POLITECNICO MILANO 1863 | DEPARTMENT OF AEROSPACE SCIENCE AND TECHNOLOGY

COMPASS

Is Active Debris Removal Beneficial? An Environmental Risk Analysis with THEMIS 1.0

03 June 2026 I **Martina Rusconi**, Emma Stevenson, Stijn Lemmens, Francesca Letizia, Camilla Colombo

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GreenSpecies

erc European Research Council Executive Agency

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Why Active Debris Removal?

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Why Active Debris Removal?

Many inactive objects in space

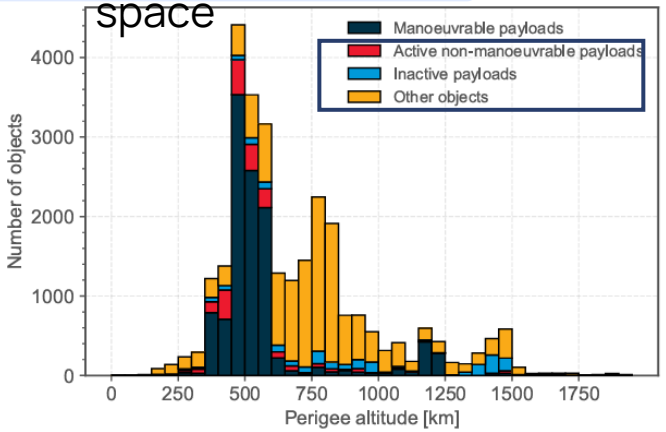


Fig. 1 Number of objects distribution in 2026

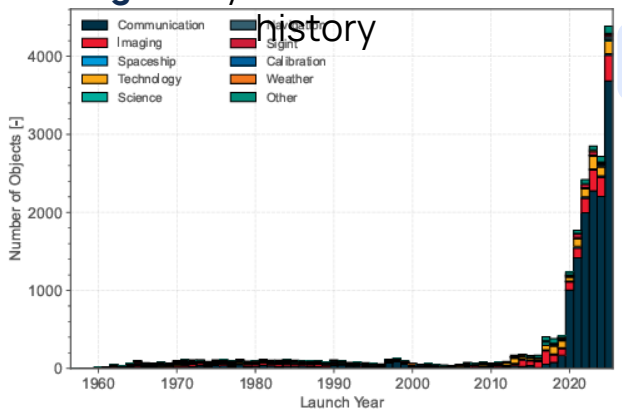


Fig. 2 Payload launch traffic history

More launches

Better adherence to mitigation guidelines

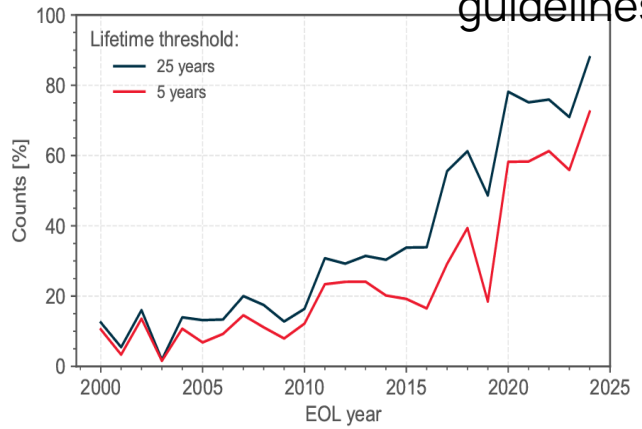


Fig. 3 Non-naturally compliant objects clearance

Missing

Additional sink mechanism

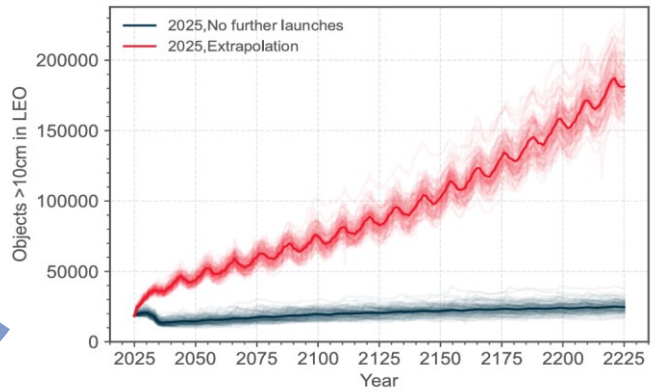


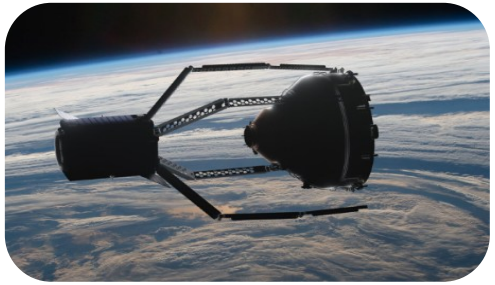
Fig. 4 Long-term simulation of current and no further launches scenarios

Still uncontrolled objects growth

➢ ESA's Space Environment Report 2026.

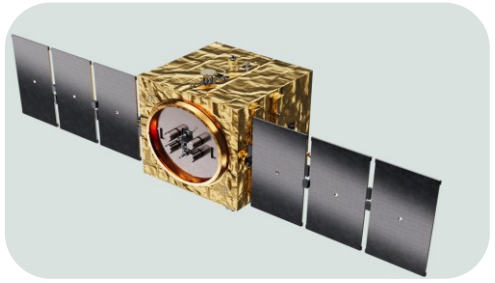
Why Active Debris Removal?

