A Handbook for Post-Mission Disposal of Satellites Less Than 100 kg

IAA Study Group 4.23

http://www.iaaweb.org/iaa/Scientific%20Activity/sg423finalreport.pdf

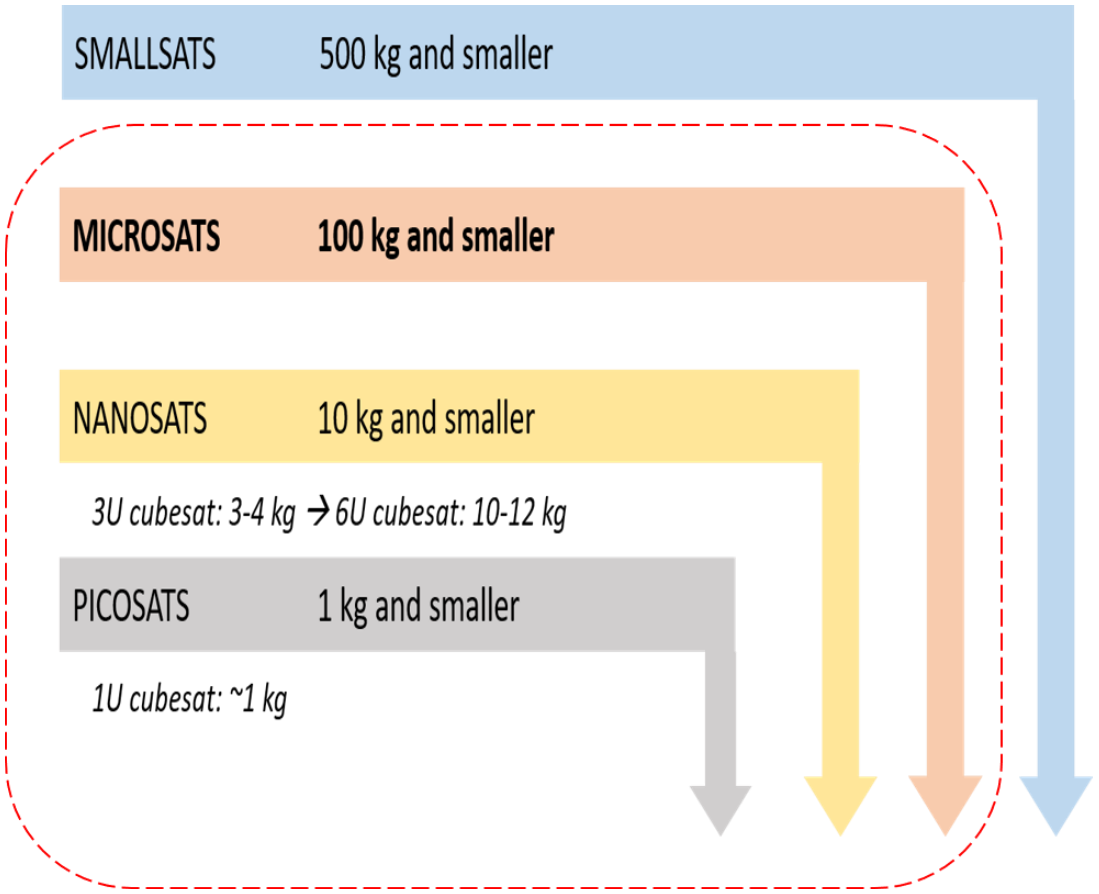
Prof. Dr. Rene Laufer

62nd UNCOPUOS Session, Vienna

June 19, 2019

Objective and Scope of PMD Design Handbook

- Identify debris mitigation guidelines and engineering options to satisfy requirements via post mission disposal (PMD)
- For satellites less than 100 kg in mass
- Written by experts in the field of debris mitigation and spacecraft design



