C05

大気上層の長期変動を考慮した宇宙開発の持続可能性評価
Evaluation of Sustainable Space Development with Considering Long-term Change in Upper Atmosphere

〇清水貴裕、吉村康広（九州大）、河本聡美、原田隆佑（JAXA 研開部門）、
花田俊也（九州大）
〇SHIMIZU Takahiro, YOSHIMURA Yasuhiro (Kyushu Univ.),
KAWAMOTO Satomi, HARADA Ryusuke (JAXA Research and Development Directorate),
HANADA Toshiya (Kyushu Univ.)

本研究は，熱圏の長期的な密度減少に起因する軌道環境の変化が，今後の宇宙開発に与える影響について評価することを目的としている．近年問題となっている温室効果が，宇宙機が多く運用されている高度 800 km までの熱圏で寒冷化を引き起こし，それによる大気密度の減少が報告されている．大気密度の減少を考慮せずに長期的な軌道環境の予測を行うと，低軌道におけるスペースデブリの数や軌道寿命が過小評価される恐れがある．本研究では，JAXA と九州大学が共同開発・運用している軌道環境推移モデルを用いて，大気密度減少化における長期的な軌道上のスペースデブリ数，スペースデブリの軌道寿命，及び宇宙機やスペースデブリの衝突確率を予測する．また，軌道環境の変化に対応可能となるよう，25 年ルールを満たす高度や必要増速量，能動的デブリ除去の効果を計算し，衛星運用の安全性向上のための方策について提案する．

There is a growing concern about climate change caused by greenhouse gases. Especially, carbon dioxide has significant influences not only on the lower atmosphere but also on the upper atmosphere such as the thermosphere where space objects are orbiting. One of the problems of increasing carbon dioxide is that it reduces the density of the thermosphere, resulting in less atmospheric drag on space objects. This paper evaluates the long- term influence of decreasing the atmospheric drag on the space environment and space activities using an orbital debris evolutionary model. In this study, Jacchia-Roberts 1971 atmospheric model is used to calculate the atmospheric density. In addition, this study makes correction to atmospheric density with considering the long-term density decrease. This paper also reveals the long-term impact of density decrease on space activity by calculating the debris number transition, the extension of debris orbital lifetime, and collision probability with debris. Furthermore, this study shows the change of delta-v and the collision probability with other objects to satisfy the 25-year rule.

C05
大気上層の長期変動を考慮した宇宙開発の持続可能性評価

Evaluation of Sustainable Space Development with Considering Long-term Change in Upper Atmosphere

Kyushu University
◯Shimizu Takahiro, Yoshimura Yasuhiro, Hanada Toshiya
Japan Aerospace Exploration Agency (JAXA)
Harada Ryusuke, Kawamoto Satomi

11/30/2022
The 10th Space Debris Workshop

九州大学

C05 Evaluation of Sustainable Space Development with Considering Long-term Change in Upper Atmosphere

1. Background 2. Method 3. Result 4. Conclusion 1

The Changes in Low-Earth Orbit ①

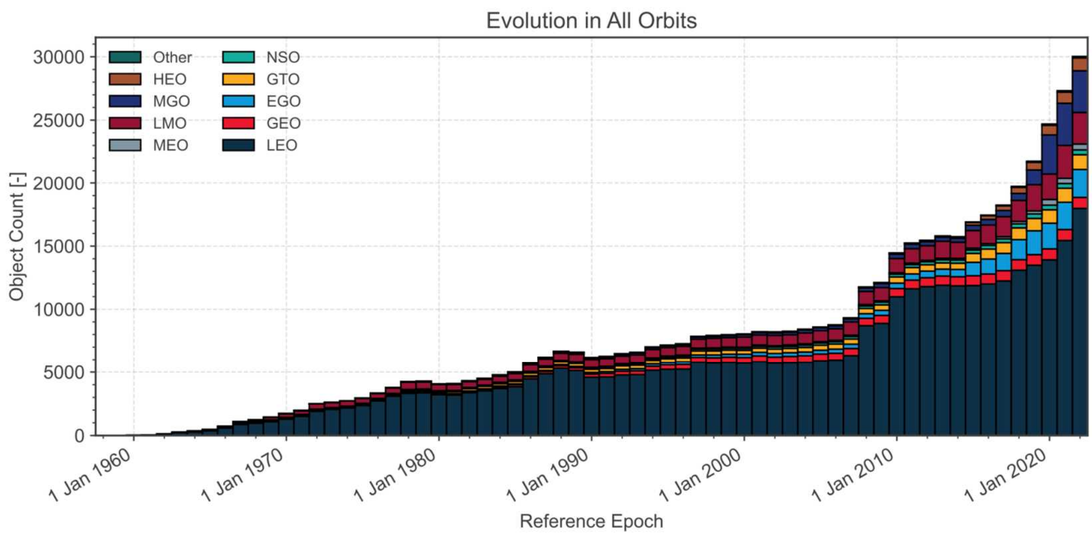


Figure 1. Evolution of number of objects in geocentric orbit[ESA, 1]

- The number of objects in Low-Earth orbit(LEO) has increased significantly since 2010 because of constellation and debris.

The Changes in Low-Earth Orbit ②

- The increase of CO_2 and cooling in the thermosphere
  - Thermosphere have been **cooling** due to the "greenhouse effect".
  - Thermospheric density decreases because of cooling.
  - ✓ The upper atmospheric data show the **long-term decrease of density**.[2–4]

→ **Atmospheric drag is reduced in the altitude where many satellite are present.**

- The impact of reduced atmospheric drag is…
  - Extension of the objects' lifetime in LEO
  - It is advantage to satellite manager in terms of fuel savings, but satellite at the end of operation may be less likely to deorbit.

The Motivation of this study

- There are little examples of cooling in the thermosphere **applied to the engineering field**.