ESA ClearSpace-1

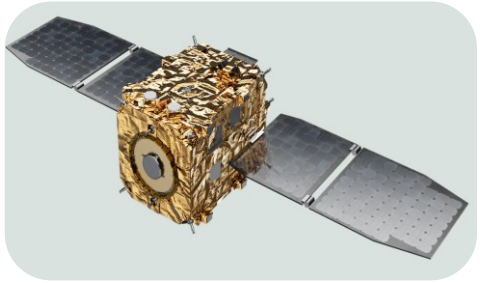


ESA CAT

Active Debris Removal



Astroscale ELSA-M



Astroscale ADRAS-J

- ESA - ClearSpace-1.
- ESA - Satellite removal mission CAT.
- ADRAS-J Mission | Astroscale's Debris Inspection Milestone.
- ELSA-M Mission | Commercial Satellite EOL by Astroscale.

Is Active Debris Removal beneficial?

02

THEMIS index

Tracking the Health of the Environment and Missions in Space

$$I = \int_{t_0}^{t_{EOL}} I(t)dt + \alpha \cdot \int_{t_{EOL}}^{t_{end}} I(t)dt + (1-\alpha) \cdot \int_{t_{EOL}}^{t_f} I(t)dt$$

One index for the
- Operational phase
- Successful PMD
- Failed PMD

α
Probability of PMD success

Risk metric

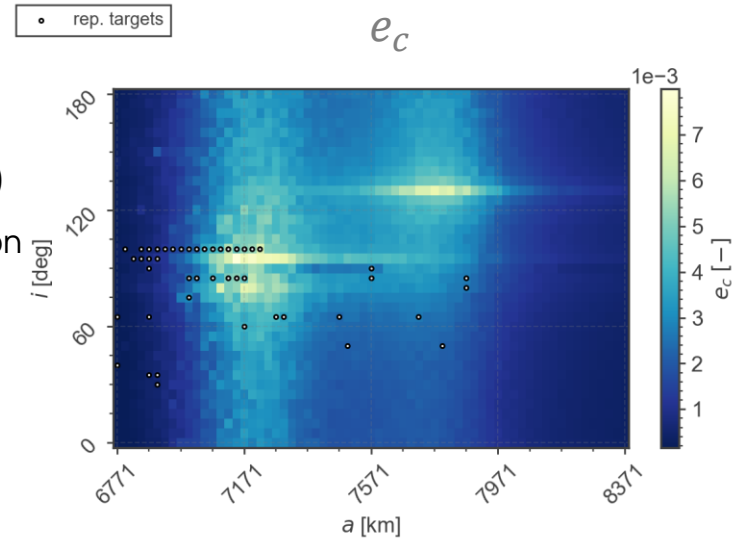
Probability × *Effect*

$$I(t) = p_c \cdot e_c + p_e \cdot e_e$$

$p_c = 1 - exp(-\Phi A_c \Delta t)$

Kinetic theory of gases formulation

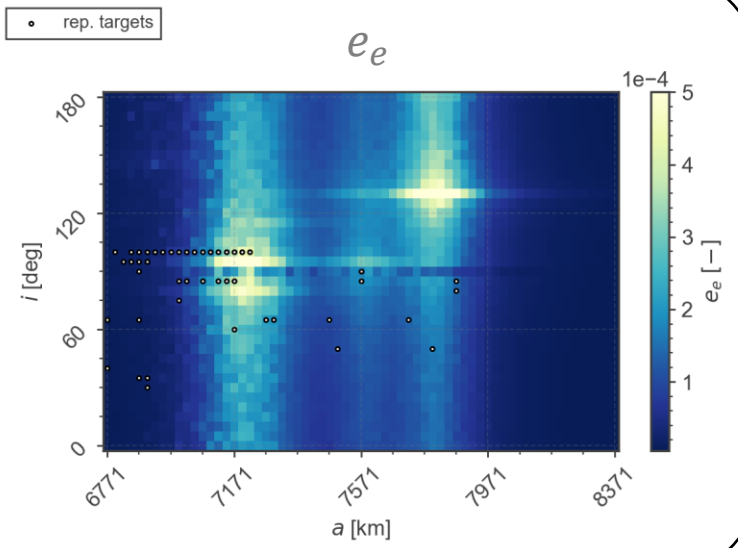
e_c



$p_e = \tilde{H}$

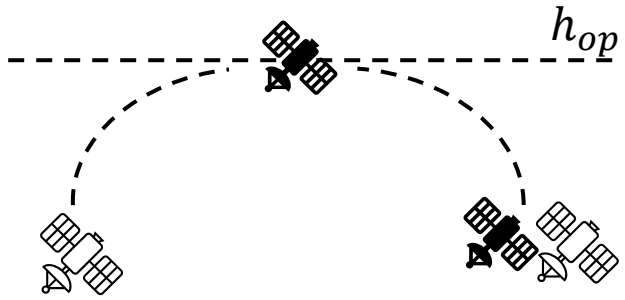
Cumulative hazard function of Nelson-Aalen estimator