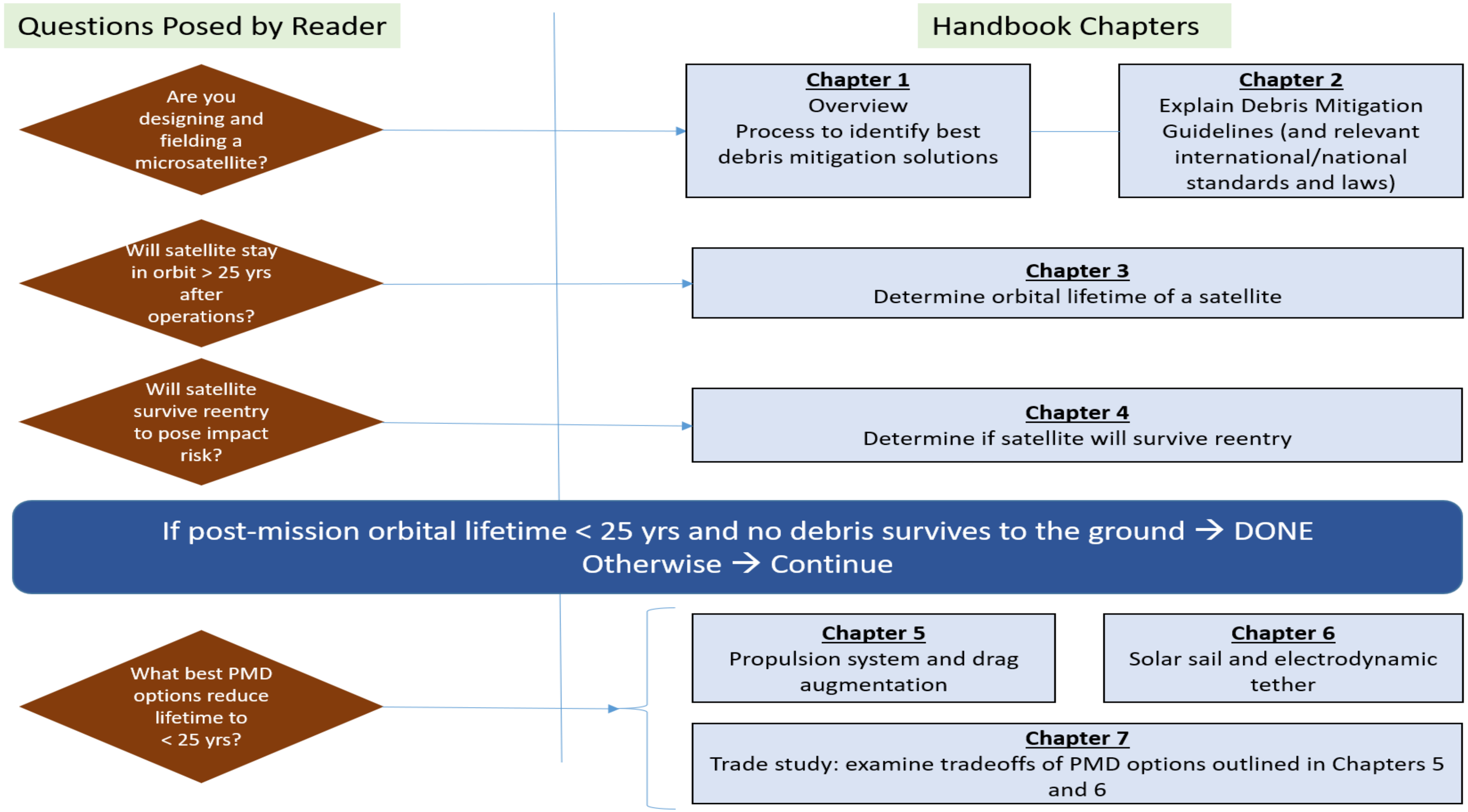
Debris Mitigation Guidelines

- In general, all the space debris mitigation rules (such as ISO 24113) apply to any spacecraft, whatever its size.
- Debris mitigation guidelines for this handbook basically present four major requirements:

1. Passivate energetic sources, such as batteries, and vent excess propellant.
2. Eliminate creation of debris, this includes avoiding explosions and collisions.
3. Ensure that all objects left on-orbit are reentered within 25 years after the end of operational life (EOL) or moved to an acceptable graveyard orbit; both with a probability of 90%.
4. Suggest re-entry casualty risk to humans be less than 10^{-4}.

