B03

JAXA 独自のデブリ推移予測用ベースラインファイルの開発状況

Development of JAXA's Original Baseline File for Debris Evolutionary Model

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デブリ推移モデルはデブリ低減策の有効性評価や国際的ルールの議論に不可欠である。JAXA では九州大学と共同開発したデブリ推移モデルを用いてデブリ数の将来推移を評価してきた。デブリ推移モデルでは、軌道上環境の初期状態として、考慮する全物体の質量特性や軌道等の情報が必要である。JAXA では公開されている TLE 履歴からの面積質量比評価や文献調査、JAXA 望遠鏡で観測された未カタログ物体等を考慮して、独自のベースラインファイルを作成した。今までは、IADC で ESA から提供されたベースラインファイルを、研究目的にのみ使用していたが、情報不足等により、具体的デブリ除去対象の評価等は不可能だった。本講演では、TLE 調査等のベースラインファイル開発方法や、開発されたベースラインの評価結果、それを用いた推移予測の結果等について報告する。特に、開発されたベースラインファイルを用いたデブリ除去対象の評価や、デブリ低減策効果の評価、また波及効果として TLE 履歴調査から分析できる情報等を紹介する。

A debris evolutionary model is indispensable for investigating effective debris mitigation measures and for developing international rules regarding space debris. JAXA has been evaluating the future space debris population using an evolutionary debris model named NEODEEM, developed in collaboration with Kyushu University. A baseline file is required for the debris Evolutionary model, which is the initial population data of the on-orbit environment, such as mass characteristics and orbits of all objects larger than 10 cm. JAXA has created its own baseline file by taking into account the area-mass-ratio evaluation from the TLE (Two Line Elements) history, literature review, and uncatalogued objects observed with the JAXA telescope, and so on. The baseline files provided by ESA at IADC have been used for research purposes only, but due to lack of information, for example, evaluation of specific debris removal targets was not possible. In this talk, the methods for developing the baseline file, the results of comparison with some debris models, and the results of debris evolutionary model predicted using the developed baseline files are reported. In particular, the evaluation of debris removal targets and the effectiveness of debris mitigation measures using the developed baseline files are introduced. In addition, the information that can be analyzed from the TLE history survey is introduced.

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9th JAXA Space Debris Workshop
第９回スペースデブリワークショップ

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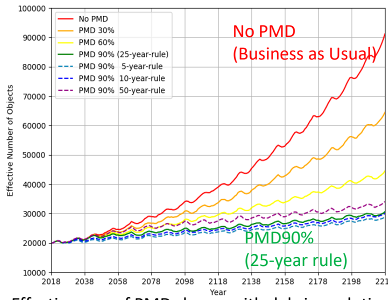
1

Introduction

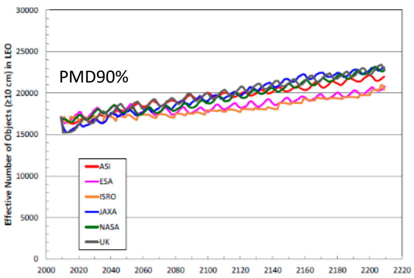
- Debris evolutionary model is indispensable as a technical basis for international rulemaking discussions such as for evaluating the effectiveness of debris mitigation measures, ADR targets, etc.
- Initial conditions (orbit, mass and other characteristics of all orbital objects larger than 10 cm, type of object, etc.) are necessary for the debris evolutionary model

⇒JAXA developed its own baseline file based on TLEs, observations, models, etc.

- デブリの国際ルール化議論にはデブリ推移モデルを用いた将来予測によるデブリ対策の有効性評価が不可欠
- デブリ推移モデルには初期条件として10cm以上全物体の軌道や質量特性等の情報が必要だが、今まで用いていたIADCでESAから提供されたデータは情報不十分かつ使用制限があったため、JAXA独自のベースラインファイルを開発

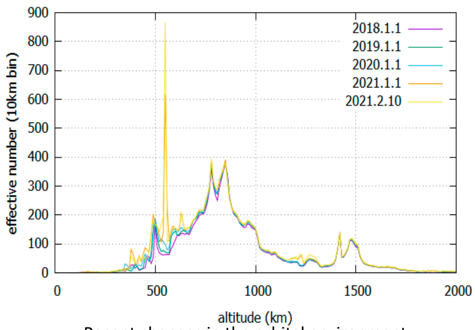


Effectiveness of PMD shown with debris evolutionary model, ***NEODEEM***, developed with Kyushu univ. and JAXA 九大と共同開発した推移モデルによる評価
Kawamoto et al. IOC 2019 (revised)



IADC-12-08, Rev. 1, Stability of the Future LEO Environment, January 2013.