e_e



Direct removal

1. SV launched to SC operational orbit
2. Rendez-vous
3. Re-entry of the system

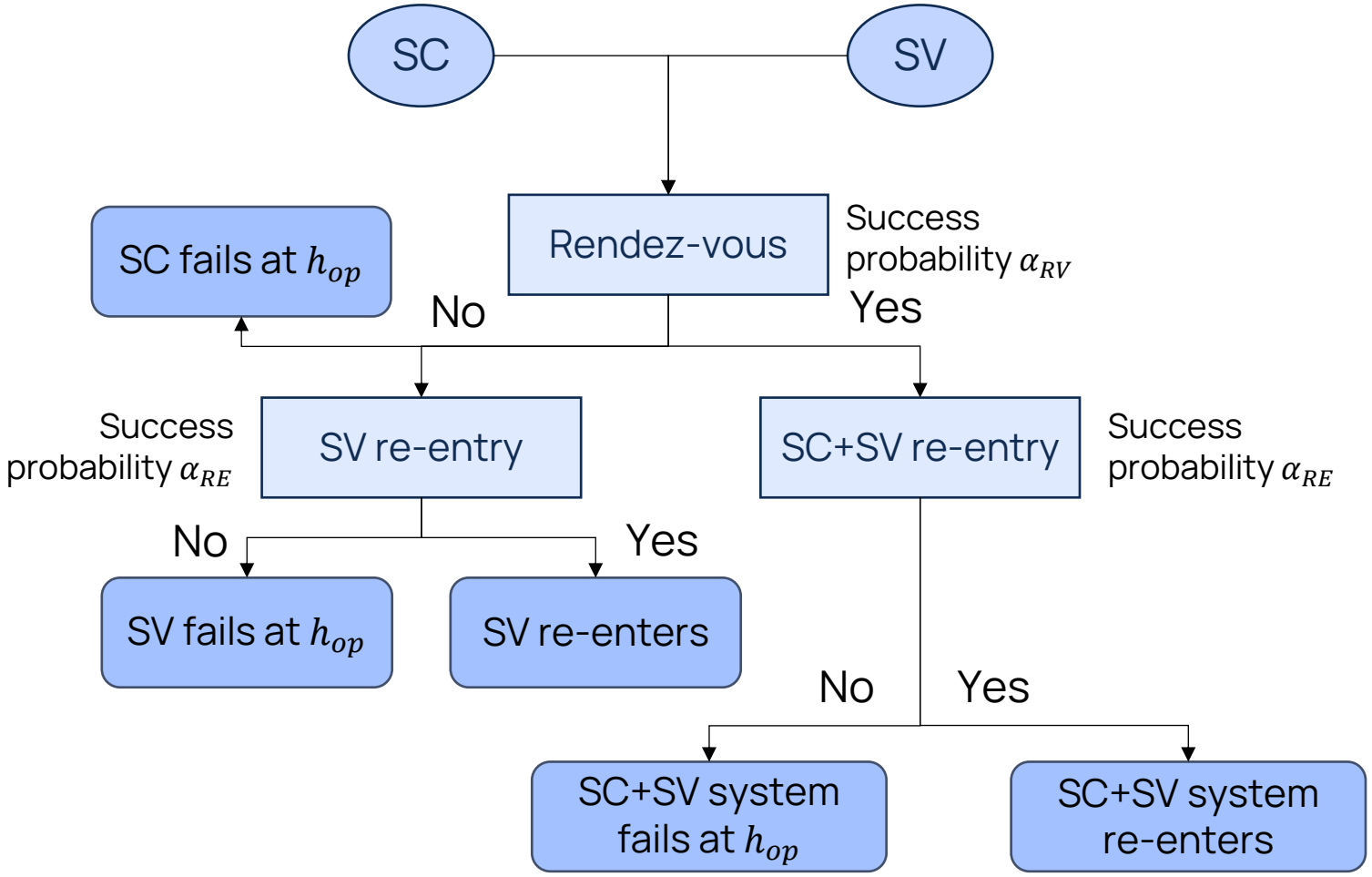


SC – Spacecraft

Operational orbit	Mass
SSO at 815 km	1100 kg

SV – Service Vehicle

Operational orbit	Mass
SSO at 815 km	180 kg



$$I^* = (1 - \alpha_{RV})I_1 + \alpha_{RV}(1 - \alpha_{RE})I_2 + \alpha_{RV}\alpha_{RE}I_{nom}$$

- Letizia F., Lemmens S., Krag H., Environment capacity as an early mission design driver, Acta Astronautica, 2020.

Direct removal

Sensitivity on:
X Success probability of rendez-vous α_{RV}
Y Success probability of direct re-entry (SV or SC+SV) α_{RE}

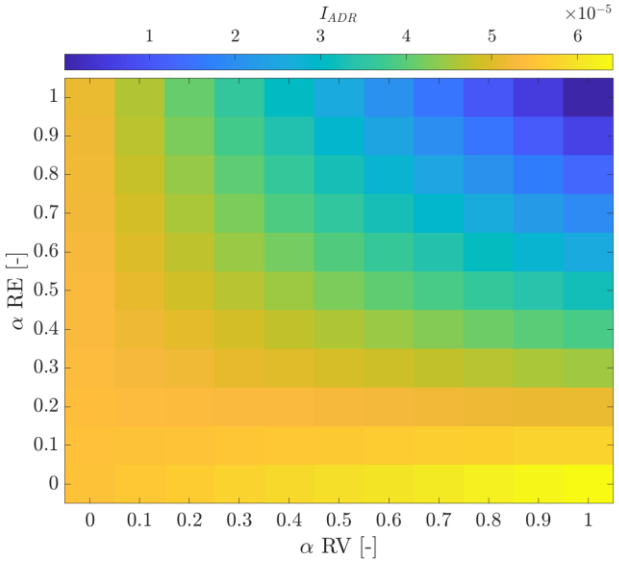


Fig. 5 THEMIS value for ADR mission with respect to α_{RV} and α_{RE}.

THEMIS index

If rendez-vous succeeds, re-entry becomes crucial to avoid failure of both SC and SV at h_{op}.

