C06

スペースデブリインデックスの活用及び定式化に関する検討

A Study of Utilization and Formulation of Space Debris Index

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JAXA 研開部門デブリモデリングチームでのペースデブリインデックス検討状況について紹介する。デブリインデックスは宇宙機やミッションの環境負荷などを示す指標として関心を集め、国際的に議論や研究がなされている。モデリングチームではデブリインデックスの定義及び用途を整理し、宇宙機が環境に与える影響のうち、どのような特徴を評価すべきかまとめた。またこの結果から考慮すべき特徴を絞り込み、インデックス式の検討を行っている。インデックス式は軌道環境に対する短期的影響及び長期的影響の観点から、それぞれ定式化を検討した。またインデックスが示す値が宇宙機が軌道環境に与える影響を正しく表せているか確認するための環境評価基準についても検討行っている。本発表では検討したインデックス式に基づき軌道上の物体を評価し、上位 100 位の物体が軌道環境に与える影響についての考察を紹介する。

This presentation describes the status of the Space Debris Index study by the debris modeling team of JAXA's Research and Development Directorate. The debris index which indicates the environmental impact of spacecraft or missions has been the subject of international discussion and research. The modeling team organized the definitions and applications of the debris index, and summarized which characteristics of the environmental impact of spacecraft should be evaluated. From this result, we narrowed down the features to be considered, and are working on an index formulation. The index is formulated in terms of short-term and long-term effects on the orbital environment. The environmental evaluation criteria are also discussed to confirm that the index values correctly represent the impact of spacecraft on the orbital environment. This presentation evaluates orbital objects based on the index formulas being considered by our modeling team and present a discussion of the impact of the top 100 objects on the orbital environment.

The 10th Space Debris Workshop 2022 11/28 mon → 30 wed

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Space Debris Index

- **Space Debris Index**
- The value associated to a spacecraft(S/C) or mission that assess the impact to orbital environment.
- Several studies* and discussions have been conducted to formulate index (especially in Europe).
- Formulations, evaluation methods and criteria have not been established yet.

- **Possible Uses Cases**

1. Adjustment of the requirement of mitigation guidelines according to the environmental impact
2. Selection of ADR targets
3. Rating of mission and S/C

***Studies of Space debris index**
1. F. Letizia et al., Assessment of breakup severity on operational satellites, Advances in Space Research 58 (2016) 1255–1274
2. A. Rossi et al., The criticality of spacecraft index, Advances in Space Research 56 (2015) 449–460
3. F. Letizia et al., Assessment of environmental capacity thresholds through long-term simulations, IAC-21-A6.4.1, 72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, 25-29 October 2021.
4. Darren McKnight et al, Identifying the 50 statistically-most-concerning derelict objects in LEO, Acta Astronautica 181 (2021) 282–291
5. S. KAWAMOTO et al, Considerations on the Lists of the Top 50 Debris Removal Targets, IAC-21-A6.2.5, 72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, 25-29 October 2021.

etc..

Space Debris Index

➢ **Possible component of Index**

Parameter	Contribution to debris environment
Operational, transfer, and disposal orbit	Collision probability, number of collision avoidance, orbital lifetime ,,
Effective area and mass of spacecraft	Collision probability, the number of new fragments,,
Failure probability due to explosion or collision	Fragmentation events, decrease of PMD compliance rate,,
PMD capability	Orbital lifetime, Collision probability,,
Collision avoidance capability Disposal strategy	Collision probability,,

Two Steps to Establish Index

Step 1. Definition of Criteria
- Criteria for judging how “good” or “bad”
- Debris evolutionary model or other sophisticated calculations are required

Examples:

< for short-term effects >
- Number of conjunctions for nearby operational satellites by fragments
- Collision rate of lethal non-trackable debris

< for long-term effects>
- Effective number of objects in 200 years
- Cumulative collision rate until reentry
- Expected number of debris to be generated
- Decrease in the number of debris when removed
- Increasing trend when constellation is injected

