effect.
4. State difference computation:

The positional deviation vector was calculated at each epoch t as

$$\Delta r(t) = \boldsymbol{r}_{Pert}(t) - \boldsymbol{r}_{ref}(t) \cdots\cdots (4)$$

5. Projection onto the RTN frame:

Projecting the deviation vector Δr(t) onto the local orbital triad—normal or cross-track (n̂), along-track (t̂), and radial (r̂)—attached to the reference orbit produced

$$\hat{r}.\Delta r(t) = d_{rad}(t) \cdots\cdots (5)$$
$$\hat{t}.\Delta r(t) = d_{along}(t) \cdots\cdots (6)$$
$$\hat{n}.\Delta r(t) = d_{out}(t) \cdots\cdots (7)$$

In the local orbital frame, these values stand for the instantaneous positional differences between the reference and perturbed trajectories. This technique has been widely used in recent SRP analyses for both Low-Earth and high area-to-mass ratio orbits because it offers a physically meaningful and numerically consistent measure of SRP-induced displacement.

The impact of the radiation pressure coefficient C_R and the area-to-mass ratio (A/m) on the orbital elements and the local RTN positional displacements was examined through numerical simulations. MATLAB was used for post-processing and visualization, and Celestial Mechanics software was used for accurate orbital propagation.

The cannonball or box-wing approach is frequently used to model the mathematical representation of SRP . The reflectivity-controlled model put forth by Mu et al. can be used to derive the acceleration components along the radial, along-track, and cross-track directions.

3. Results and Discussion

Variation of Orbital Elements with Different (A/m) Ratios

The time evolution of the orbital elements (semi-major axis a, eccentricity e, inclination i, right ascension of the ascending node Ω, and argument of perigee ω) for various (A/m) values ranging from $0.01\ to\ 0.05\ m^2/kg$ is depicted in **Figures (1, 2 ,3 and 4).**

There is a discernible pattern: the influence of solar radiation pressure (SRP) increases with increasing (A/m), leading to greater deviations in the orbital elements over time.

There is a discernible pattern: the influence of solar radiation pressure (SRP) increases with increasing (A/m), leading to greater deviations in the orbital elements over time. In particular

Confirming the SRP-induced secular effects reported by the semi-major axis and eccentricity show quasi-periodic oscillations whose amplitude increases with (A/m).

1. Due to the coupling between SRP and Earth's oblations, the inclination shows detectable oscillations at higher ratios, but is almost constant for low values of A/m. J-2 terms
2. The right ascension of the ascending node Ω and argument of perigee ω show perceptible long-term drift, consistent with resonance conditions in high area-to-mass ratio satellites obtained by.

These results show how the area-to-mass ratio of the object strongly influences SRP perturbations, enhancing both periodic and secular changes in orbital geometry [18].

Effect of the Radiation Pressure Coefficient C_R

To evaluate its effect on orbital dynamics, the radiation pressure coefficient C_R has been varied between 1.0 and 1.6.

Stronger perturbations result from an effective scaling of the SRP acceleration magnitude with an increase in C_R.

The findings indicate that:

1. The semi-major axis and eccentricity oscillate with greater amplitudes as C_R increases. With C_R, the rate of drift in ω and Ω rises almost linearly.
2. Secondary oscillations in a and e for $C_R < 1.4$ correspond to SRP-J_2 coupling resonances, as also reported by.

These patterns demonstrate that A/m and C_R both function as scaling parameters for SRP influence, altering the orbital oscillations' amplitude and phase.

RTN Displacement Analysis

For various (A/m) and C_R values, the calculated displacements in the RTN frame-radial d(rad), along-track d(along), and cross-track d(out)-were examined **(Figures 4, 5, 6, 7, 8, 9, 10, 11 and 12).**

1. With A/m and C_R, the radial displacement d(rad) increases in amplitude, suggesting that SRP-induced orbit expansion and contraction cycles are more pronounced.
2. The strongest secular drift, which represents the cumulative phase change between the perturbed and reference orbits, is shown by the along-track displacement d(along). This pattern aligns with the analytical forecasts of [19].
3. Because of the out-of-plane SRP component, the cross-track component d(out) stays relatively small but slightly increases for higher inclinations and $A/m > 0.5$.

The displacements' magnitude ordering is as follows:

$$| d_{along} |>| d_{rad} |>| d_{out} |$$

which is consistent with earlier SRP sensitivity analyses for the near-circular orbits and {Carvalho}.