THEMIS index for ADR is generally higher than nominal PMD within 5 and 25 years

BUT: test case operates at 815 km

ADR
No action

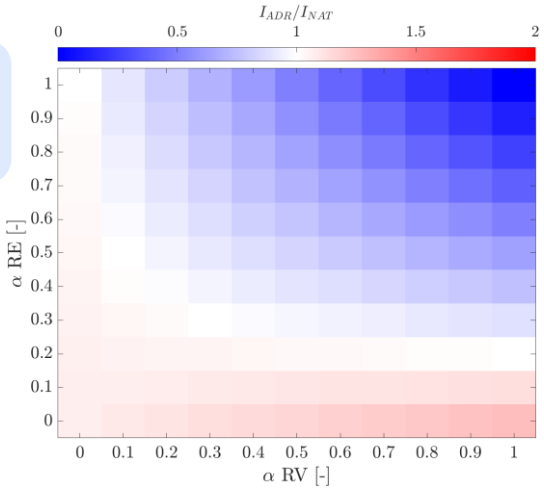


Fig. 6 Ratio of THEMIS index values for ADR mission and natural decay.

ADR
5 y PMD

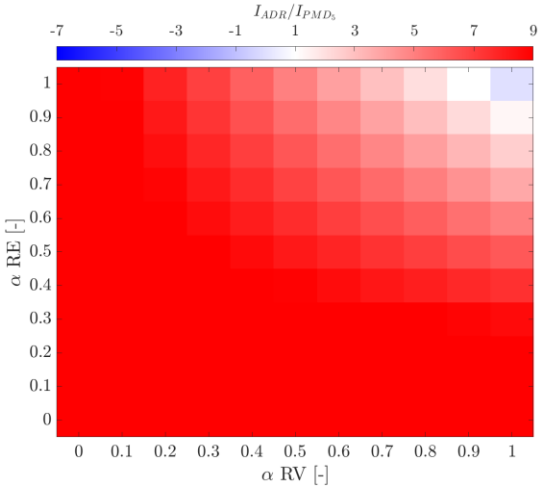
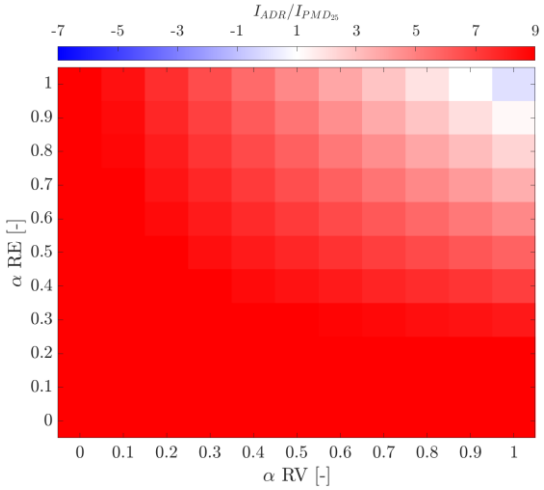


Fig. 7 Ratio of THEMIS index values for ADR mission and PMD within 5 y.



ADR
25 y PMD

Fig. 8 Ratio of THEMIS index values for ADR mission and PMD within 25 y.

Direct removal

Sensitivity on:
X $\boldsymbol{mass}$ of the target satellite*
Y Operational altitude of the target satellite $\boldsymbol{h_{op}}$

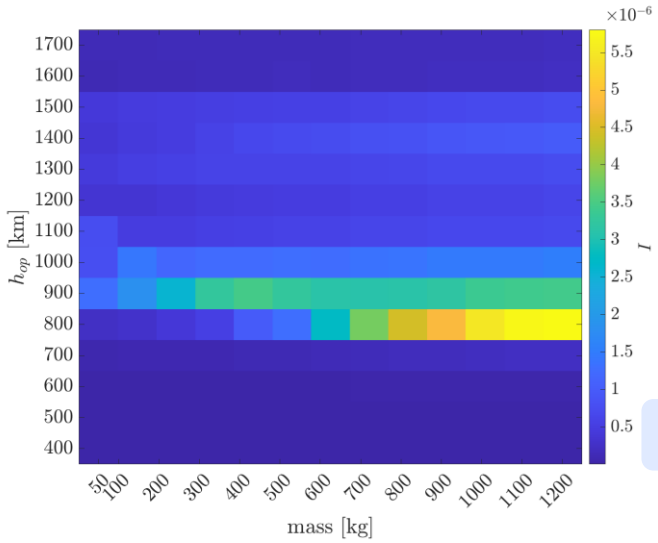


Fig. 9 Sensitivity matrix of THEMIS index value for ADR mission with respect to h_{op} and $mass$.

THEMIS index

800-900 km, which are **high effect regions** in THEMIS

THEMIS index **scales with mass**

*N.B. The mass of the service vehicle performing ADR is kept constant. α values all set to 90%.

Direct removal

Sensitivity on:
X $\boldsymbol{mass}$ of the target satellite*
Y Operational altitude of the target satellite $\boldsymbol{h_{op}}$

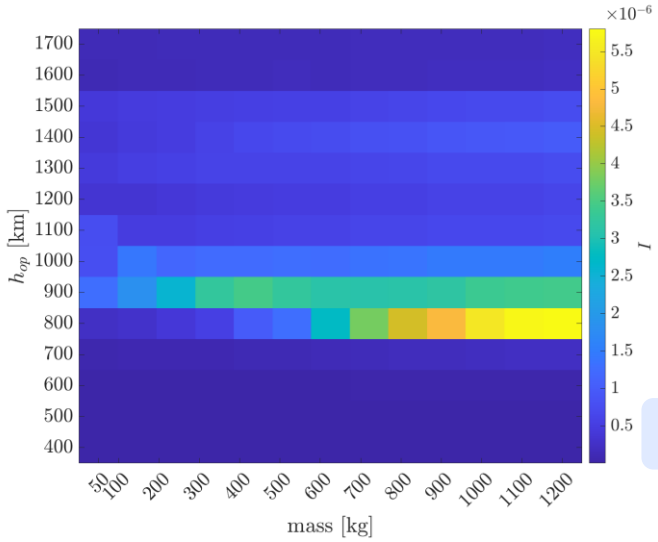


Fig. 9 Sensitivity matrix of THEMIS index value for ADR mission with respect to h_{op} and $mass$.