Pros: Meaningful values allow for comparative evaluation of how good or bad the object is and some threshold can be set.
Cons: Cannot evaluate without evolutionary model

Step 2. Formulation of the Space Debris Index

How to formulate the index:
1) Consider index that can be evaluated using evolutionary model (e.g. $eFRG \times Life$)

2) Assess whether the index is appropriate using the criteria defined in Step 1. (cf. p.15)

3) Modify the index formulas that can be evaluated without using environment evolutionary model (e.g. $Pc \times M \times Life$)

4) Check whether formulas 1) and 3) are essentially the same evaluation by using the evaluation criteria in Step 1.(cf. p.16, 17)

Pros: Easily evaluated by anyone without using evolutionary model
Cons: Threshold cannot be determined from this index alone

Concept of Index Formulation

➢ **Short-term effect:**

Short-term safety features such as collision avoidance frequency and collision probability with non-trackable debris.

Example of short-term effect index:
- eFRG → Expected number of fragments (JAXA's index in top 50 selection[Ref. 1])
- eFRG x Φ → Expected number of fragments x Spatial Density (Altitude only)
- NOC → Number of conjunctions

➢ **Long-term effect**:

Long-term environmental stability due to accumulation of fragments.

e: Euler's number = 2.718281...
a = 14.18
b = 0.1831
c = -42.94

Example of long-term effect index:
- eFRG x Life_AM0.012 → The orbital lifetime is calculated with altitude, assuming that A/M for all objects is 0.012[Ref.2].
  (*Life* [yr] =e^(a x *Altitude*^b + c) When the *Altitude* >= 1000 km, its altitude is assumed as 1000 km (upper limit))
- eFRG x Life → The orbital life is calculated based on altitude, taking into account the A/M of each object.
  (*Life* [yr] =e^(a x *Altitude*^b + c) x 0.012/(A/M) When the *Altitude* >= 1000 km, its altitude is assumed as 1000 km (upper limit))
- eFRG x Life_MAX1000yr → The orbital life is calculated based on altitude, taking into account the A/M of each object.
  (*Life* [yr] =e^(a x *Altitude*^b + c) x 0.012/(A/M) When the *Life* >= 1000 yr, its lifetime is assumed as 1000 yr (upper limit))

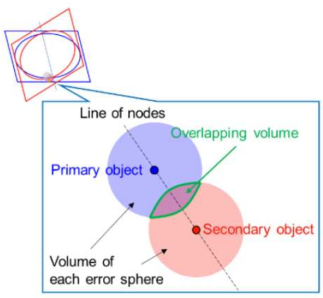
It is also necessary to define **how to evaluate "good" or "bad"** in the short-term or long-term, respectively.

Ref. 1 Darren McKnight et al, Identifying the 50 statistically-most-concerning derelict objects in LEO, Acta Astronautica 181 (2021) 282–291
Ref. 2 A Rossi et al, Criticality of Spacecraft Index, Advances in Space Research 56 (2015) 449 460

NEODEEM: Debris Evolutionary Model

NEODEEM (Near-Earth Orbital Debris Environment Evolutionary Model)

- developed jointly by Kyushu University and JAXA.
- Calculates the trajectories of all objects larger than 10 cm in 5 day-steps by considering such orbital perturbations as air drag and geo potential.
- Simulates a collision between each object using a random number when each error sphere overlaps.
- Generates fragments (≥ 10cm) according to the NASA standard breakup model.
- Outputs the average of 100 Monte Carlo simulation runs.