Comparative Discussion

When all simulation results are compared, it becomes clear that

1. The amplitude and frequency of oscillations in a, e, ω, and d(along) increase as A/m increases, confirming the quadratic dependence of SRP acceleration on exposed area.
2. As expected by the SRP acceleration formulation, increasing C_R amplifies these effects linearly.

$$a_{SRP} = \frac{C_R P_{\odot} A}{m}$$

3. Since the along-track displacement is most sensitive to both parameters, it may be the best observable to use when looking for SRP effects in drag-free or orbit determination experiments [20].

The study's trends generally concur with recent research findings, especially those by, and confirming the accuracy of the numerical models created with the Celestial Mechanics and MATLAB environment.

Findings by Alessi et al. and Eapen are in line with the observed changes in semi-major axis and eccentricity with increasing A/m ratios.

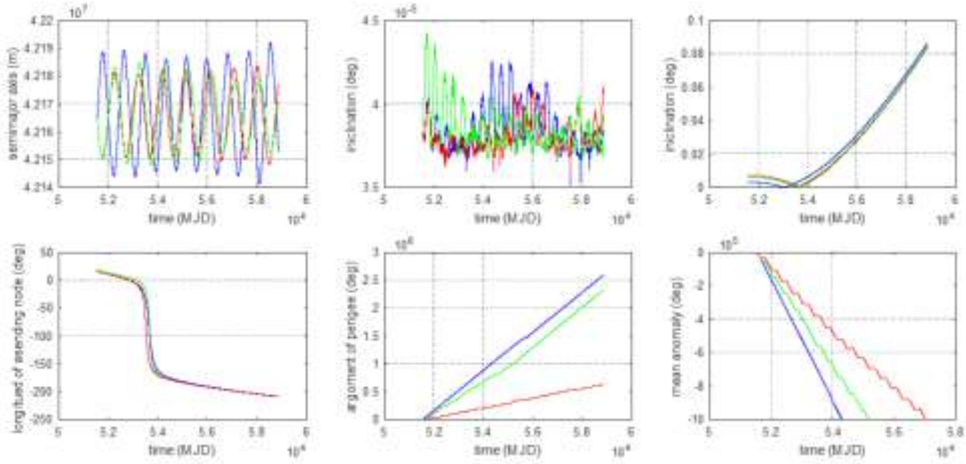

Figure 1. Show the perturbation caused by solar radiation pressure at varying C_R and (A/m) ratios =0.6 (C_R=1.1, 1.2 and 1.4)

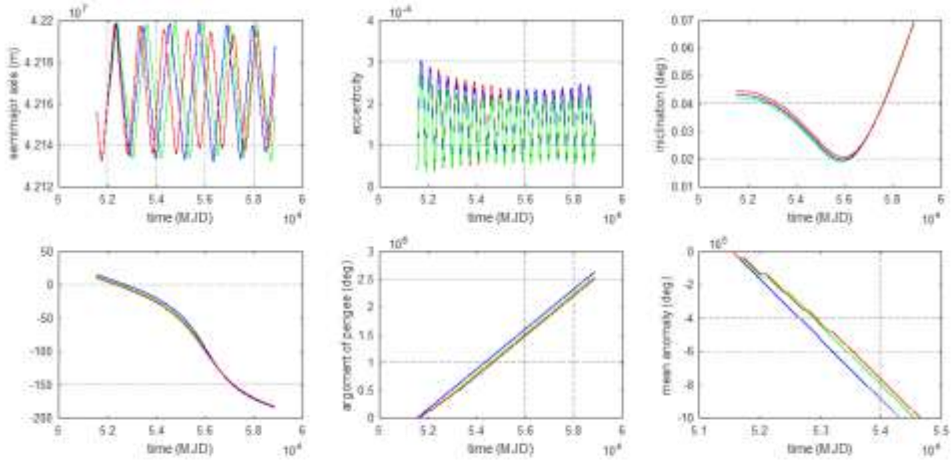

Figure 2. Show the perturbation caused by solar radiation pressure at varying C_R at (A/m) ratios =0.7 (C_R=1.1, 1.2 and 1.4)