THEMIS index

ADR more beneficial than no action with $\mathbf{h_{op}}$ **higher than a threshold** variable with mass
Mass influences also the **drag** effect

Risk of ADR in already **critical regions of THEMIS**

ADR brings larger index **reduction over 25 y** PMD than 5 y

ADR
No action

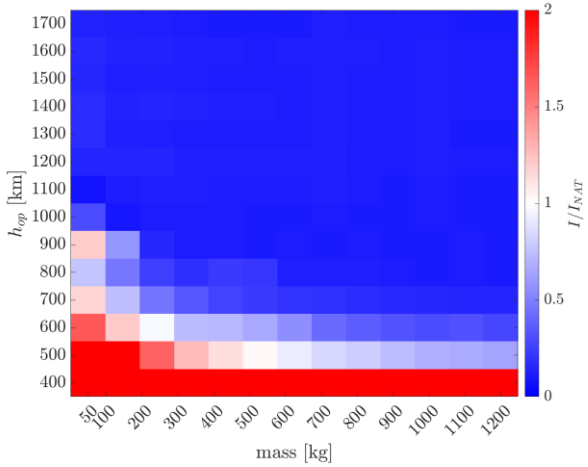


Fig. 10 Ratio of THEMIS index values for ADR mission and natural decay.

ADR
5 y PMD

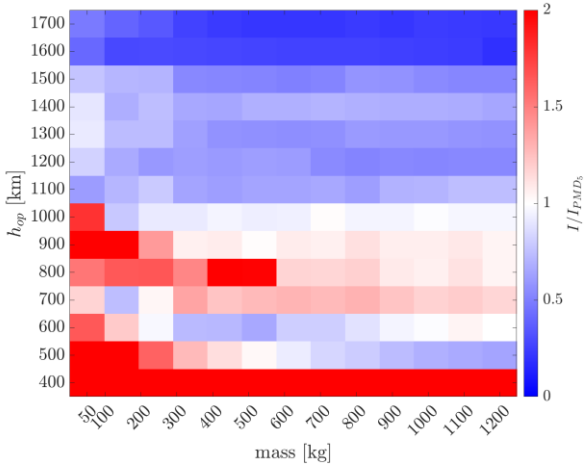
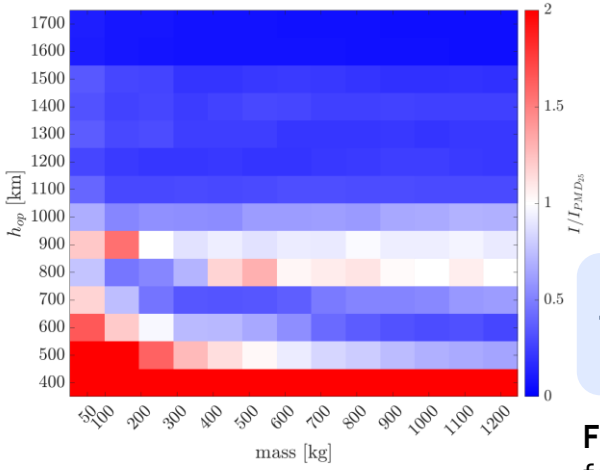


Fig. 11 Ratio of THEMIS index values for ADR mission and PMD within 5 y.