Collision probability

$$C_{12}=\frac{p_2 \Delta V}{V}\frac{p_1}{V}A_{12}U_{12}$$

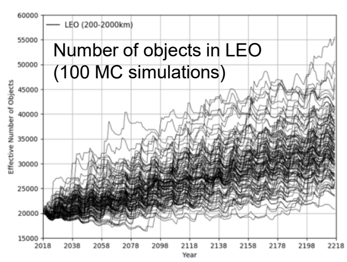
Number of fragments by collision

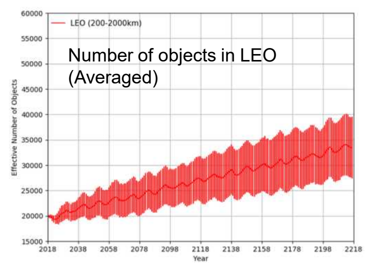
Catastrophic

$$N(L_c)=0.1(M_1+M_2)^{0.75}L_c^{-1.71}$$

Non-catastrophic

$$N(L_c)=0.1(M_2 U_{12}^2)^{0.75}L_c^{-1.71}$$





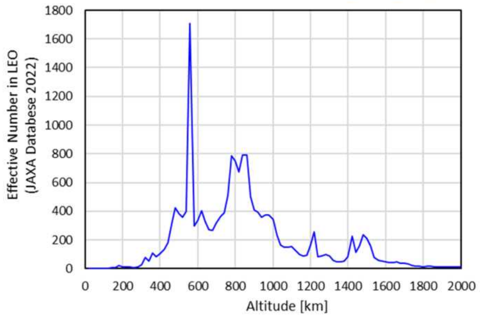
Initial Population & Background Environment

JAXA database as of 2022:

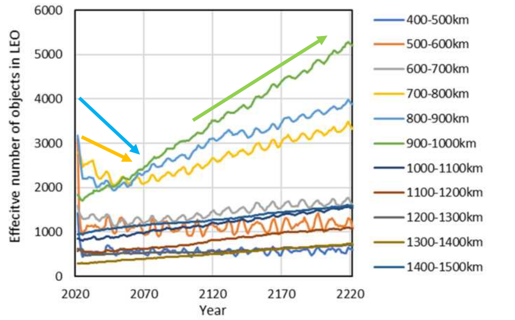
- Two-Line Elements (TLE) obtained from Space Track
- Optical observations using JAXA telescopes
- Breakup models

Prediction of Background Environment

- Assumptions
  - 90 % of PMD success rate, accidental collision, and a repeat of recent eight-year launches
  - No explosion
- Result
  - Total number of objects will increase, especially at altitudes **900-1000 km**
  - Number of objects and the collision probabilities in the altitude bands of **700**–**800** km were high
    -> Decay shortly due to atmospheric drag but return to increase.



Background objects distribution as of 2022



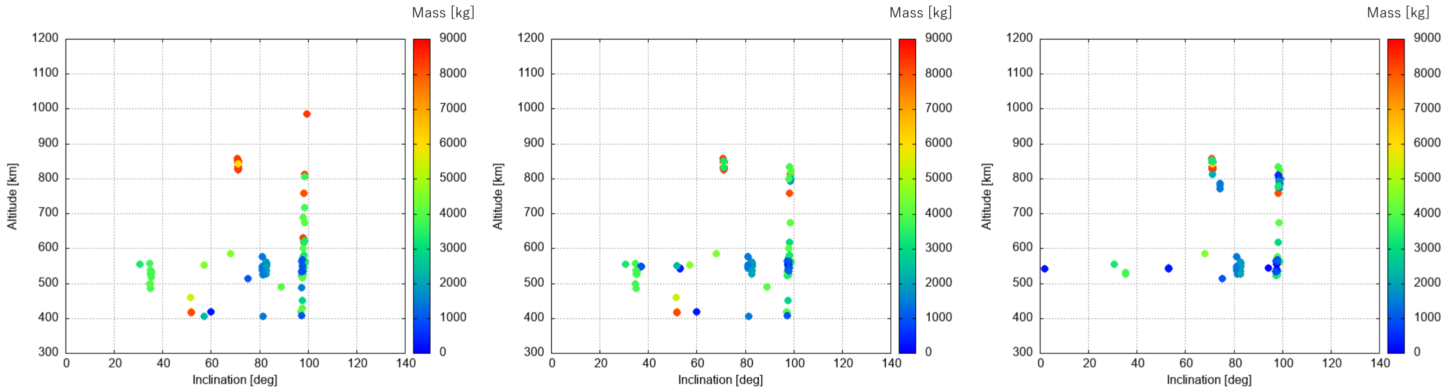
Future population in LEO from 2022 to 2222

Comparison of Short-term Index

<Numerical Simulation>

Three indexes (eFRG, eFRGxΦ, NOC) that assess **Short-term** effects are considered.