The Objective of this study

- Assessing the impact of density reduction associated with thermospheric cooling **on the orbital environment**

Study flow

- Apply density decrease to **atmospheric models**
- Analyze by **NEODEEM** and comparison with the previous result
- Verify Post-Mission Disposal(PMD) effects
- Analyze **orbital lifetime and 25-year rule**

The Calculation of Long-Term Change in Thermosphere

◆ Thermospheric density trend is -2 to -5 %/decade

- Several studies using orbital data since the 1960s suggest this trend
- This trend will keep because the CO_2 concentration keep increasing

□ Calculation Method

- ρ is the atmospheric density
- ν is the trend of density

$$d\rho = \nu\rho dt \quad \Rightarrow \quad \rho_c = \rho_0 e^{\nu(t-t_0)}$$

ρ_c : Atmospheric density **after** correction

ρ_0 : Atmospheric density **before** correction

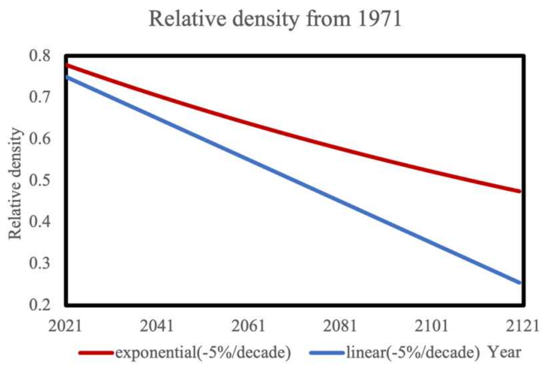


Figure 2. Relative density after correction

Orbital Environment Simulation ①

□ Condition in NEODEEM

- This study uses the density calculated by the Jacchia-Roberts 1971 atmospheric model and corrected by above-mentioned formula.
- PMD rate is 0, 0.3, 0.6, and 0.9
- PMD is trying to drop to an altitude that would fall in 25 years, assuming JR 1971 (uncorrected) is right.

Table 1. Simulation condition

Parameters	Conditions
Initial Population	Objects in 2021 (≥10 cm)
Span	2021 – 2120
MC Runs	150
Atmospheric Model	Jacchia-Roberts 1971
Perturbations	Air drag, SRP, Third body, Geopotential
Space activity	New launch PMD, Collision
Density trend ν	0, -2, -5 %/decade

Orbital Environment Simulation ②

☐ Evaluation items

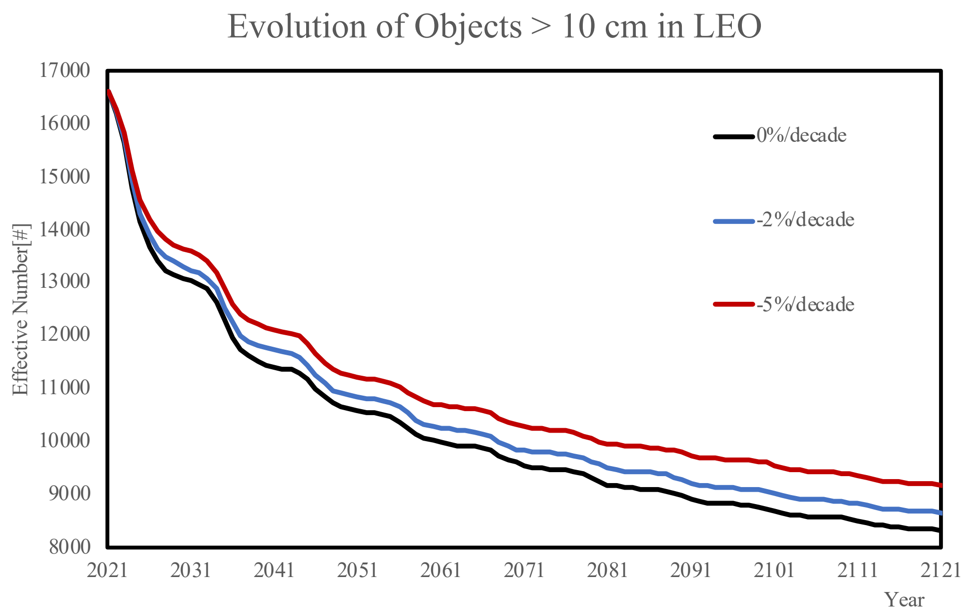
- **Population of objects more than 10 cm in LEO**
- Spatial density as a function by altitude
- Effectiveness of PMD

☐ Analysis and evaluation based on orbit propagation results

- **Lifetime** of initial objects
- Relationship between **lifetime**, **area-to-mass ratio** and **initial altitude**

Evolution of Initial Population

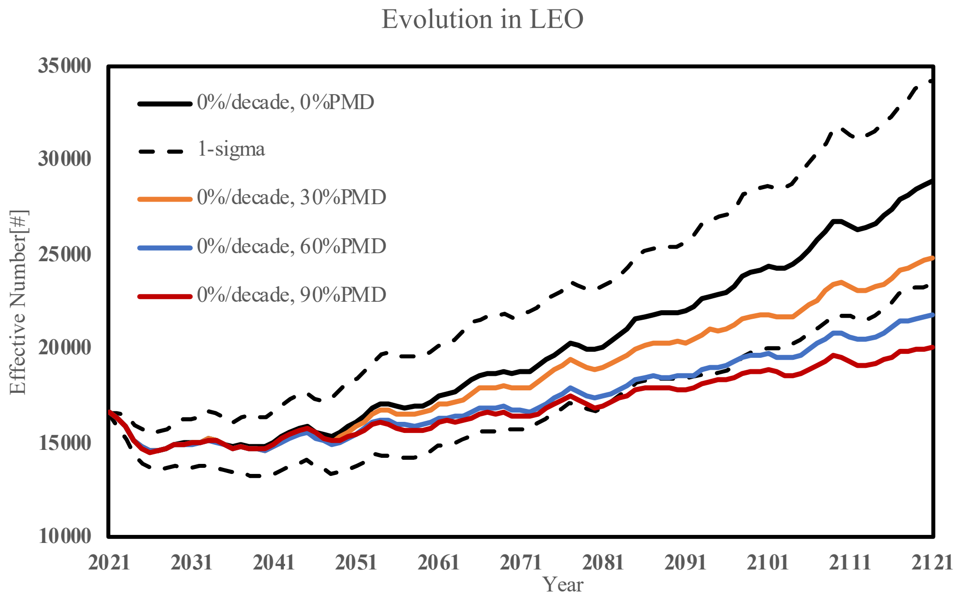
No Collisions, PMD, and New Launches



➢ Greater density decreasing trends lead to more objects remaining.

