C2

地球周回近領域デブリの影響評価及び その起源イベントの識別

Evaluation of the impacts of near-Earth-orbit debris removal & track of impactful events' origins

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本研究は，スペースデブリ除去による地球周回環境への影響を評価することが目的です。4 つのシナリオについて，軌道環境予測モデルによる 200 年間のモンテカルロシミュレーションを100回行った。2009 年の宇宙機初期分布から、ENVISAT 衛星、ADEOS2 衛星、18 個の SL-16 ロケット上段の除去の有無による影響について，全く除去を行わないシナリオと比較することで解析を行った。その結果，ENVISAT と ADEOS2 の場合、将来の宇宙環境に影響があまりなく、SL-16 の場合は、物体分布が少し下がることが判明した。本研究から，除去の有効性は、物体の高度と除去する数を評価基準にできることが分かった. さらに，本研究では、将来発生する可能性がある破片に関して，親物体を特定するアルゴリズムの開発を行なって、除去の有効性が高い物体の識別ができた. この手法により、どんな物体を今から除去すべきか分かるようになることが期待されます.

This proposed study aims to evaluate the effects of remediation activities on the future evolution of the space environment around the Earth. 4 scenarios were run over 200 years, through 100 Monte-Carlo simulations. The focus was made on the removal of respectively ENVISAT satellite, ADEOS 2 satellite, and 18 pieces of SL-16 rocket upper stage from the initial population of year 2009, and the results were compared to the Baseline (scenario without removal). The analysis let underline noticeable differences between the scenarios: removing ENVISAT or ADEOS 2 reveals not to have significant impact on the future population; but removing 18 pieces of SL-16 rocket conducts to a decrease of the debris population at same epoch, which demonstrates the importance of the number of objects to be removed in order to strengthen the impact of a remediation activity. The altitude of removed objects also appeared as a significant criterion. In addition, a program has been implemented in order to track the origins at initial year of all fragments present in a given year in order to determine the most impactful objects in terms of debris generation. This process lets expect to better understand the conditions for an effective removal procedure
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Thursday Session - Modelling

Evaluation of the impacts of near-Earth-orbit debris removal & track of impactful events' origins

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Structure of the presentation

- Introduction – Motivation of the study

I. Presentation of evolutionary model / initial conditions

II. a. Study of 3 removal scenarios
- ADEOS 2
- ENVISAT
- SL-16 R/B (18 pieces)

b. Comparison with baseline scenario
c. Conclusions / Proposal to interpret results

III. Presentation of debris-origin-tracking function
a. Implementation
b. Results on study-cases / application to part. II

- Conclusion

Introduction – Motivation of the study

- 2 directions :
  → Estimate the future evolution of the population (200 years)
  → Track the generative events in the past

- 1st part :
  → Study the effects of removal of target objects
  → Tentative to understand : Are these targets the good ones ??

- 2nd part :
  → Determine today's objects that generate tomorrow's debris
  → Question : Which objects may be good candidates for removal ?
  → Results on mean of 94 statistical cases

I. Structure of the evolutionary model

- NEODEEM (Kyushu University – JAXA*)
  → Near-Earth Orbit Debris Environment Evolutionary Model

*Japan Aerospace Exploration Agency

- Prediction of future environment
  → Existing objects & occurring events at each year
  → Here : from year 2009 to year 2209

- Regions : LEO, MEO & GEO

- Included forces :
  - Sun & Moon gravitation
  - Solar radiation pressure
  - Atmospheric drag (Jacchia-Roberts density model)
  - Non-spherical part of Earth's gravitational attraction

I. Evolutionary model : Initial conditions

- Initial population as baseline for the simulation
  → all catalogued objects as of May, 1st 2009
  → 20,788 objects / 5 types *(provided by ESA for IADC WG2 AI27.2)*

- Launch traffic frequency = 8-year cycle
  → 2003-2010 recorded launches *(but not used in this study)*
  → 699 recorded objects

Table of the objects' repartition in the input files

Object type	Initial population	Launch traffic records
Space crafts	2 014	320
Rocket upper stages	1 332	256
Mission related objects	851	123
Explosion fragments	16 591	0
Collision fragments	0	0