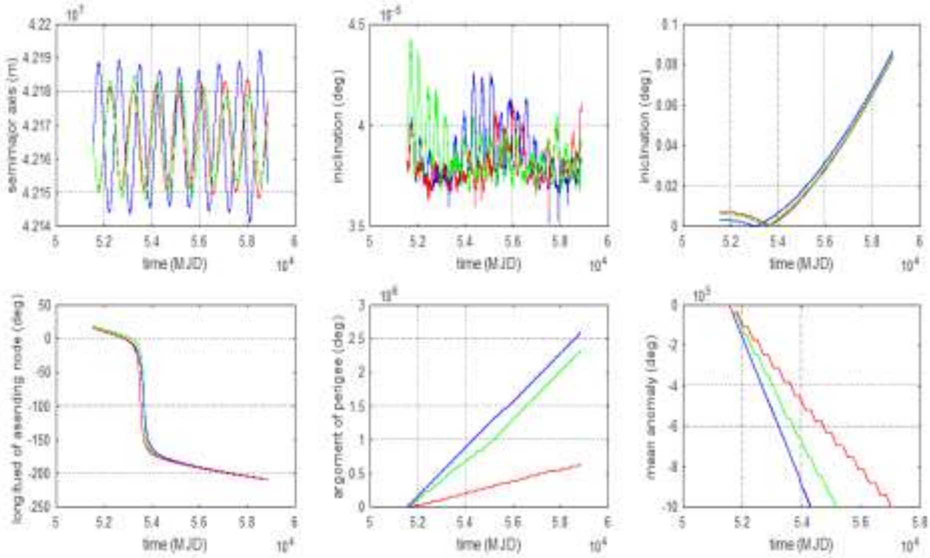

Figure 3. Show the perturbation caused by solar radiation pressure for varying C_R at (A/m) ratios =0.9 (C_R=1.1, 1.2 and 1.4)

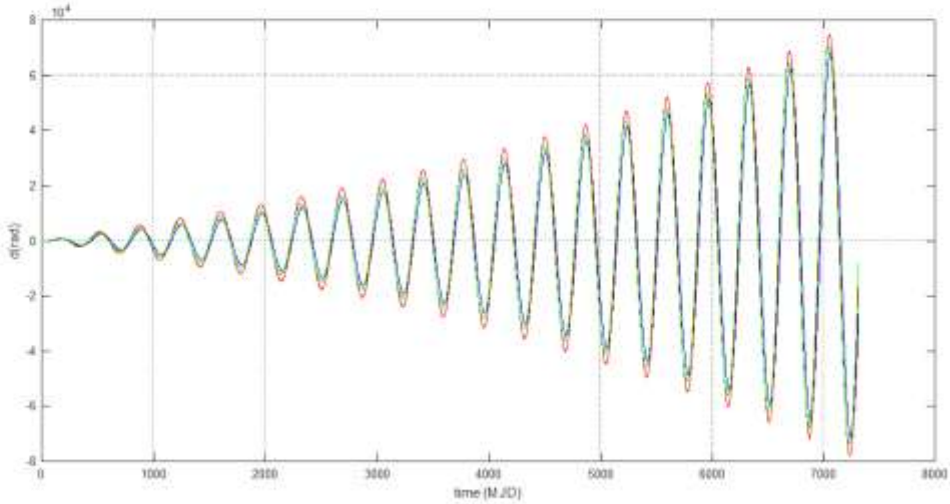

Figure 4. Show the displacements in the RTN frame-radial d(rad) for varying C_R at (A/m) ratio=0.6 (C_R=1.1, 1.2 and 1.4)