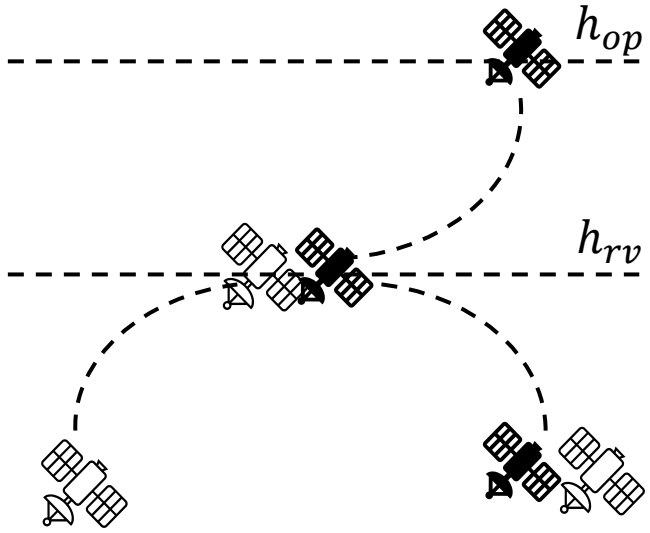
ADR
25 y PMD

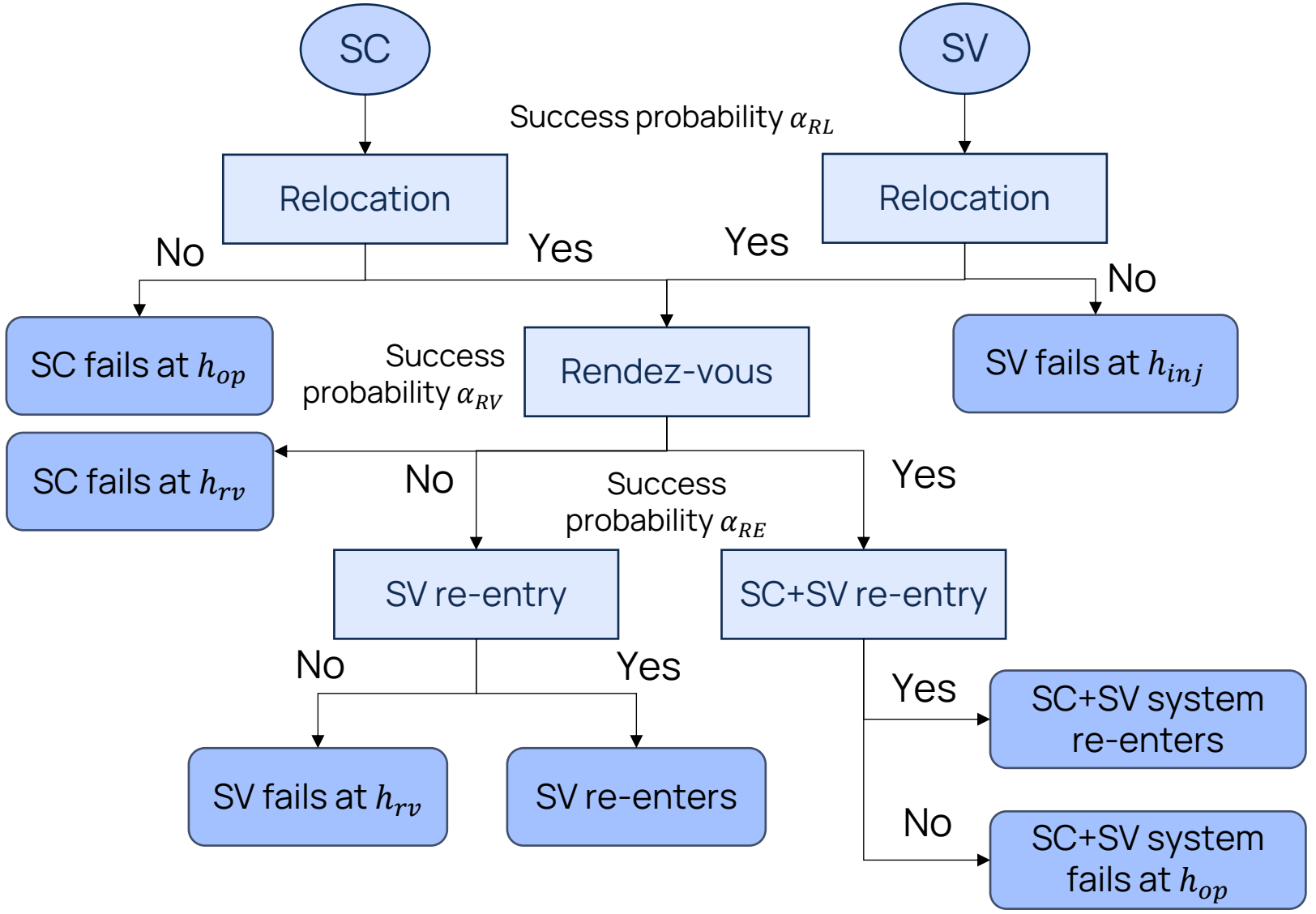
Fig. 12 Ratio of THEMIS index values for ADR mission and PMD within 25 y.

Removal with relocation

SV:
1. Injection at 500 km
2. Relocation to rendez-vous orbit
3. Rendez-vous
4. Re-entry

SC:
1. Relocation to rendez-vous orbit (from 815 km)
2. Rendez-vous
3. Re-entry





Removal with relocation

Sensitivity on:
- Success probability of relocation (SV or SC) $\boldsymbol{\alpha_{RL}}$

X Success probability of direct re-entry (SV or SC+SV) $\boldsymbol{\alpha_{RE}}$

Y Success probability of rendez-vous $\boldsymbol{\alpha_{RV}}$

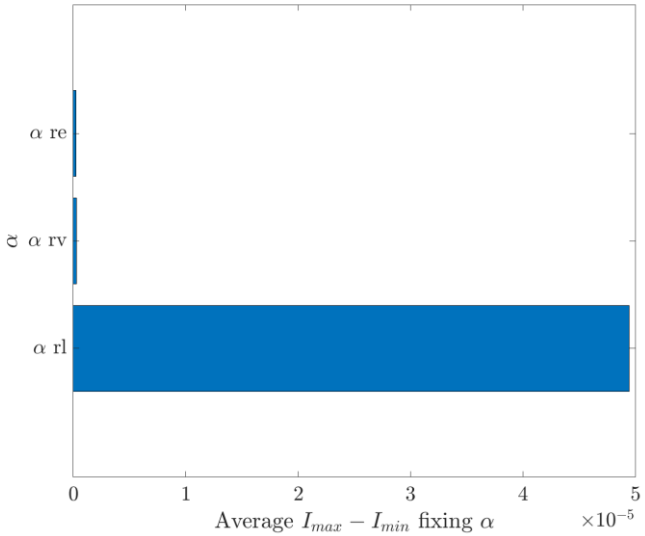
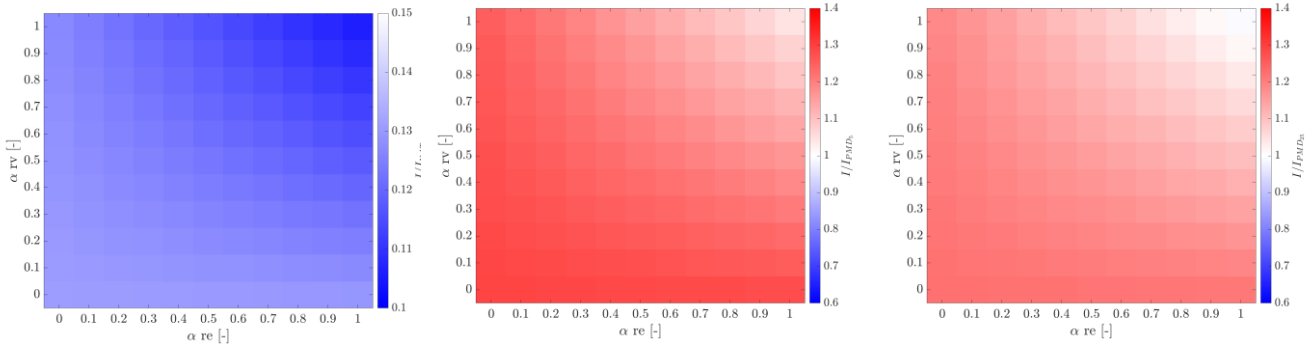


Fig. 13 THEMIS index average maximum variation due to α_{RL}, α_{RV}, α_{RE}.