II. Impact of 3 targeted objects' removal

- Aim : evaluate the effect of presence/suppression for

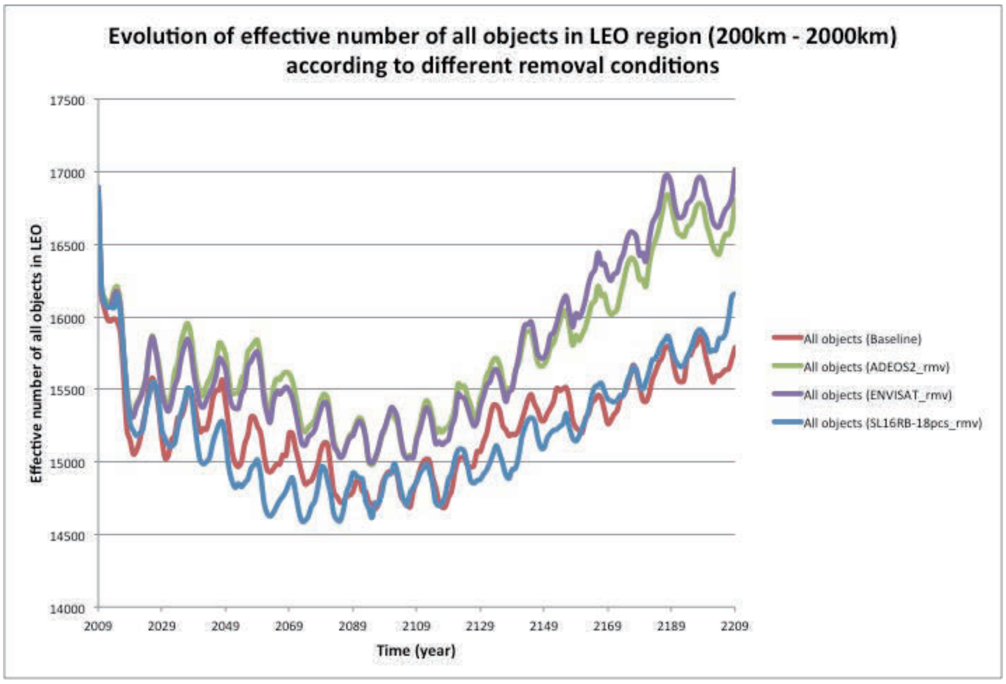
Target object	Mass (kg)	Size (m)	Inclination (deg.)	Altitude (km)
ADEOS 2 (s/c), Japan	3680	4.05	98	805
ENVISAT (s/c), Europe	8110	8.96	98	775
SL-16 (R/B – 18 pieces), Russia	9000	9.85	71	825

- Comparison with Baseline scenario (all objects present, included targets)

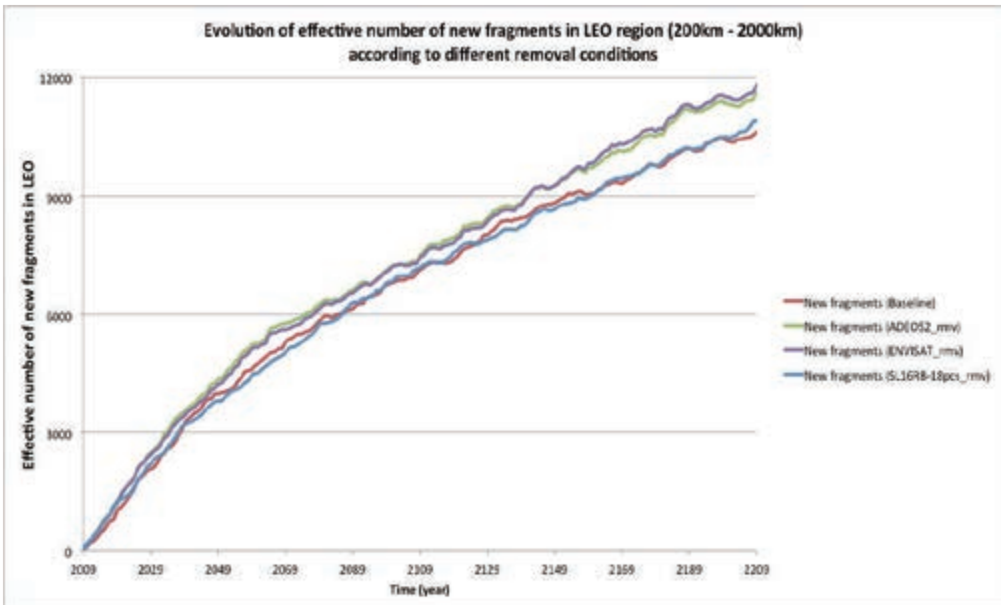
- Period : 2009/05/01 (initial population) – 2209/01/01
- Setting conditions (simulation assumptions) **100 MC simulations**