Evolution in LEO ①

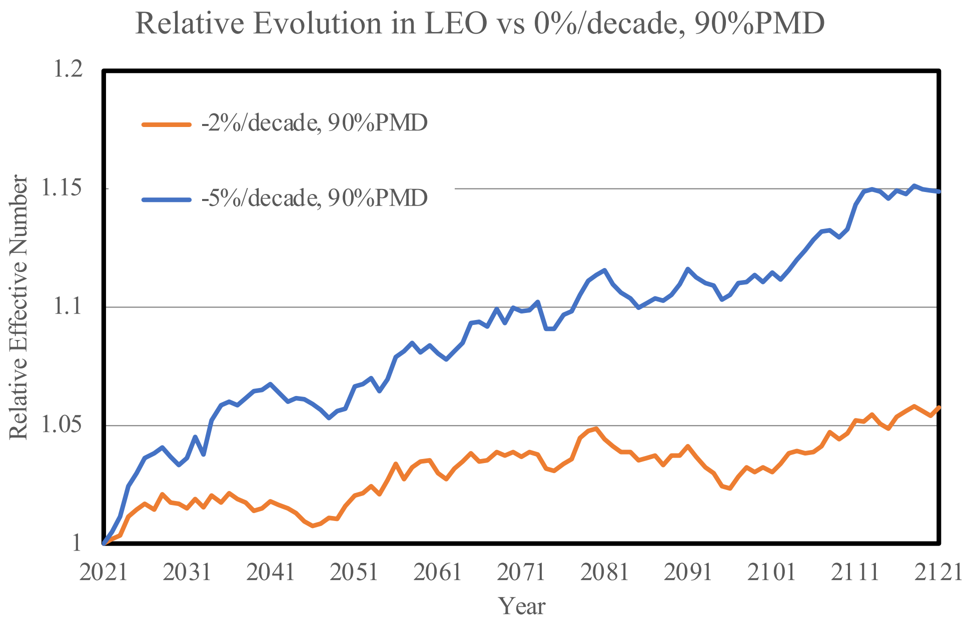
With Collisions and New Launches



- 90% PMD(this is the obligation to make effort regarding PMD success rates set by IADC Space Mitigation Guidelines[5]) is effective to lessen the objects in LEO.

Evolution in LEO ②

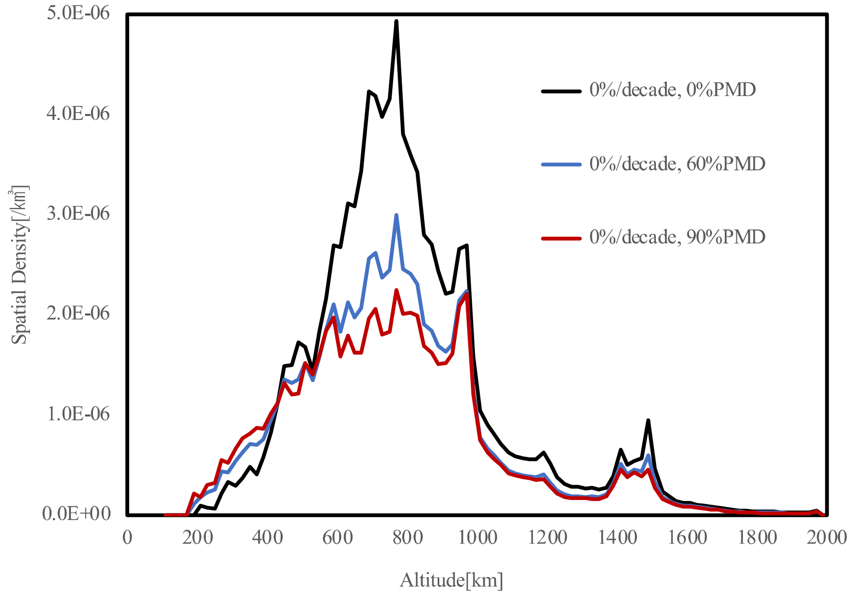
With Collisions and New Launches



- <u>Density decrease in the thermosphere can diminish the effectiveness of PMD.</u>