IADCで実施した６機関の推移予測



Recent changes in the orbital environment
(based on *spacetrack.org*)
近年環境激変のため最新データが重要

2

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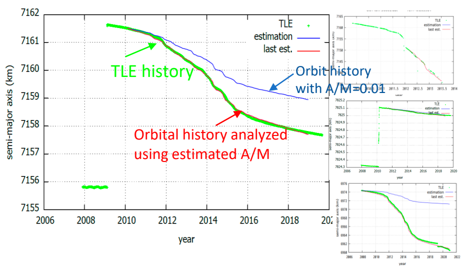
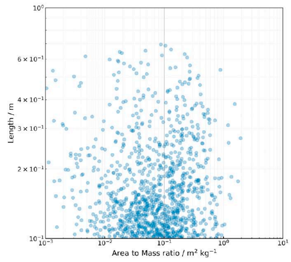
How to develop the baseline file

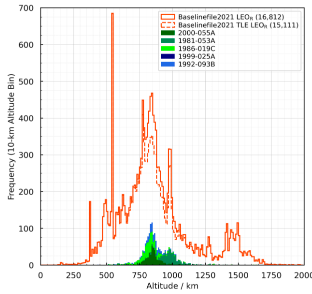
- Daily check of TLEs of all catalogued objects, about 20000 available from space-track.org, and estimation of area-to-mass (A/M) ratio from orbit history
- Mass characteristics of intact objects and other data are from literature survey
- Mass characteristics of fragment objects are randomly set to match the estimated A/M with fragments generated by NASA standard breakup model
  - Actual size of each object may be different from the assigned size, but it is acceptable since the goal is to be able to evaluate statistically
- Uncataloged objects from ground observation data are added(see next page for details)
- 約2万個のTLE（軌道履歴）データからの面積重量比(A/M)推定、文献調査、破砕モデル、地上観測から破片追加



Daily check of TLEs and A/M estimation



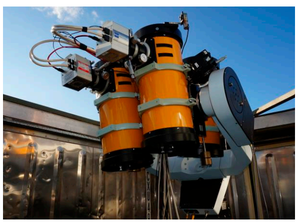
A/M and size distribution of fragments generated by standard breakup model

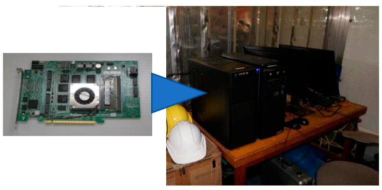


Altitude distribution of fragments added using breakup model

Addition of uncataloged objects from ground-based observations

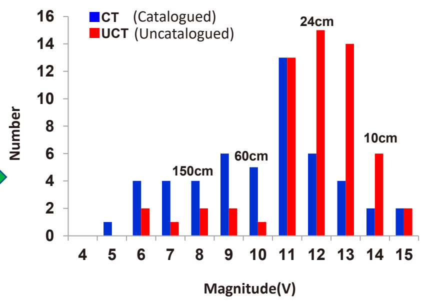
- LEO survey results conducted with JAXA remote observation site in Australia are added to the baseline file.
- 豪州遠隔観測所での観測データから未カタログ物体を追加

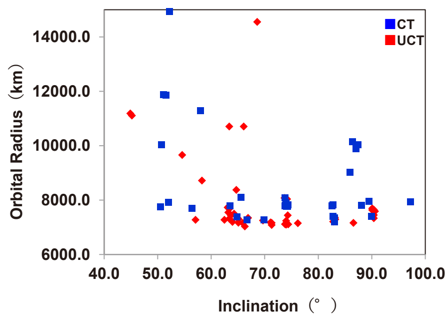




Data acquisition using the quadruple telescope and fast data analysis using FPGA system

Yanagisawa et al. ASR 2015





Calculation of the brightness (size) distribution and the simple orbital elements