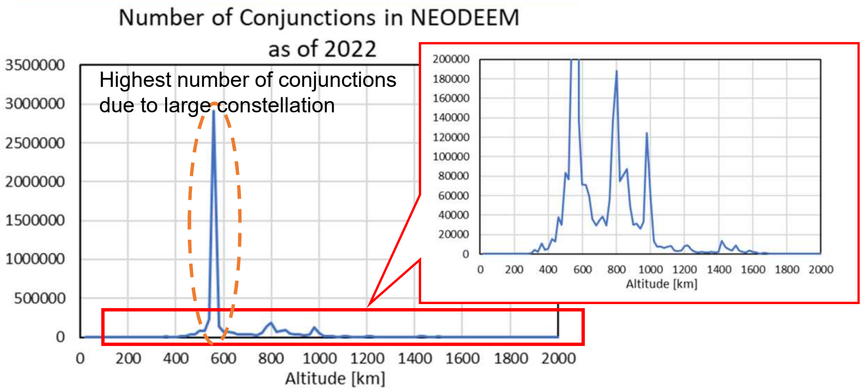
Top 100 objects are defined from JAXA_Database_2022, and assessed the number of conjunctions with these objects for 10 years



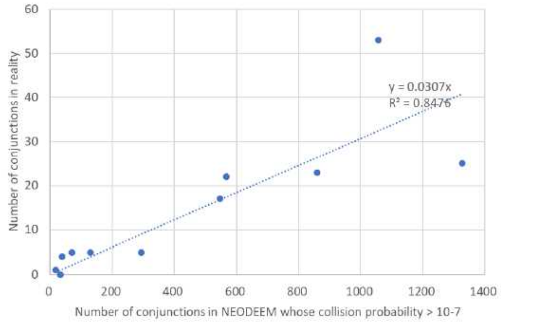
eFRG **eFRG xΦ** **NOC**

Orbital distribution of top 100 objects selected from JAXA_Database_2022 by short-term index