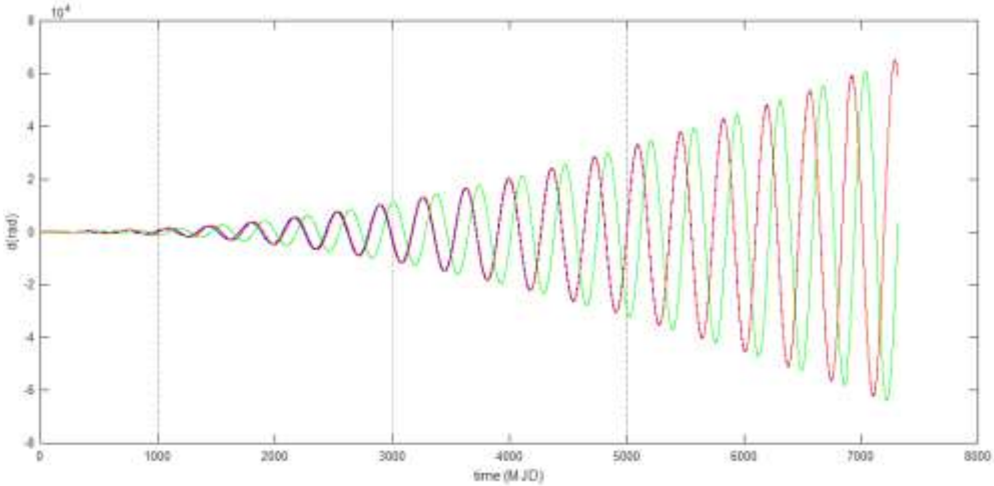

Figure 5. Show the displacements in the RTN frame-radial d(rad) for varying C_R at (A/m) ratio=0.8 (C_R=1.1, 1.2 and 1.4)

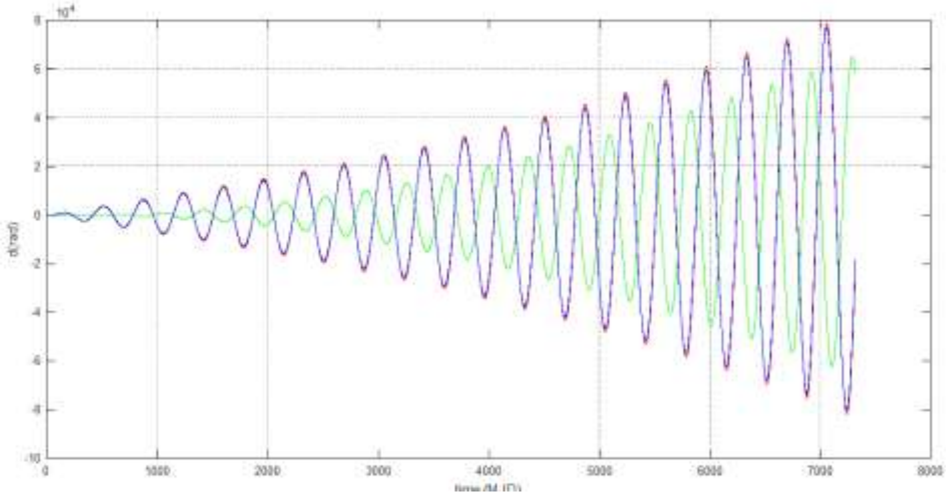

Figure 6. Show the displacements in the RTN frame-radial d(rad) for varying C_R at (A/m) ratio =1.0 (C_R=1.1, 1.2 and 1.4)

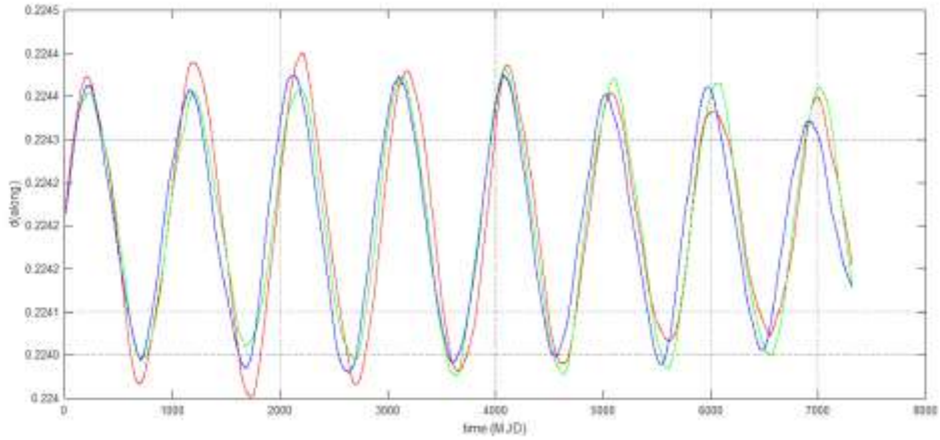

Figure 7. Show the displacements in the RTN frame along-track d(along)for varying C_R at (A/m) =0.6 (C_R=1.1, 1.2 and 1.4)