Spatial Density by Altitude ①

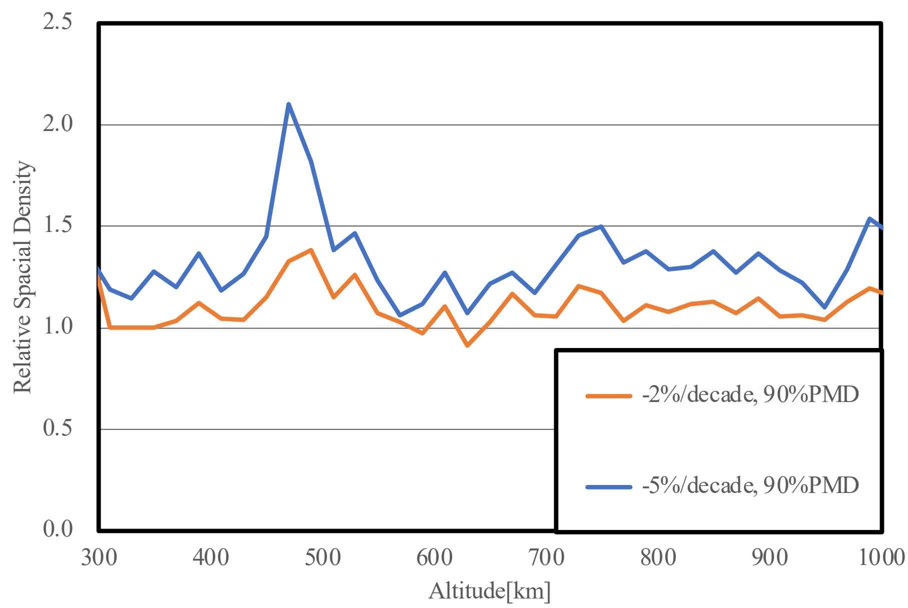
With Collisions and New Launches



➢ Spatial density <u>at altitudes above 600 km</u> decreases due to PMD

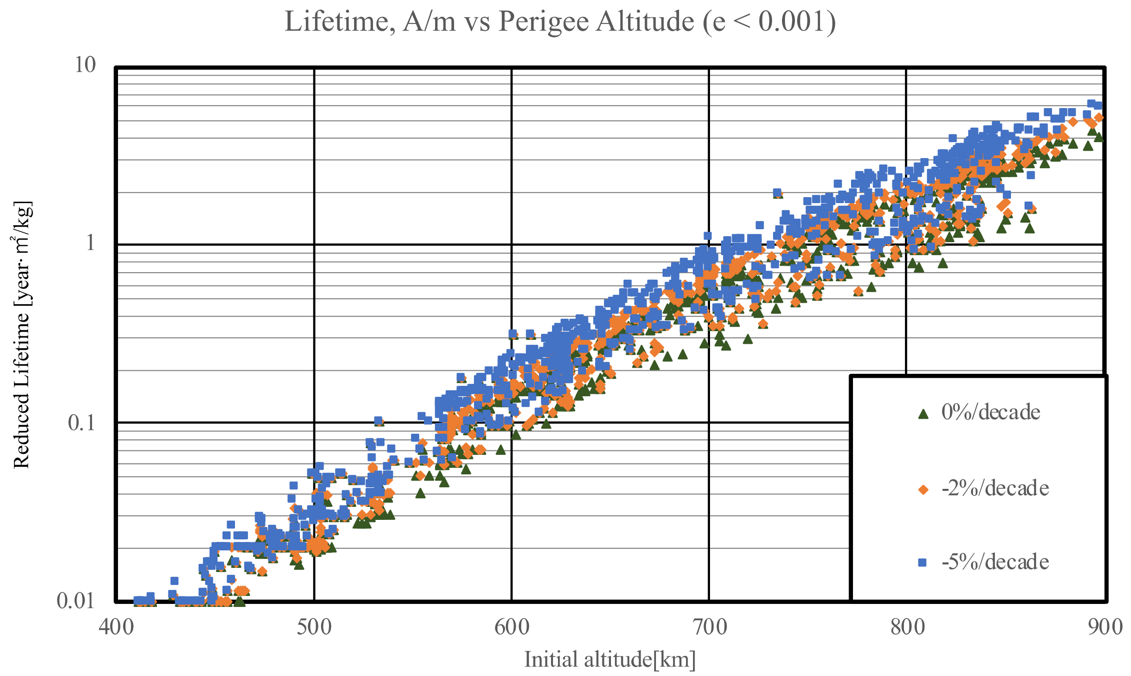
Spatial Density by Altitude ②

With Collisions and New Launches



➢ <u>Density decrease in the thermosphere can diminish the effectiveness of PMD</u>.

Analysis of Lifetime and 25-year rule

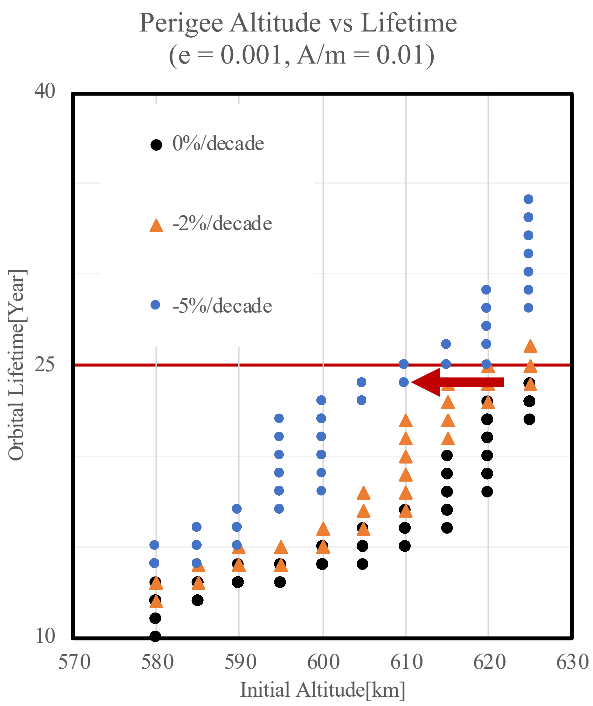


- The vertical axis is the **product of A/m and lifetime**

Analysis of Lifetime and 25-year rule

- The right figure is the propagation result of objects, which have the A/m = 0.01, e = 0.001, and inclination angles every 5 degrees, from 0 to 100 degrees.
- Spacecraft must lose more altitude to meet the 25-year rule.

→ **PMD Cost Rise**



Summary

☐ Impact of density decrease on LEO

- In LEO, the stronger density decrease trend, the greater debris increase.
- Especially, **spatial density at the lower altitude** increases significantly.

☐ Effectiveness of PMD

- 90% PMD is effective in the debris reduction at altitude above 600 km
- Density decrease in the thermosphere can diminish the effectiveness of PMD.

☐ Lifetime of satellites and 25-year rule compliance

- The stronger density decrease trend, the lower initial altitude must be.
- To comply with 25-year rule, the perigee altitude must be reduced more.

Reference

[1] ESA Space Debris Office, "ESA's Annual Space Environment Report," 2022.

[2] Emmert, J. T. (2015), Altitude and solar activity dependence of 1967–2005 thermospheric density trends derived from orbital drag, J. Geophys. Res. Space Physics, 120, 2940–2950, doi:10.1002/ 2015JA021047.

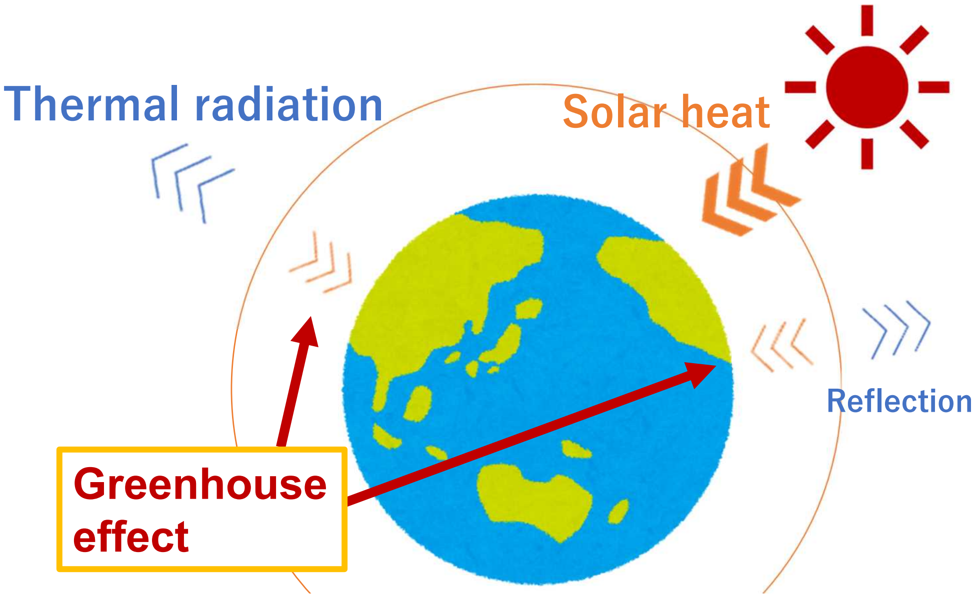
[3] Emmert, J. T., J. M. Picone, J. L Lean, and S. H. Knowles (2004), Global change in the thermosphere: Compelling evidence of a secular decrease in density, J. Geophys. Res., 109, A02301, doi:10.1029/2003JA010176.

[4] Brown, M. K., Lewis, H. G., Kavanagh, A. J., & Cnossen, I. (2021). Future decreases in thermospheric neutral density in low Earth orbit due to carbon dioxide emissions. *Journal of Geophysical Research*: *Atmospheres*, *126*, e2021JD034589.