Reflection to the baseline file

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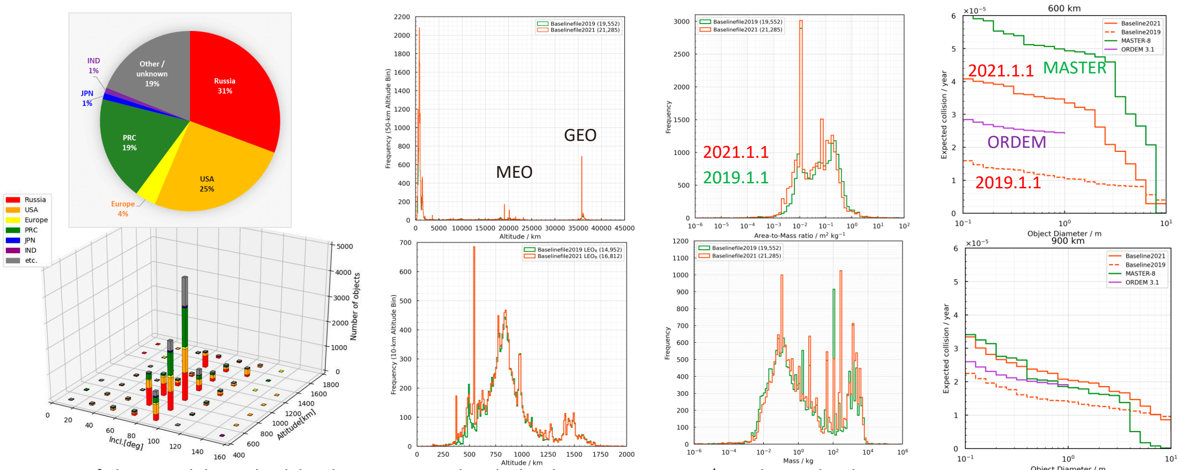
Results of developed baselines

- About 21,000 objects were considered and baseline file as of January 1, 2021 has been developed
- Collision flux by size have been compared with debris environment models (ORDEM, MASTER) and confirmed that there is a lack of fragments debris at some altitudes while the sizes of some objects might be too large.
- 約21000個の物体を考慮し2021年1月1日時点のデータベースを開発、環境モデルと比較。破片不足、要サイズ修正



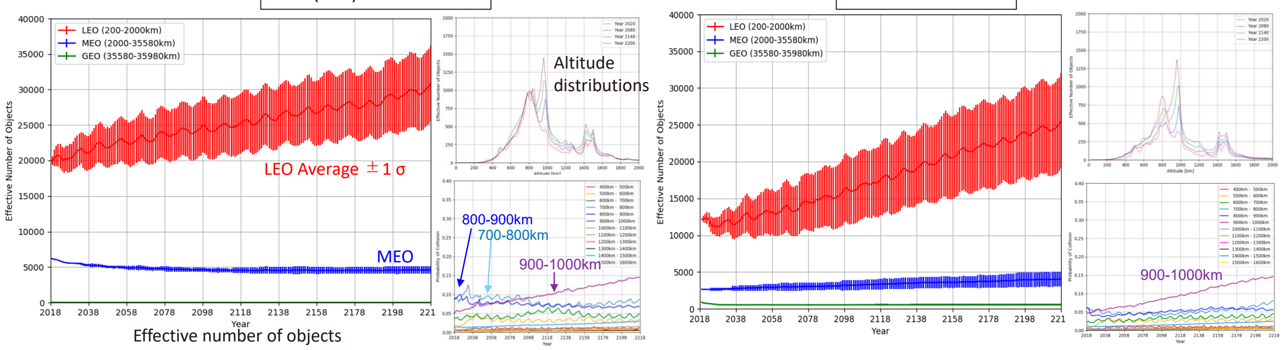
Origins of objects and their orbital distribution | Altitude distribution | A/M and Mass distribution | Flux comparison

5

Prediction results using the developed database (1)

- **PMD90%** (8-year repeated launch, Post Mission Disposal compliance rate 90%)
  - Prediction with the JAXA database as of January 1, 2019 and with the January 1, 2018 of ESA database provided for IADC studies, as presented in previous papers
  - Total number of LEO objects (especially fragments) in JAXA baseline file is still insufficient
- 2019年１月１日時点データでPMD90%ケースの推移予測を比較。一致した傾向の結果を確認