Number of Conjunctions in NEODEEM



Number of Conjunctions in NEODEEM as of 2022

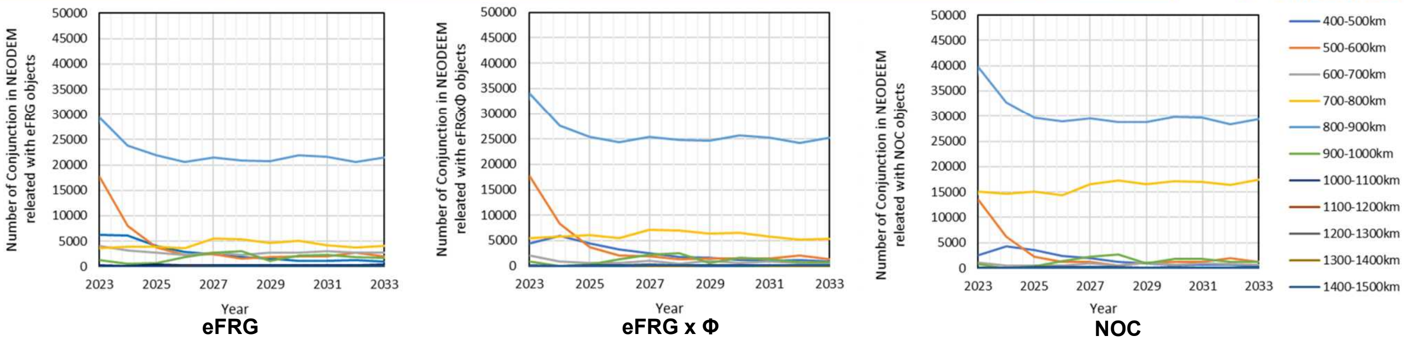


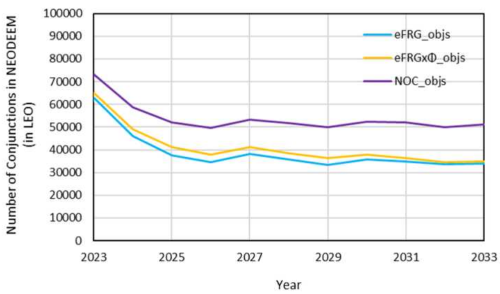
Correlation between the number of conjunctions in NEODEEM and the actual number of conjunctions for several JAXA satellites (Ref, S. KAWAMOTO et al, IAC-21-A6.2.5, 72nd IAC, Dubai)

・NEODEEM can only predict the average number of conjunctions and collisions.

・However, there is a sufficient correlation between the number of conjunctions in NEODEEM for several JAXA satellites and the number of actual times necessary to consider collision avoidance maneuvers.

Comparison of Short-term Index: Number of Conjunction





Parameter	Value
Initial population	JAXA database 2022
Future launch	past 8 years launch cycle
Background objects conditions	90 % of PMF success rate, accidental collision, and no explosion

・NOC shows the largest effects in a short-term.
・eFRG and eFRGxΦ have mostly same contribution.

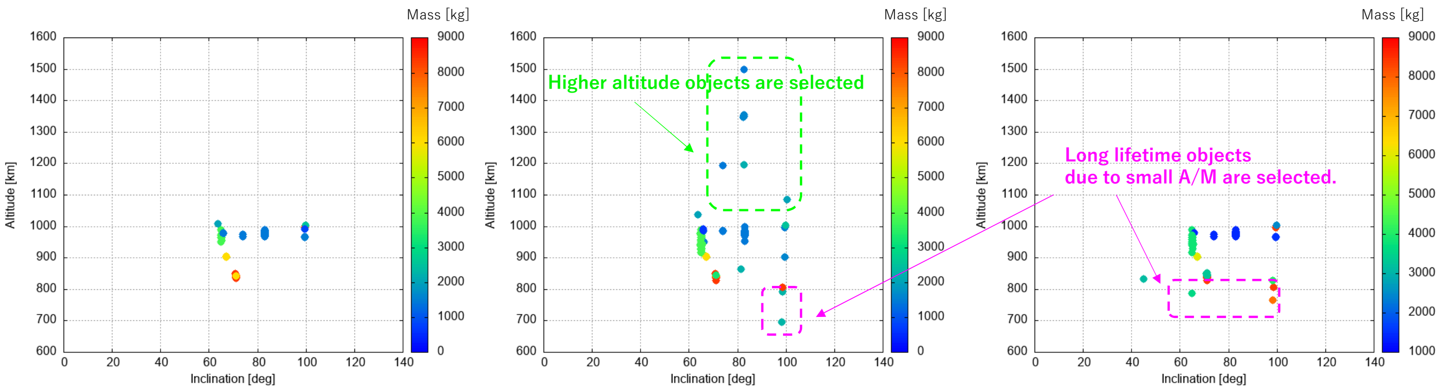
Number of conjunctions with selected objects for 10 years in each altitude band (upper) and in LEO (bottom)

Comparison of Long-term Index

<Numerical Simulation>

Three indexes (eFRG x Life_AM0.012, eFRG x Life, eFRG x Life_MAX1000yr) that assess **Long-term** effects are considered.