[5]https://orbitaldebris.jsc.nasa.gov/library/iadc-space-debris-guidelines-revision-2.pdf

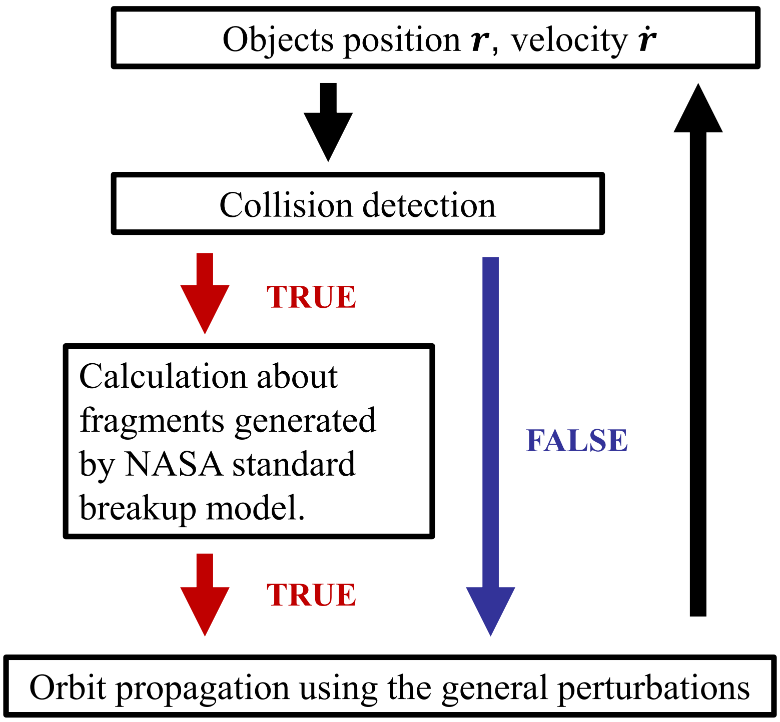
The diagram of cooling in the thermosphere

- Some of the heat returns to the surface due to the nature of CO_2
  - In the thermosphere, the supply of heat is reduced, and cooling occurs.



Orbital Environment Simulation

- **NEODEEM**
  - NEODEEM can predict the orbital environment with the assumption of new launch, collisions, and more.
  - The diagram on the right shows the flow of an orbit environment simulation using NEODEEM.



The summary of density trends calculated by orbital data[2]

	Study 1[6]	Study 2[3]	Study 3[7]	Study 4[2]
Density trends [%/decade]	-4.9 ± 1.3	-2.8 ± 1.0	-1.7 ± 0.2	-2.0 ± 0.5

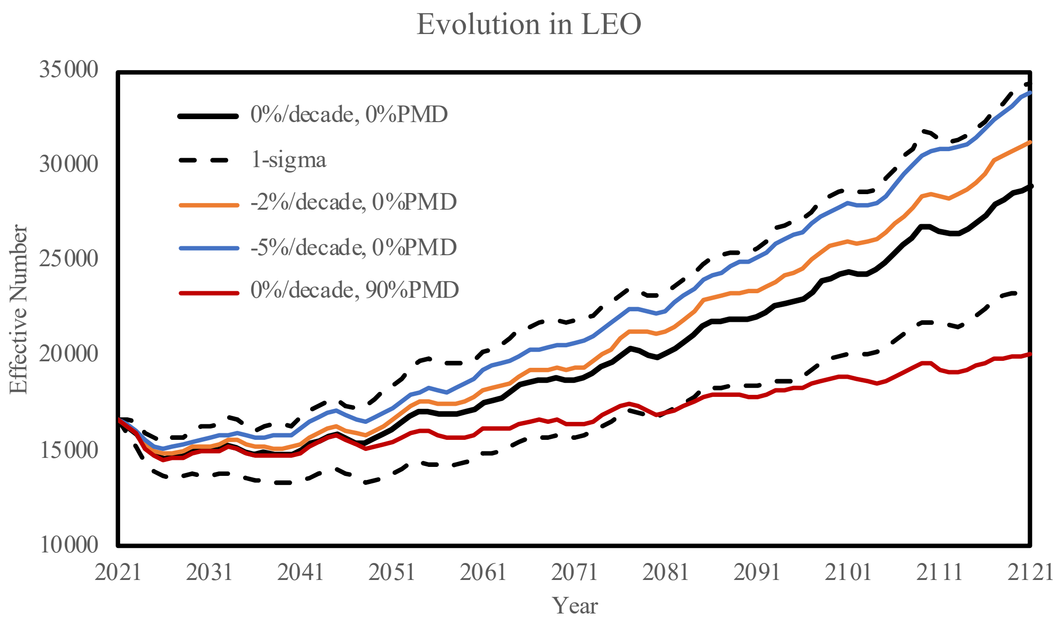
◆ The thermospheric density trend is -2 to -5 %/decade

[6] Keating, G. M., R. H. Tolson, and M. S. Bradford (2000), Evidence of long term global decline in the Earth's thermospheric densities apparently related to anthropogenic effects, Geophys. Res. Lett., 27, 1523–1526, doi:10.1029/2000GL003771.

[7] Marcos, F. A., J. O. Wise, M. J. Kendra, N. J. Grossbard, and B. R. Bowman (2005), Detection of a long-term decrease in thermospheric neutral density, Geophys. Res. Lett., 32, L04103, doi:10.1029/2004GL021269.

Evolution in LEO

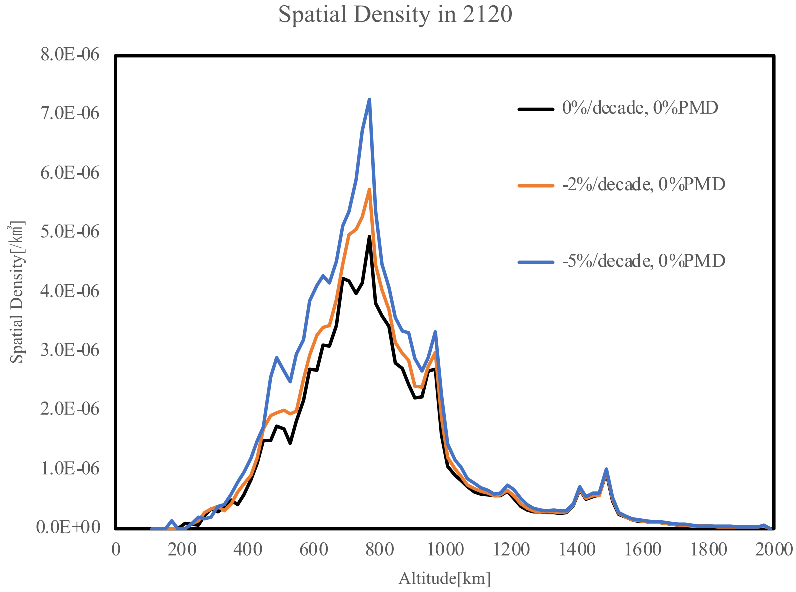
With Collisions and New Launches



➢ The number of objects is greater by the stronger density decrease trend.