Event	Status in the simulation
New launches	No
Other objects' removal	No
Future explosions	No
Collisions	Yes
Performed PMD	90% success rate

II. Targeted objects' removal - Results



II. Targeted objects' removal - Results



II. Target objects' removal – Proposal for interpretation

- **SL-16 R/B** case :
  - global trend : similar to Baseline
  - slight decrease of population in 2 periods (from 2035 and from 2120)

- **ADEOS2 & ENVISAT** cases : no positive effects on future population reduction
  - slight increase of population w/r. Baseline
  - tentative to understand → Analyze collisions in **Baseline scenario**

Use of origin-tracking program

Object	Collision year	Collided object (mass)	Number of direct fragments	Number of remaining fragments in 2109
ENVISAT (7 collisions)	2030 (10th MC)	1760 kg (r/b)	4633	1192
	2031	0.607 kg	4	0
	2047	0.0539 kg	0	0
	2060 (66th MC)	717 kg (s/c)	4243	1402
	2110	0.215 kg	4	0
	2125	4.084 kg	19	0
	2068	0.472 kg	3	0
ADEOS 2 (2 collisions)	2050	0.370 kg	0	0
	2068 (84th MC)	1420 kg (r/b)	2839	953

II. Target objects' removal – Conclusions

- 1st conclusion: number of removed objects = key parameter for efficiency

- 2nd conclusion: effects of altitude = reentry of fragments from low-altitude collision with time

- Question / wondering : collision with ADEOS2 or ENVISAT
  ➔ avoidance of more catastrophic collision in scenarios where absents (?)

  Ex. : ENVISAT-removed scenario
  → study of the 1760kg-object that may collide with ENVISAT in Baseline (10th MC)
  → After 2030 :

Scenario	MC recurrence	Collision recurrence	Number of generated fragments	Mean number of fragments on 100 MC
Baseline	7	7	4383	43.83
ENVISAT-removed	7	8	7765	77.65

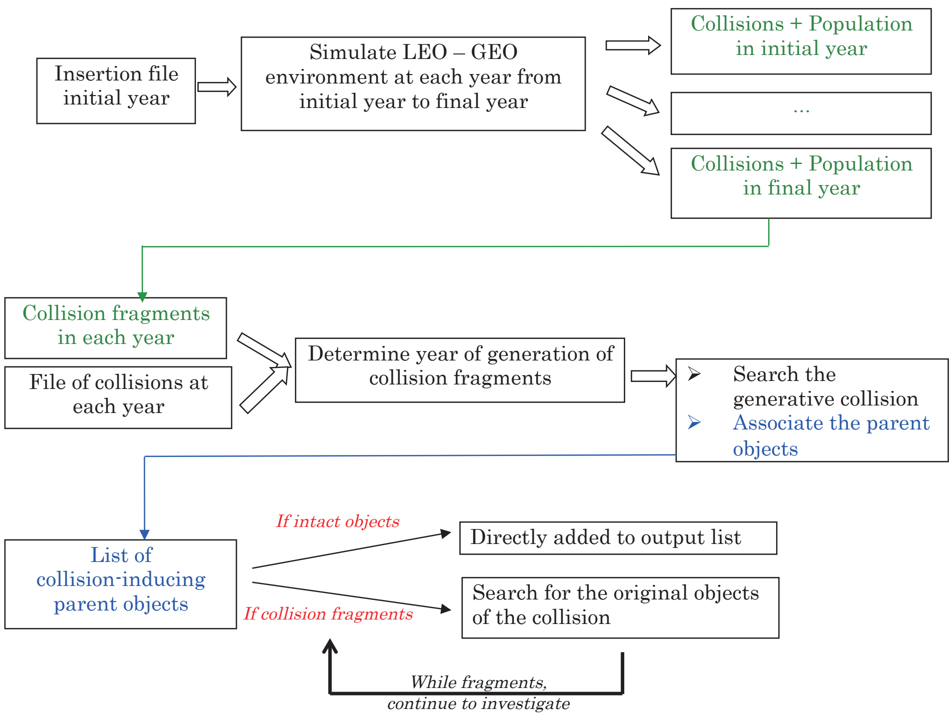
→ *Collision with ENVISAT may avoid catastrophic collisions in the future* ***(?)***