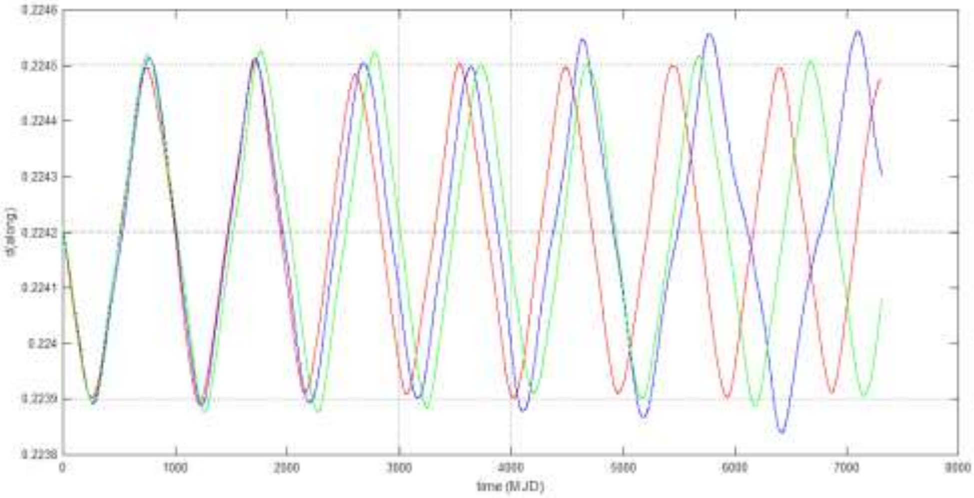

Figure 8. Show the displacements in the RTN frame along-track d(along)for varying C_R at (A/m) =0.8 (CR=1.1, 1.2 and 1.4)

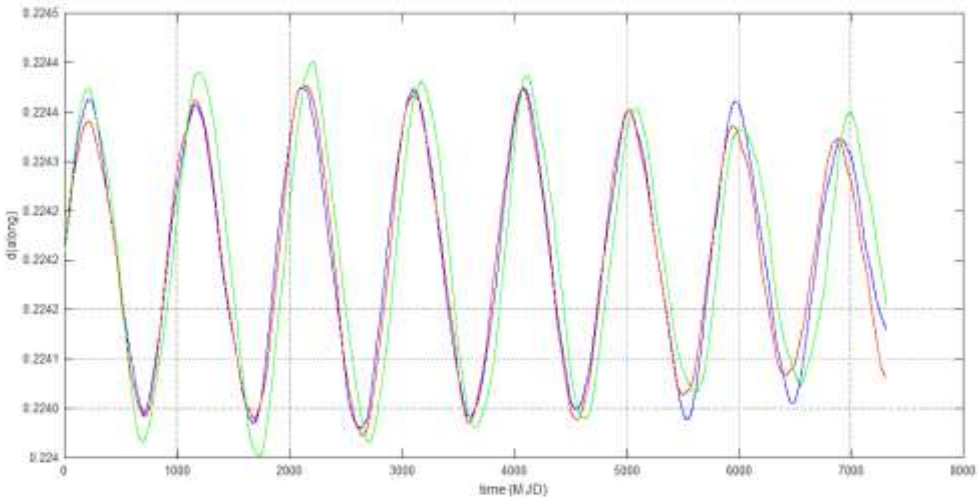

Figure 9. Show the displacements in the RTN frame along-track d(along)for varying C_R at (A/m) =1.0 (C_R=1.1, 1.2 and 1.4)

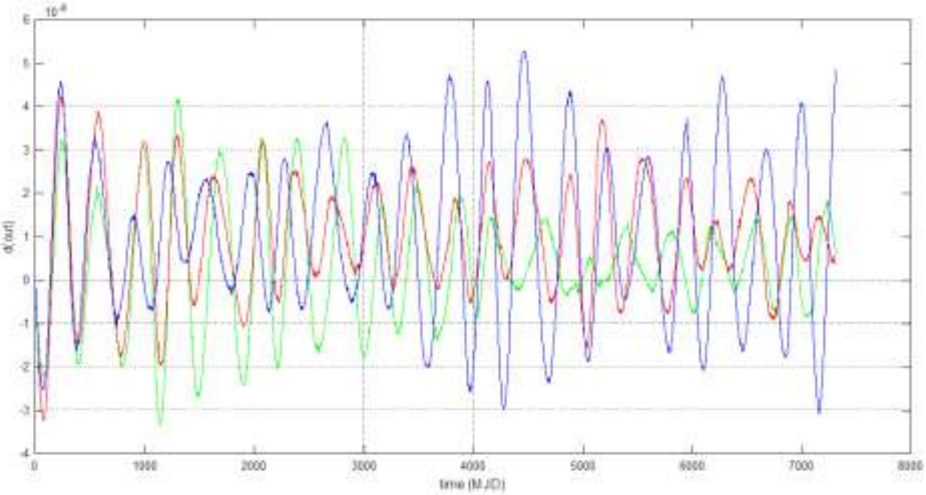

Figure 10. Show the displacements in the RTN frame cross-track d(out) for varying C_R at (A/m) ratio =0.6 (C_R=1.1, 1.2 and 1.4)