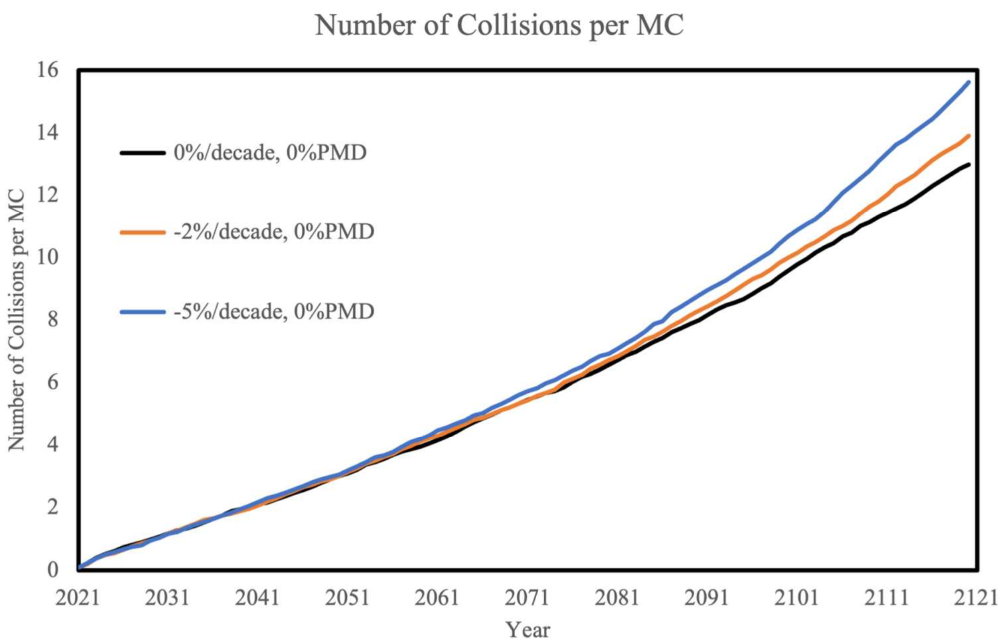
Spatial Density by Altitude

With Collisions and New Launches



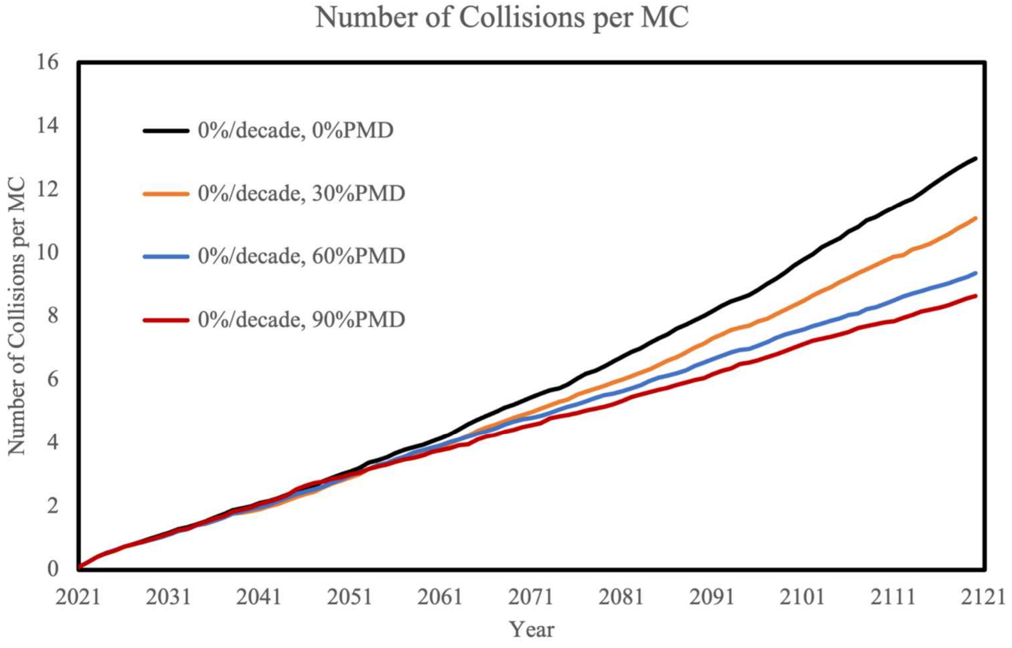
➢ Spatial density <u>up to 1000 km altitude</u> range increases because of density decrease

Number of Collisions up to 1,000 km ①



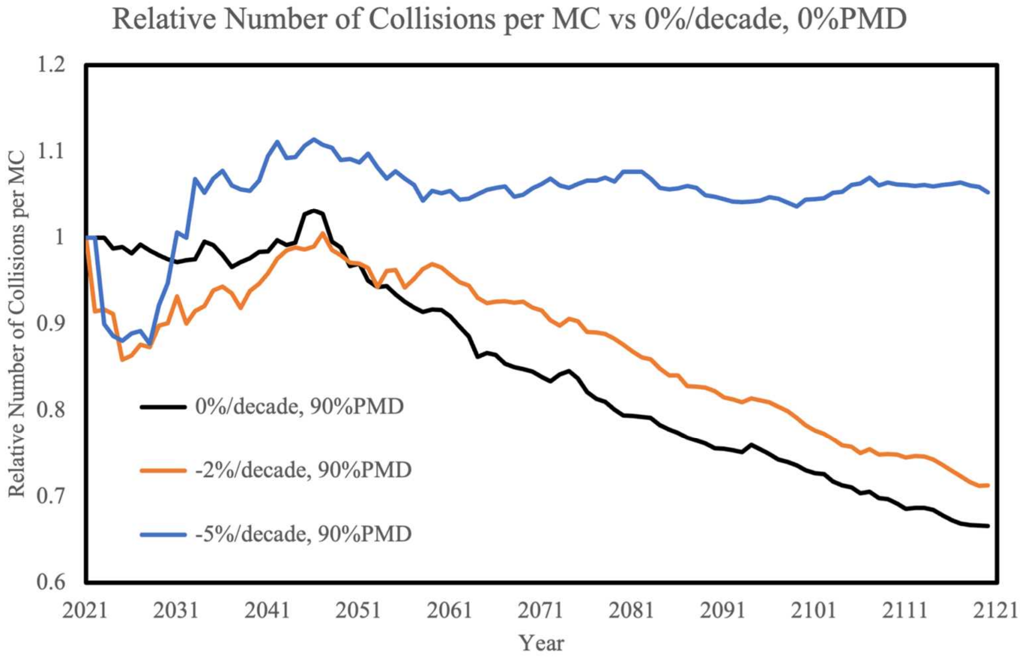
➢ The stronger density decrease trend can cause the long-term increase of breakups