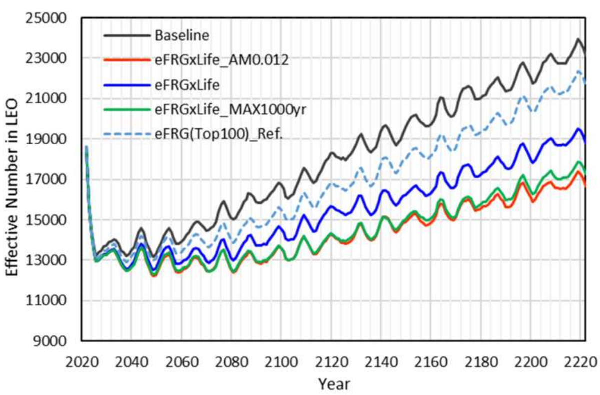
Top 100 objects are defined from JAXA_Database_2022, and removed at the beginning of 2022.



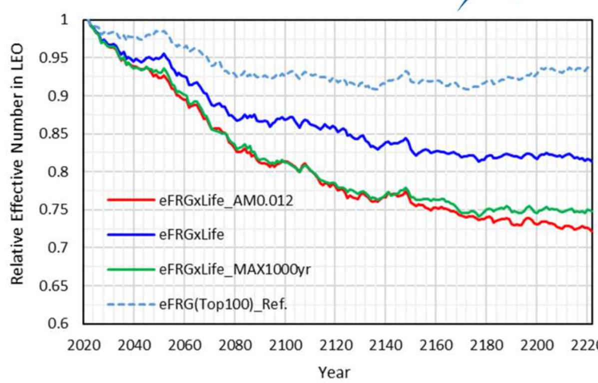
eFRG x Life_AM0.012 — eFRG x Life — eFRG x Life_MAX1000yr

Orbital distribution of top 100 objects selected from JAXA_Database_2022 by long-term index

Comparison of Long-term Index: Effective Number (in LEO)



Predictions of the effective number of debris objects for 200 years with and without ADR of each top 100 objects (average of 300 MC runs).

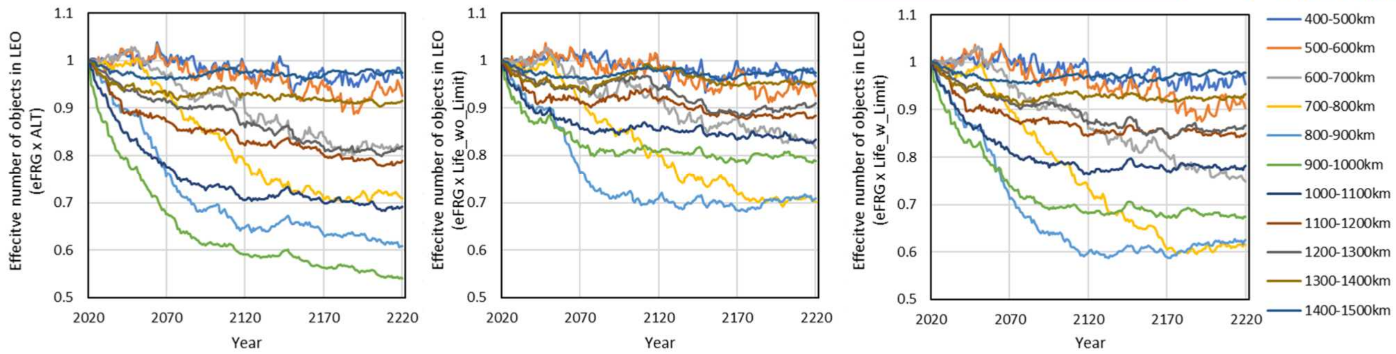


Relative effective number of debris objects for 10 years with ADR of each top 100 objects (average of 300 MC runs).

Cumulative decreasing rate [%]	for 200 yrs
eFRG x Life_AM0.012	-32
eFRG x Life	-21
eFRG x Life_MAX1000yr	-29

- eFRG x Life shows the lowest improvement effects in a long-term.
- eFRGxLife_AM0.012 and eFRGxLife_MAX1000yr have mostly same effectiveness (in 3% difference).