IADC(ESA)-2018 version | JAXA-2019 version



Effective number of objects

Kawamoto et al. IOC 2019 (revised. revision of atmospheric model and bug fixes)

Collision probabilities in each altitude band

6

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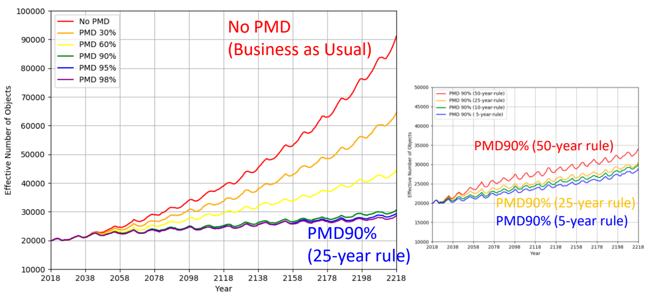
Prediction results using the developed database (2)

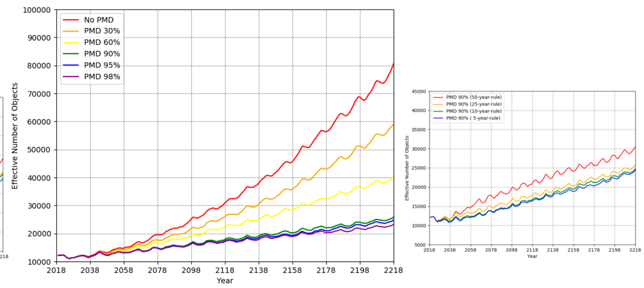
- Effectiveness of debris mitigation measures were evaluated, and the same results were obtained
  - High PMD compliance rate is important
  - As for PMD time period, 25-year rule is effective enough
- デブリ低減策評価についても、25年ルールの有効性等、一致した結果を確認

IADC(ESA)-2018 version



Effective number of objects

JAXA-2019 version



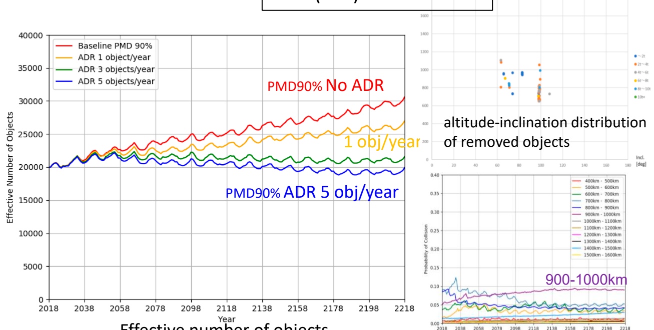
Effective number of objects

Kawamoto et al. IOC 2019 (revised)

Prediction results using the developed database (3)

- Effectiveness of ADR
  - The increase of future debris populations could be suppressed by ADR of about 3 – 5 debris objects per year
- デブリ除去についても、同様の効果を確認（年間３～５個程度大型デブリを除去すれば自己増殖を抑制）

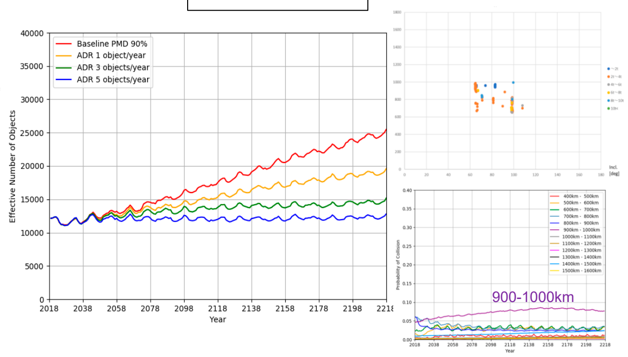
IADC(ESA)-2018 version



Effective number of objects

Collision probabilities in each altitude band

JAXA-2019 version



Kawamoto et al. IOC 2019 (revised)