Number of Collisions up to 1,000 km ②



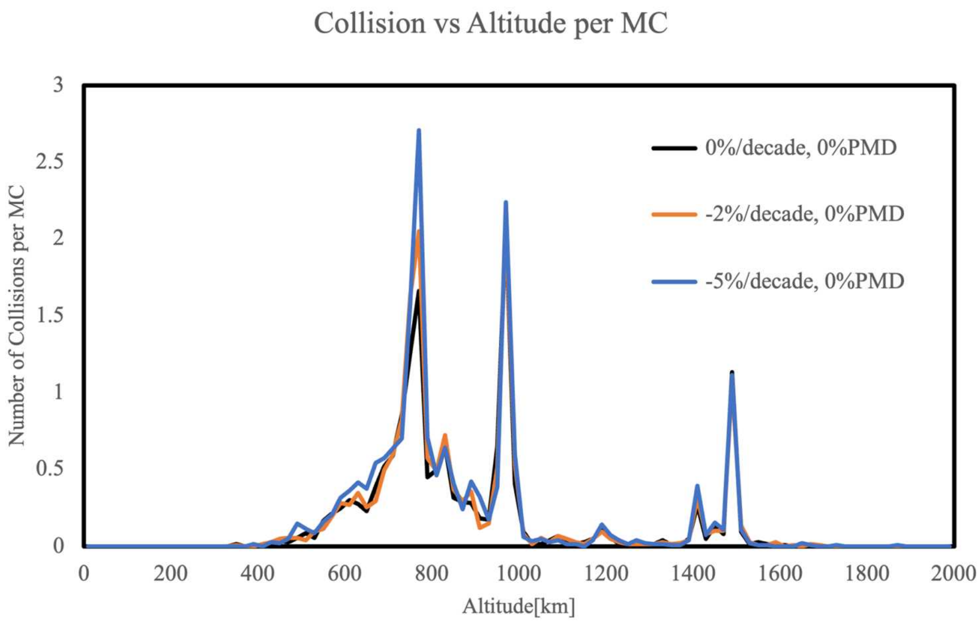
- ➢ PMD is effective in the reduction of long-term breakups

Number of Collisions up to 1,000 km ③



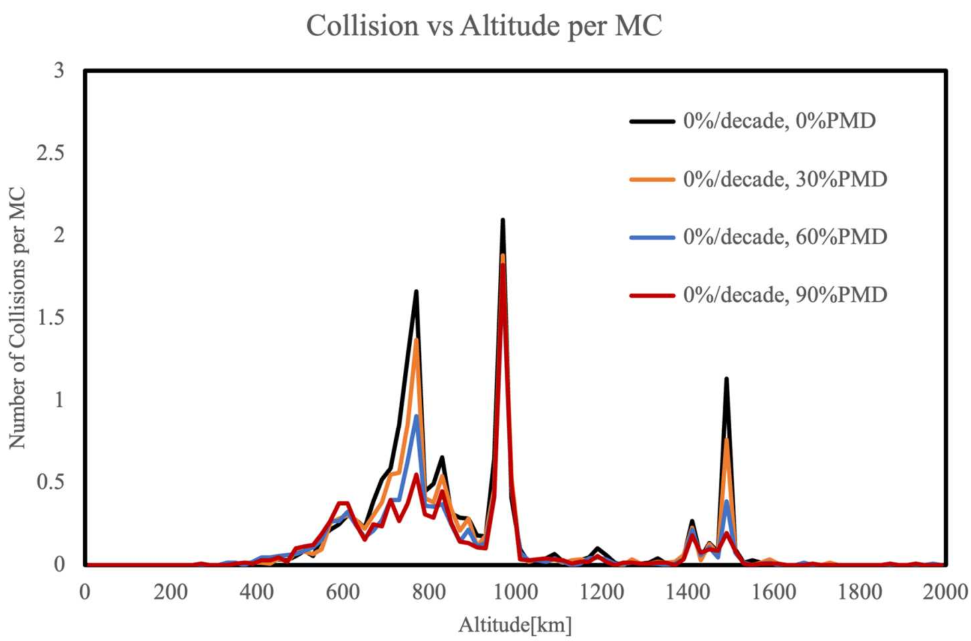
- ➢ The strong density decrease trend leads to more breakups despite high PMD rate.

Number of Collisions by Altitude ①



➢ The greater density decrease trend leads to the increase of collisions at the low altitude

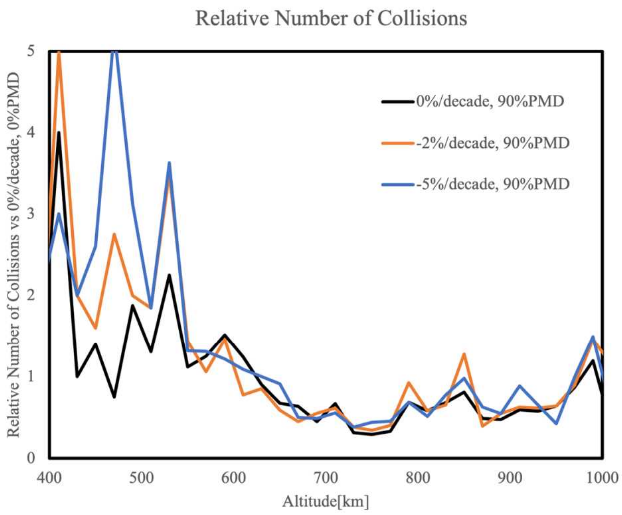
Number of Collisions by Altitude ②



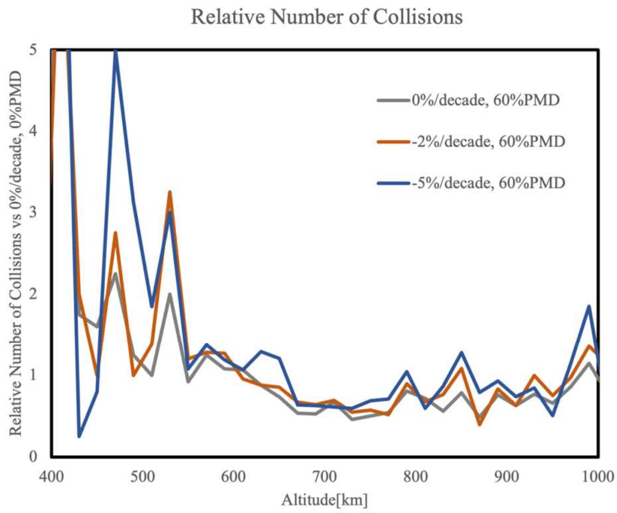
➢ The higher PMD rate reduces the collisions at altitude around 700 km