Comparison of Long-term Index: Effective Number (in Each Altitude Band)



eFRG xLife_AM0.012 **eFRG x Life** **eFRG x Life_MAX1000yr**

Relative effective number of objects for 200 years with ADR of each top 100 objects in each altitude band

- eFRGxLife selects objects higher than 1,000km in altitude. However, the number of objects in orbits over 1,000km is not so much and the increment of population is smaller than lower altitude. -> Less effectiveness
- eFRGxLife_AM0.012 mainly selects objects in altitude of 900-1000 km, and that makes the best effectiveness. However, the difference between eFRGxLife_AM0.012 and eFRG x Life_MAX1000yr is quite small.
- eFRG x Life_MAX1000yr can select long lifetime objects even though its altitude are not so high.

Conclusion

1. The definition and applications of the debris index are sorted out.

- Adjustment of the requirement of mitigation guidelines according to the environmental impact
- Selection of ADR targets
- Rating of mission and S/C

2. Two steps to establish index are suggested

- Definition of Criteria
- Formulation of the Space Debris Index

3. The effects of short / long–term effects are simulated

- Short-term index: Number of conjunctions with collision probability larger than 1e-07
- Long-term index: eFRG x Life_MAX1000yr

Backup

Space Debris Index

Index: The value associated to a spacecraft(S/C) or mission that assess the impact to orbital environment.
＜Possible Use Cases＞

1. Adjustment of the requirement of mitigation guidelines according to the environmental impact

For examples:

- Designers and Operators can choose their mission orbits (altitudes or inclinations) with smaller environmental impact, or limit the number of S/Cs depending on the operating orbit.
- For large constellation, required PMD success rate and the altitude of disposal orbit might be changed depending on the orbit and number of S/Cs.
- The index can evaluate which operation has less impacts, operating 200 S/Cs of 300kg each at 500 km alt. or 600 S/Cs of 100kg each at 450 km alt.

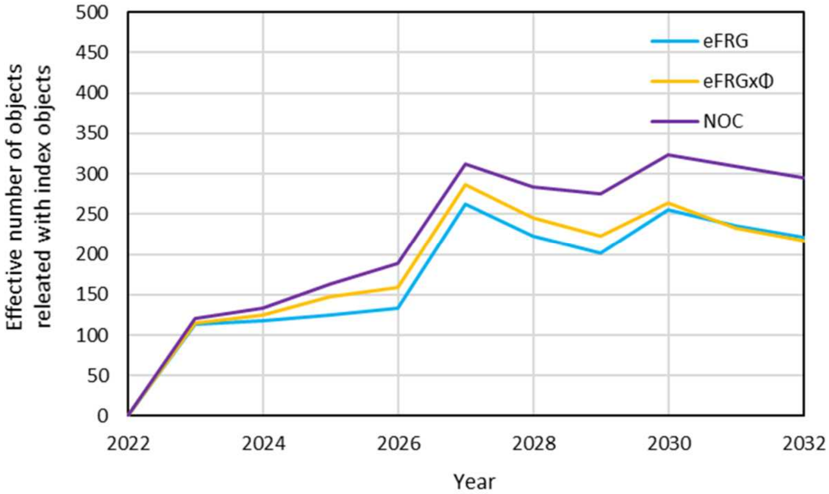
2. Selection of ADR targets

- ADR provider can identify the high-risk objects in order to maximize the ADR effects.
- For example, if the same total index value means same ADR effects, then cost-effectiveness comparison can be made.
  Plan 1) Sat.-A 1pt, Sat.-B 9pt -> Total 10pt
  Plan 2) Sat.-A 1pt, Sat.-C 5pt, Sat.-D 4pt -> Total 10pt
  Plan 3) Sat.-A 1pt, Sat.-D 4pt, Sat.-E 2pt, Sat.-F 2pt -> Total 10pt

3. Rating of mission and S/C

- Evaluators can rate missions by environmental impact, establish insurance premiums, etc.