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Specific targets for ADR

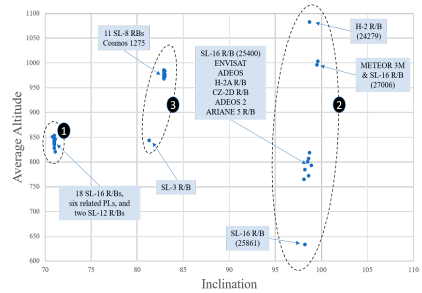
- IADC data did not show the specific target names, but now we can see them
- Participated to international paper “**Identifying the 50 Statistically-Most-Concerning Derelict Objects in LEO”** (McKnight et al., IAC 2020)
  - 11 teams listed ADR targets in their respective evaluations, and merged them into a Top 50 list, confirming that SL-16 and others are ADR targets.
  - Reasonable results with a high rate of agreement with other teams
- IADCデータにはデブリ名称等の情報がなかったが、除去対象を議論する国際論文にも参加できるようになった

	McKnight	Witner	Anselmo/Pardini	Letizia/Lemmens	Rossi	Baranov/Grishko	Lewis	Kawamoto	Nicolls	Dolado Perez/Ruch	Jing/Dan/Wang
1	**27006**	12504	**27006**	**27386**	**27006**	**28353**	**27006**	**27386**	**23705**	17240	27601
2	**27001**	14625	**25400**	**26070**	**24298**	**24298**	**28353**	**23088**	**19120**	**27006**	24277
3	14625	12835	27470	**23088**	**28353**	**22220**	**27001**	**22285**	19119		
4	**25407**	**27006**	**17974**	**23705**	**31793**	**22566**	24279	**23405**	27601		
5	**31793**	10776	**22803**	**20625**	**20625**	**25407**	**23405**	**17590**	24277		
6	**22220**	12786	**24298**	**19650**	**23088**	15334	**16182**	**26070**	**16182**		
7	**22285**	13272	**22285**	**28353**	**22566**	**31793**	21090	**20625**	**22285**		
8	10732	12092	**28353**	**24298**	**22285**	**23705**	14966	**22803**	23087		
9	17290	15890	**31793**	**23405**	**23705**	**19650**	20491	**27006**	28352		
10	**17974**	25861	**23405**	**22566**	**23405**	**16182**	21232	**28353**	**26070**		
11	13113	7594	**23705**	**25407**	**26070**	2825	22488	**22566**	**22220**		
12	12092	23180	**17590**	**16182**	**19650**	15772	**22803**	**17974**	24297		
13	25861	18959	**20625**	**31793**	**25407**	**19120**	**20625**	**25407**	**22803**		
14	**22566**	10731	**22220**	**25400**	**16182**	1245	12298	**31793**	**31793**		
15	10138	**22220**	**26070**	**17974**	**22220**	**26070**	22969	**19650**	23704		
16	13917	10693	**19650**	**17590**	**22803**	**17974**	15598	**23705**	**19650**		
⋮											

Combined results of 11 teams

Evaluation results of the Top 50 ADR targets (debris listed by 3 or more teams are shown in bold, by all teams in red)

Ranking	Score	SATNO	SATNAME	APOGEE, km	PERIGEE, km	INCL., deg	MASS, kg	COUNTRY	LAUNCH
1	4048	22566	SL-16 R/B	848	837	71.0	9000	CIS	3/26/1993
2	3710	22220	SL-16 R/B	848	827	71.0	9000	CIS	11/17/1992
3	3500	31793	SL-16 R/B	846	843	71.0	9000	CIS	6/29/2007
4	3470	26070	SL-16 R/B	854	827	71.0	9000	CIS	2/3/2000
5	3330	16182	SL-16 R/B	844	833	71.0	9000	CIS	10/22/1985
6	3300	20625	SL-16 R/B	853	834	71.0	9000	CIS	5/22/1990
7	2880	27006	SL-16 R/B	1006	986	99.5	9000	CIS	12/10/2001
8	2862	23705	SL-16 R/B	852	831	71.0	9000	CIS	10/31/1995
9	2826	25407	SL-16 R/B	844	835	71.0	9000	CIS	7/28/1998
10	2800	23405	SL-16 R/B	845	838	71.0	9000	CIS	11/24/1994
11	2547	17974	SL-16 R/B	846	823	71.0	9000	CIS	5/13/1987
12	2412	23088	SL-16 R/B	845	841	71.0	9000	CIS	4/23/1994
13	2296	22285	SL-16 R/B	844	840	71.0	9000	CIS	12/25/1992
14	2240	22803	SL-16 R/B	850	823	71.0	9000	CIS	9/16/1993
15	1813	19650	SL-16 R/B	848	831	71.0	9000	CIS	11/23/1988
16	1771	24298	SL-16 R/B	863	839	70.8	9000	CIS	9/4/1996
17	1650	28353	SL-16 R/B	848	842	71.0	9000	CIS	6/10/2004
18	1617	17590	SL-16 R/B	841	831	71.0	9000	CIS	3/18/1987
19	1547	19120	SL-16 R/B	842	814	71.0	9000	CIS	5/15/1988
20	1477	25400	SL-16 R/B	813	801	98.6	9000	CIS	7/10/1998
21	1320	27386	ENVISAT	766	764	98.1	7800	ESA	3/1/2002
22	1182	27001	METEOR 3M	1013	994	99.6	2500	CIS	12/10/2001
23	805	24277	ADEOS	794	793	98.9	3560	JPN	8/17/1996
24	600	27601	H-2A R/B	836	734	98.2	3000	JPN	12/14/2002
25	564	15334	SL-12 R/B(2)	847	838	71.0	2440	CIS	9/28/1984