Number of Collisions by Altitude ③

PMD 90%

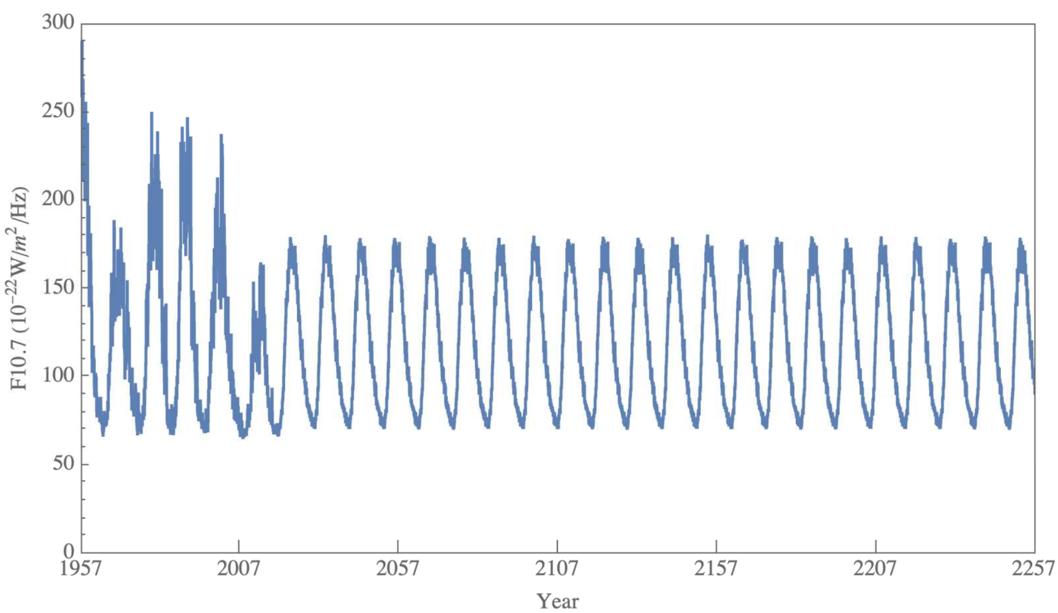


PMD 60%

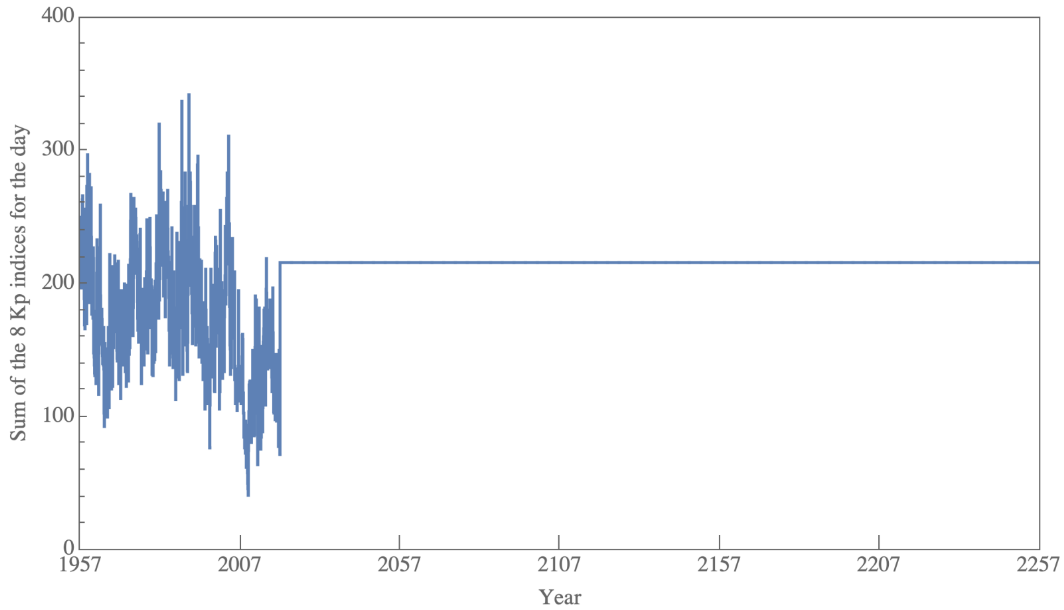


- Higher PMD rate prevents collisions occurring, especially around 700 km.
- However, lower PMD rate (60 %) do not work enough to decrease collisions.

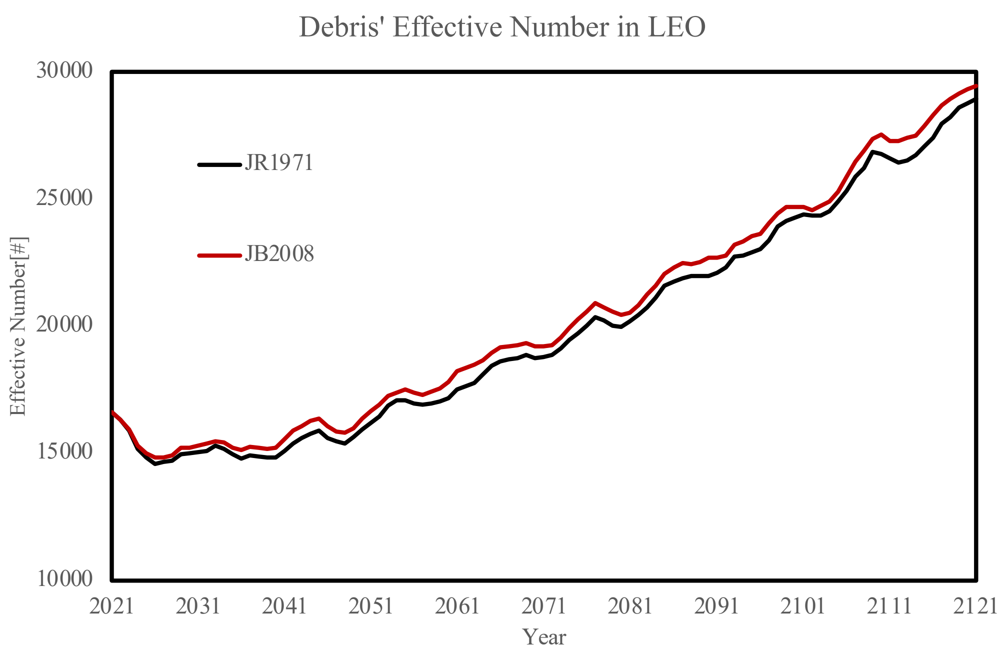
Space Data ① (Solar Cycle)



Space Data ② (Kp index)



Evolution in LEO



➢ The difference between atmospheric models (Jacchia-Roberts 1971 vs Jacchia-Bowman 2008)