Comparison of Short-term Index: Effective Number (in LEO)



Predictions of the effective number of debris objects for 10 years with top 100 objects (average of 300 MC runs).

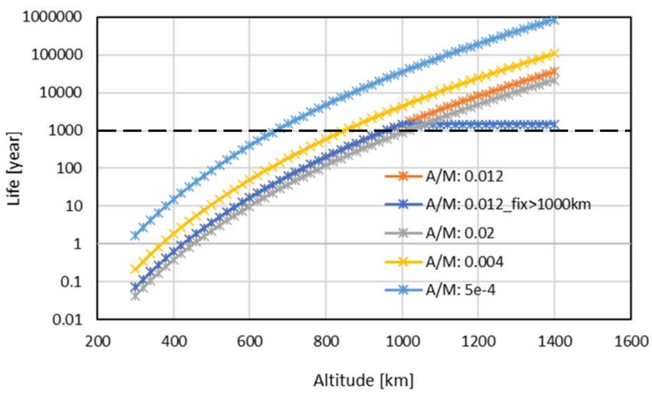
Orbital Lifetime of Objects

Orbital lifetime is calculated based on the below equation that assumed A/M =0.012 in original*.
This study takes into account A/Ms of each object.

$$\log(lifetime) = a * Altitude^{b} + c \ / \ (\text{A/M of each objs})$$

Original equation

a: 14.18
b: 0.1831
c: -42.94
with A/M=0.012

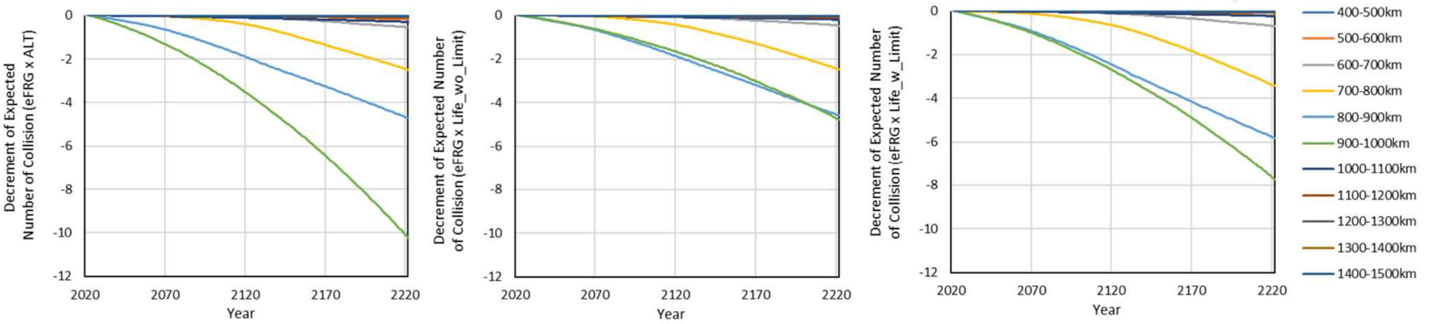


As the altitude of objects becomes higher or the A/M becomes smaller, the orbital lifetime would be long.

➡ Is it more effective to remove objects of which lifetime are greater than 1000 year for Long-term environmental stability?

*A Rossi et al, Cliticality of Spacecraft Index, Advances in Space Research 56 (2015) 449–460

Comparison of Short-term Index: Expected Number of Collision



eFRG xLife_AM0.012 | eFRG x Life | eFRG x Life_MAX1000yr

Decrement of expected number of collision for 200 years in each altitude band

Decrement of expected number of collision	for 200 yrs
eFRG x Life_AM0.012	-18.7
eFRG x Life	-12.8
eFRG x Life_MAX1000yr	-18.4

- eFRGxLife_AM0.012 and eFRGxLife_MAX1000yr have mostly same effectiveness (in 3% difference).
- According to the future population and the collision risk, the long-term effects of these two indexes can be considered the same.