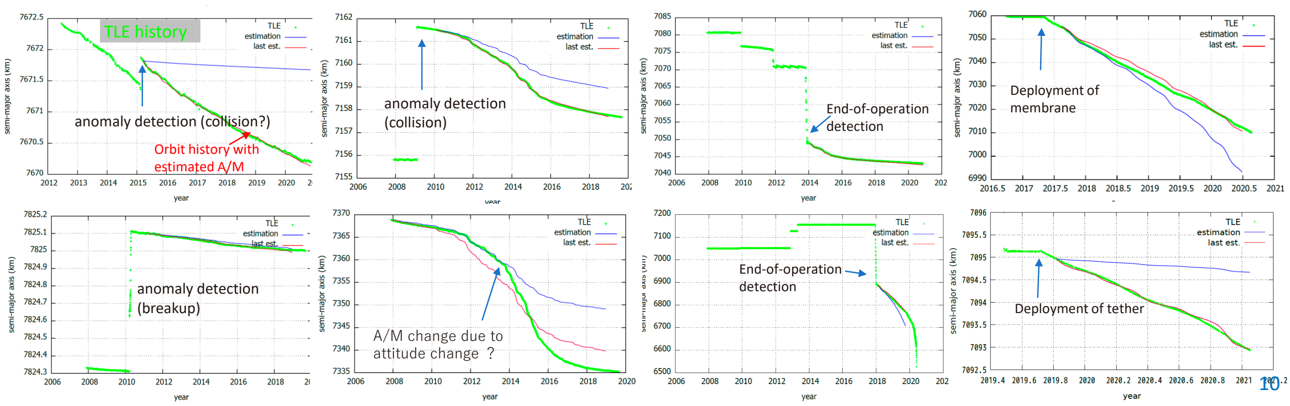


Evaluation results of the Top 50 ADR targets

9

Byproducts of TLE surveys

- Daily check of the TLEs of all cataloged objects (about 20,000 available from space-track.org) to detect anomalies such as collisions, explosions, end-of-operation, deployment of deorbit devices, generation of new debris, disappearance from TLEs, etc.
- Possibility of detecting attitude mode change of an object based on the difference in the estimated A/M, or evaluating debris environment models
- 毎日のTLEチェックにより衝突・破砕等による軌道変化や、運用終了、PMDデバイス展開等を検出可能。



10

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Summary

- JAXA's original database for debris evolutionary model have been developed.
- Although the number of debris objects is still insufficient, we are now able to evaluate debris mitigation measures, and specific removal targets, etc. using the developed baseline file.
- We will continue to analyze the TLE and add data from surveys and observations to improve the completeness.
- デブリ推移予測に必要な、JAXA独自のデブリデータベースを構築した。破片等はまだ不足しているため、継続的に日々のTLEデータチェック等で改良する予定
- 最新・使用制限のないデータで、デブリ対策の有効性評価や具体的デブリ除去対象等を評価可能となった。国際議論に備えるためにどのような評価をすべきか、ご要望等があればご連絡ください

Acknowledgement:
- *We used JAXA Supercomputer System generation 2 (JSS2).*
- *Part of the initial population for this study was provided by the ESA Space Debris Office.*
- *Part of this study was supported by J-SPARC (JAXA Space Innovation through Partnership and Co-creation)*

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