III. Debris-origin-tracking function

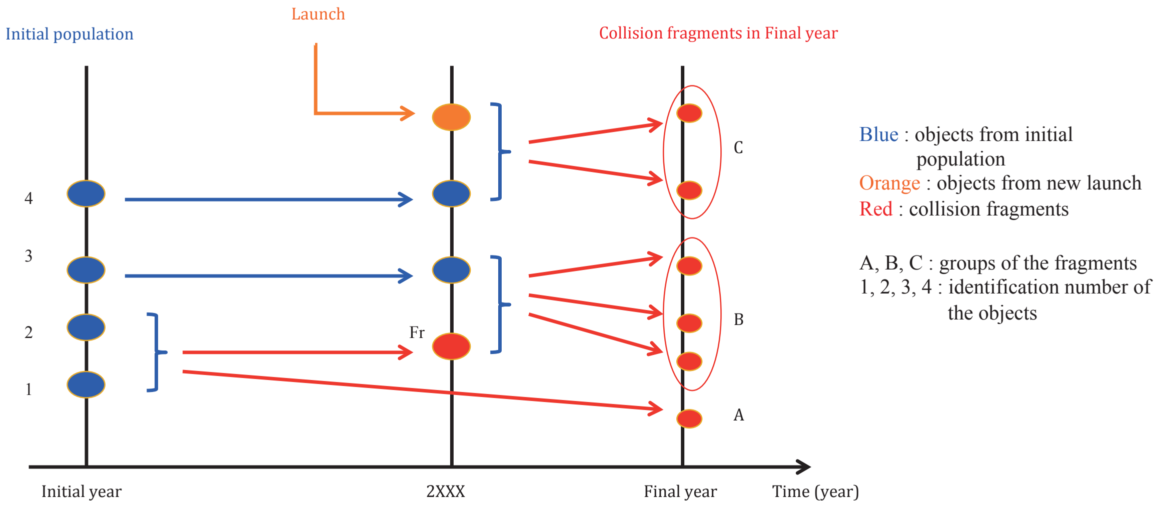
- Aim
  ➔ Find out the origin of debris estimated in a final year (future)
  ➔ Track this origin back to past, until current year (present)

- In one simulation :
  * input = list of collisions at each year
  list of all objects at each year
  * output = list of debris-inducing objects in present year

III. Origin tracking function - Implementation



III. Origin tracking function - Implementation



Process inside 1 MC simulation – after identifying the collision fragments in Final year

- Groups defined w/r. time-closest generative collision
- In each group : access to mass and size of each fragment
- Ex. : 1,2 → grps A&B / 3 →grp B / 4 → grp C

Data provided in the list of parent objects 1 to 4:
→Number of generated fragments in Final year
→Fragments' group number(s)

III. Origin tracking function – Study-case results (Application to Removal study Part. II)

Object's number	Type	Number of generated fragments	Groups of fragments
878	Spacecraft	1859	1 & 9
1415	Spacecraft	1859	1 & 9
1236	Rocket body	1124	2
2580	Spacecraft	1124	2
1183	Explosion fragment	4	3
11312	Explosion fragment	4	3
1354	Rocket body	856	4
4443	Explosion fragment	856	4
1476	Spacecraft	498	5
1967	Spacecraft	498	5
1629	Rocket body	565	6 & 10
6025	Explosion fragment	565	6 & 10
1352	Rocket body	1119	7 & 8 & 12
2323	Spacecraft	1119	7 & 8 & 12
1400	Spacecraft	2	8
1609	Rocket body	712	9
3466	Mission related object	24	10
825	Spacecraft	1284	11
3097	Spacecraft	1284	11
2477	Explosion fragment	3	12
2185	Spacecraft	1904	13 & 14
2383	Spacecraft	1904	13 & 14
1318	Rocket body	960	14