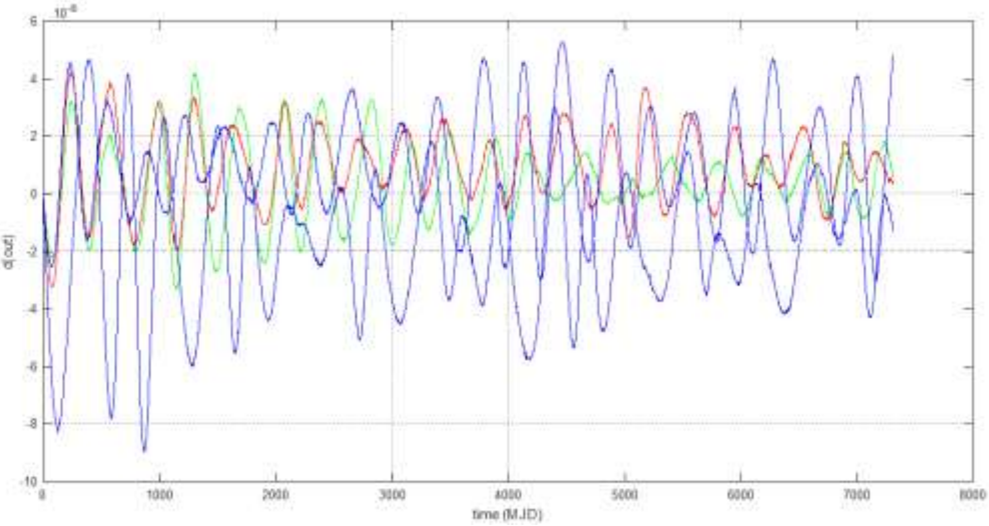

Figure 11. Show the displacements in the RTN frame cross-track d(out) for varying C_R at (A/m) ratio =0.8 (C_R=1.1, 1.2 and 1.4)

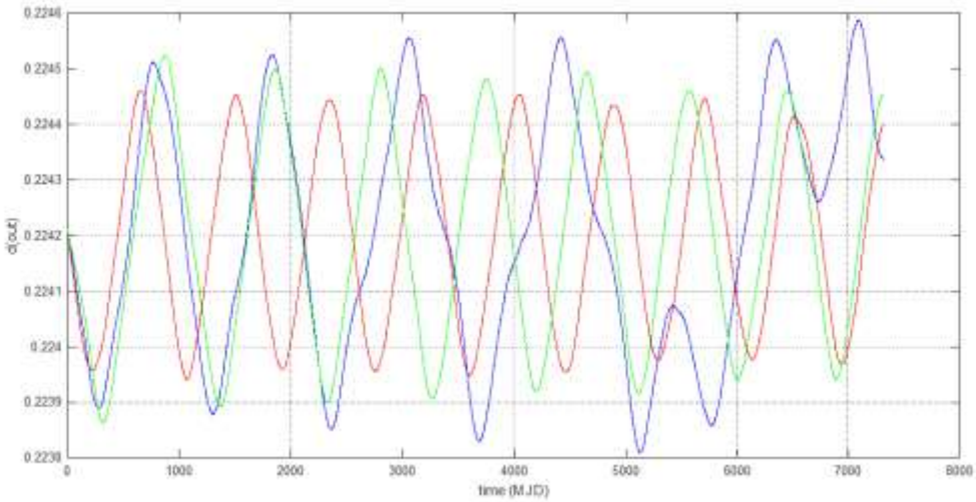

Figure 12. Show the displacements in the RTN frame cross-track d(out) for varying C_R at (A/m) ratio =1.0 (C_R=1.1, 1.2 and 1.4)

4. Conclusion

Using the Radial-Transverse-Normal (RTN) reference frame, the current study examined the impact of solar radiation pressure (SRP) on the long-term evolution of orbital elements and positional displacements. A numerical integration model grounded in celestial mechanic's principles was used for the analysis, and MATLAB visualization was used for validation. The solar radiation pressure coefficient (C_R) and the area-to-mass ratio (A/m), which both control the size of SRP perturbations affecting the spacecraft

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