$\boldsymbol{\alpha_{RL}}$ is the parameter that **influences the most** the index value

Success probability of relocation (SV or SC) α_{RL} set to **90%**



Success probability of relocation (SV or SC) α_{RL} set to **95%**

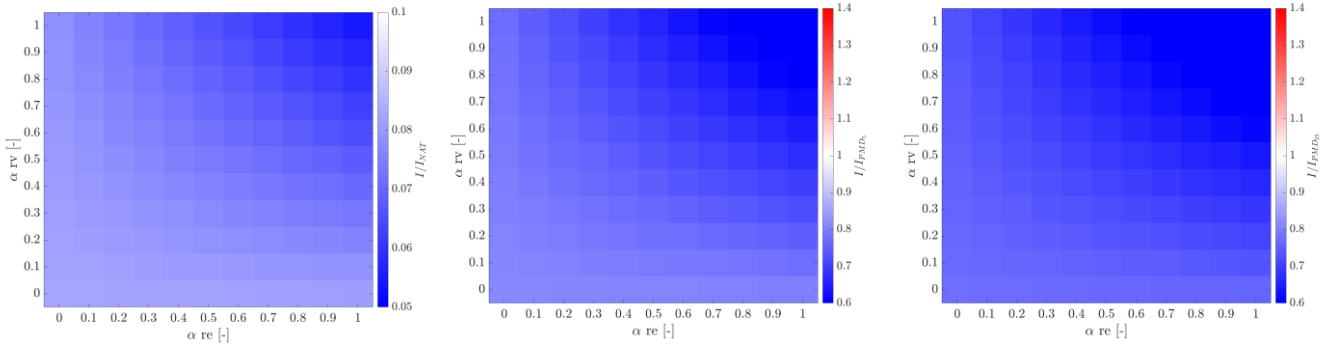


Fig. 14a Ratio of THEMIS index for ADR mission and natural decay.

ADR / **No action**

Fig. 14b Ratio of THEMIS index for ADR mission and PMD within 5 y.

ADR / **25 y PMD**

Fig. 14c Ratio of THEMIS index for ADR mission and PMD within 25 y.

ADR / **5 y PMD**

Removal with relocation

Sensitivity on:
X Rendez-vous altitude for ADR removal $\boldsymbol{h_{rv}}$
Y Operational altitude of the target satellite $\boldsymbol{h_{op}}$

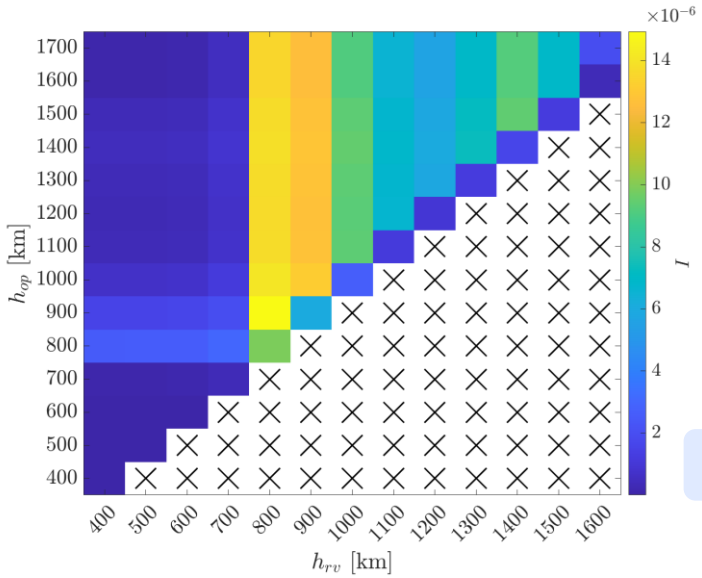


Fig. 15 Sensitivity matrix of THEMIS index value for ADR mission with respect to h_{op} and h_{rv}.*

ADR index has a sharp **increase** when the **high-risk regions** above 800 km are considered as **rendez-vous altitude**.

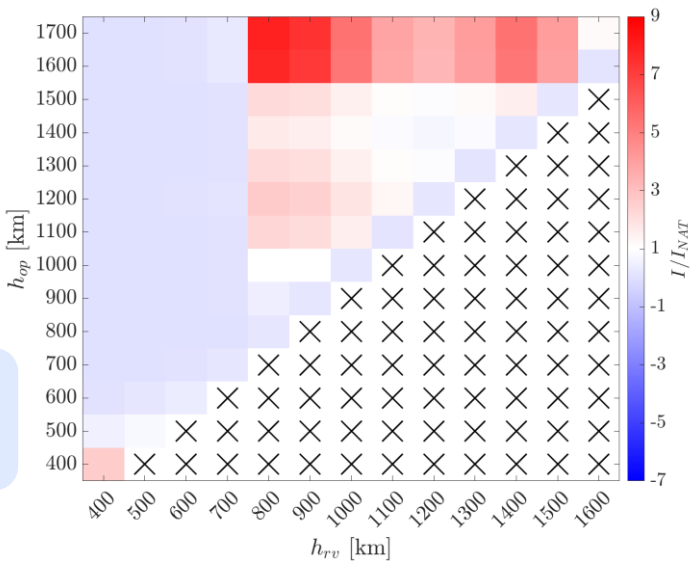
THEMIS index

*N.B. h_{rv} values higher than h_{op} are discarded. α values all set to 90%.