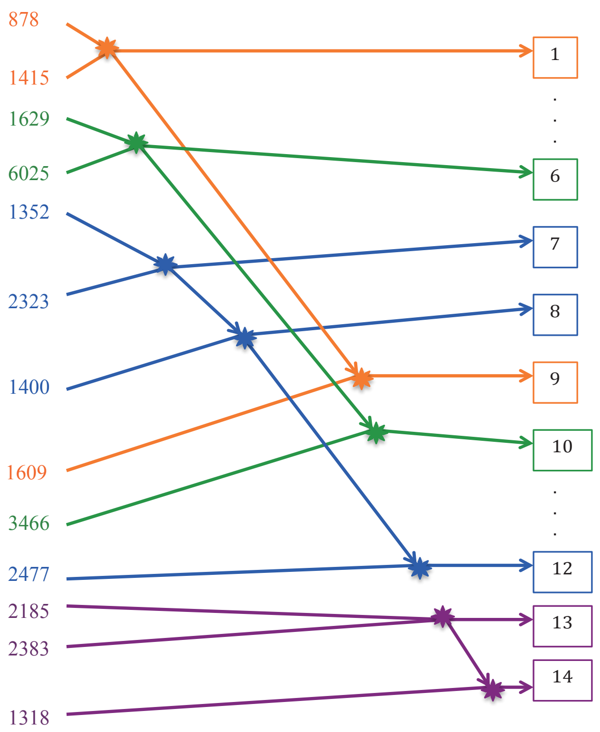
Application on 1MC

Example of Baseline scenario:
Initial year : 2009
Final year : 2109
2nd MC simulation
PMD 90%
No launch
ADR 0
No explosion

23 objects at the origin of fragments estimated in 2109

→ 14 groups
→ Total number of collision fragments : 9213

III. Origin tracking function – Study-case results (Application to Removal study Part. II)



Example of Baseline scenario:
2nd MC simulation

Initial year : 2009
Final year : 2109

PMD 90%
No launch
ADR 0
No explosion

Multi-group generating objects

III. Origin tracking function – Results on 94MC mean (Application to Removal study Part. II)

Object's number		Mean number of fragments	Mean number of fragments > mass criterion	Mean number of fragments > size criterion
876	s/c	121.4	4.7	120.5
754	r/b	119.8	7.6	118.8
700	frg	104.5	6.5	104.5
841	r/b	92.9	5.0	92.0
1349	r/b	89.6	3.0	88.6
466	r/b	83.4	5.2	82.4
818	r/b	81.6	4.1	80.6
659	r/b	77.4	3.3	76.4
709	frg	74.5	2.5	73.6
815	r/b	72.3	4.7	71.4
1318	r/b	65.2	2.4	64.3
2309	r/b	64.1	2.1	63.1
1411	r/b	63.7	5.4	62.8
936	r/b	63.4	2.2	62.5
1535	s/c	62.9	2.4	61.9
1607	r/b	60.7	4.3	59.8
795	r/b	60.3	3.4	59.3

List of year-2009 objects generating more than 60 fragments in mean on 94 MC

Example of Baseline scenario:
Mean on 94 MC simulations

Initial year : 2009
Final year : 2109

PMD 90%
No launch
ADR 0
No explosion

Criteria for size & mass :
→ Mass criterion = 10kg
→ Size criterion = 0.1m

s/c : spacecraft
r/b : rocket body
frg : explosion fragment

III. Origin tracking function – Study-case results (Application to Removal study Part. II)

Which objects are first estimated candidates for removal ?
→ Top 5 *(among 94 MC)*

Type	Mass (kg)	Altitude (km)	Inclination (deg)	Object
Spacecraft	4500	949.8	74.94	COSMOS 952
Rocket body	8230	842.4	71.0	SL-16 R/B (1990-046B)
Explosion fragment	2990	947.4	70.94	?
Rocket body	8230	833.8	71.01	SL-16 R/B (1998-045B)
Rocket body	1420	975.0	82.92	SL-16 R/B (1979-028B)

Study concerning Removal scenarios :
In the 94 MC-mean list, 3 pieces of SL-16 R/B:
→Among top 5 debris-generating objects.

Correlation of results

→If top 10: 6 pieces of SL-16 R/B ; 1 SL-8 R/B ; 1 COSMOS 952; 2 expl. fragments

But : ADEOS2 nor ENVISAT don't appear here

Conclusion

- Study of the effects of targets' removal
  → Surprising results w/r. evolution of population
  → Conclusions: altitude & number of removed objects
  → Assumption: more catastrophic collision avoidance (?)
  → Results strengthened through origin-tracking investigation

- Track of debris origin : completed
  → Could propose **new list of potential targets**
  → Plan: * complete mean on 100 MC
  * rerun simulation without targeted objects
  (for double-check to strengthen the list)

- *Acknowledgements to ESA for providing list of year-2009 initial population*