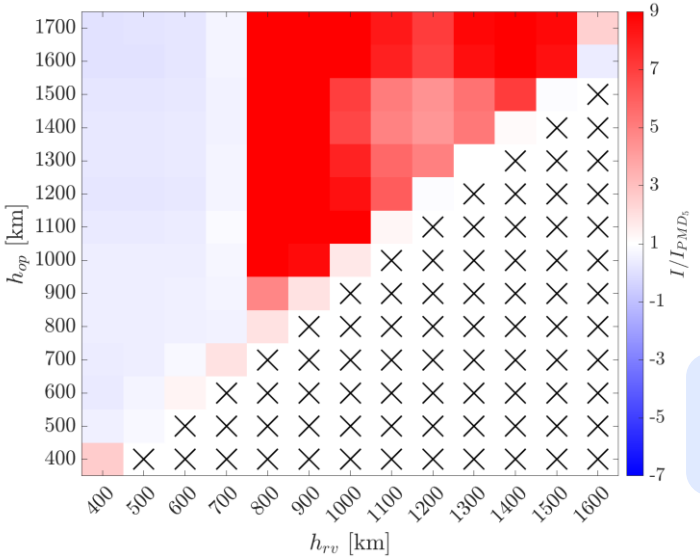
Removal with relocation

Sensitivity on:
X Rendez-vous altitude for ADR removal h_{rv}
Y Operational altitude of the target satellite h_{op}

ADR
No action



ADR
5 y PMD

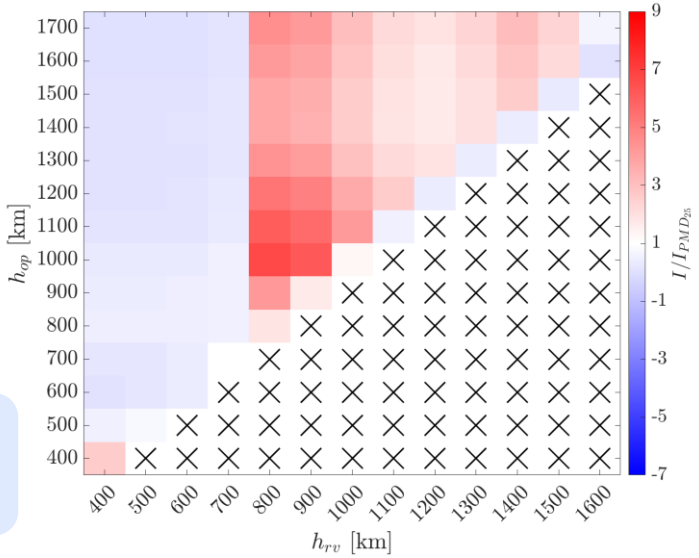


Relocation from very high altitude would cause **crossing all the high effect regions** during re-entry

SC relocation is a **possibly failing phase**

Direct **ADR from h_{rv} is more convenient** than natural re-entry, up until SC relocate from very high altitude and low effect orbit.

ADR
25 y PMD



ADR
PMD at h_{rv}

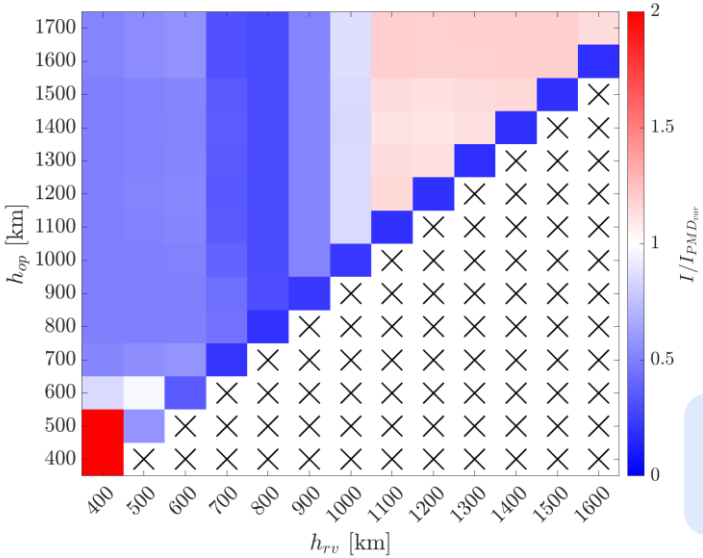


Fig. 16 Ratio of THEMIS index values for: ADR mission and natural decay (**top left**), ADR mission and PMD within 5 y (**top right**), ADR mission and PMD within 25 y (**bottom left**) and ADR mission and PMD at h_{rv} (**bottom right**, different scale).

Is Active Debris Removal Beneficial? An Environmental Risk Analysis with THEMIS 1.0

It depends

An ADR mission involves deploying an **additional satellite** into an already **hazardous environment**, which inherently increases the overall environmental risk

High reliance of the mission phases is crucial
ADR mission profile plays a fundamental role

The most **densely populated** and hazardous regions of the space environment are those where **mitigation measures are most urgently needed**

Nominal PMD can be more beneficial in risky regions

Mission-based environmental indicators can be used for **ADR mission design** and **long-term mitigation planning**

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Thank you for the attention

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