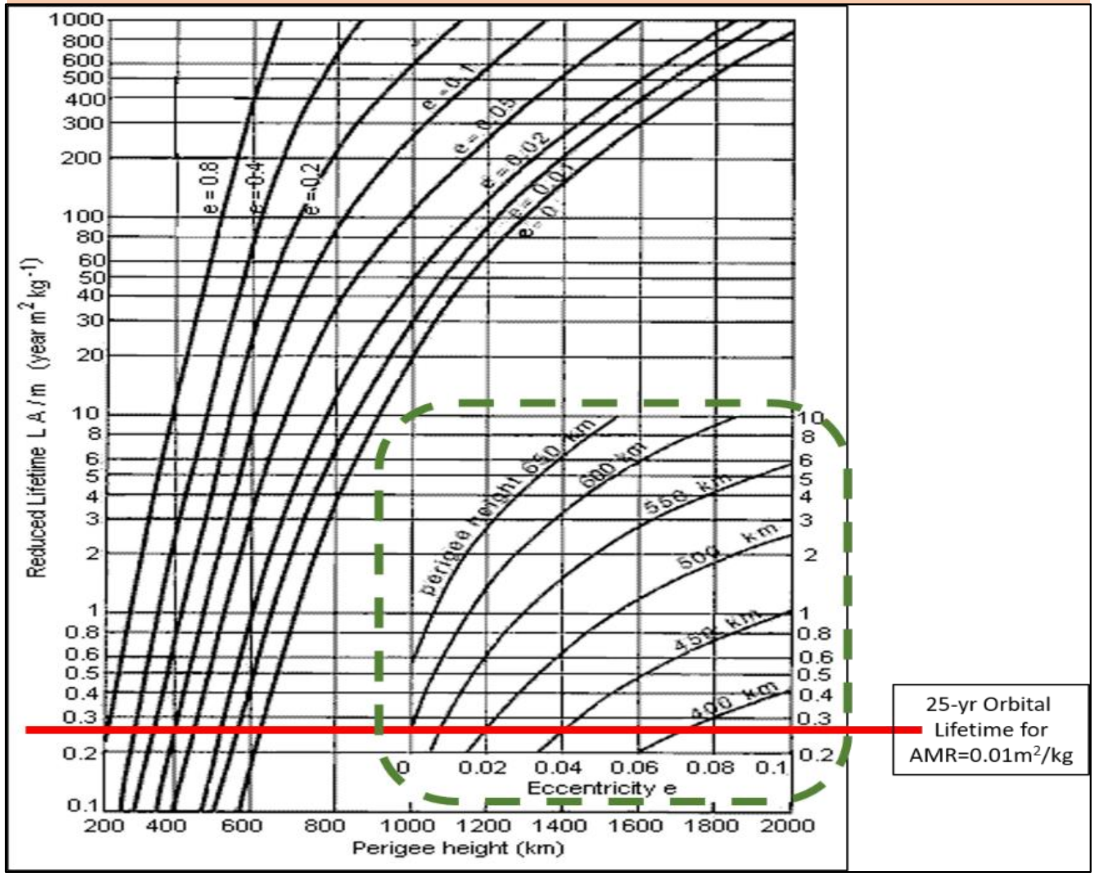
- This handbook primarily focuses on the last two requirements.

Handbook Organization



Calculating Orbital Lifetimes: An Art and Science

Empirical – Simple, Intuitive



Analytical – Complete, Accurate

- STELA
  - ✓ **S**emi-analytic **T**ool for **E**nd of **L**ife **A**nalysis
  - ✓ Procured by *CNES* to support the *French Space Operations Act*
  - ✓ STELA is available for download
    - ❑ https://logiciels.cnes.fr/en/content/stela
- Provides flexibility and accuracy in dealing with varying spacecraft orientations, solar activity levels, and altitudes/orbits

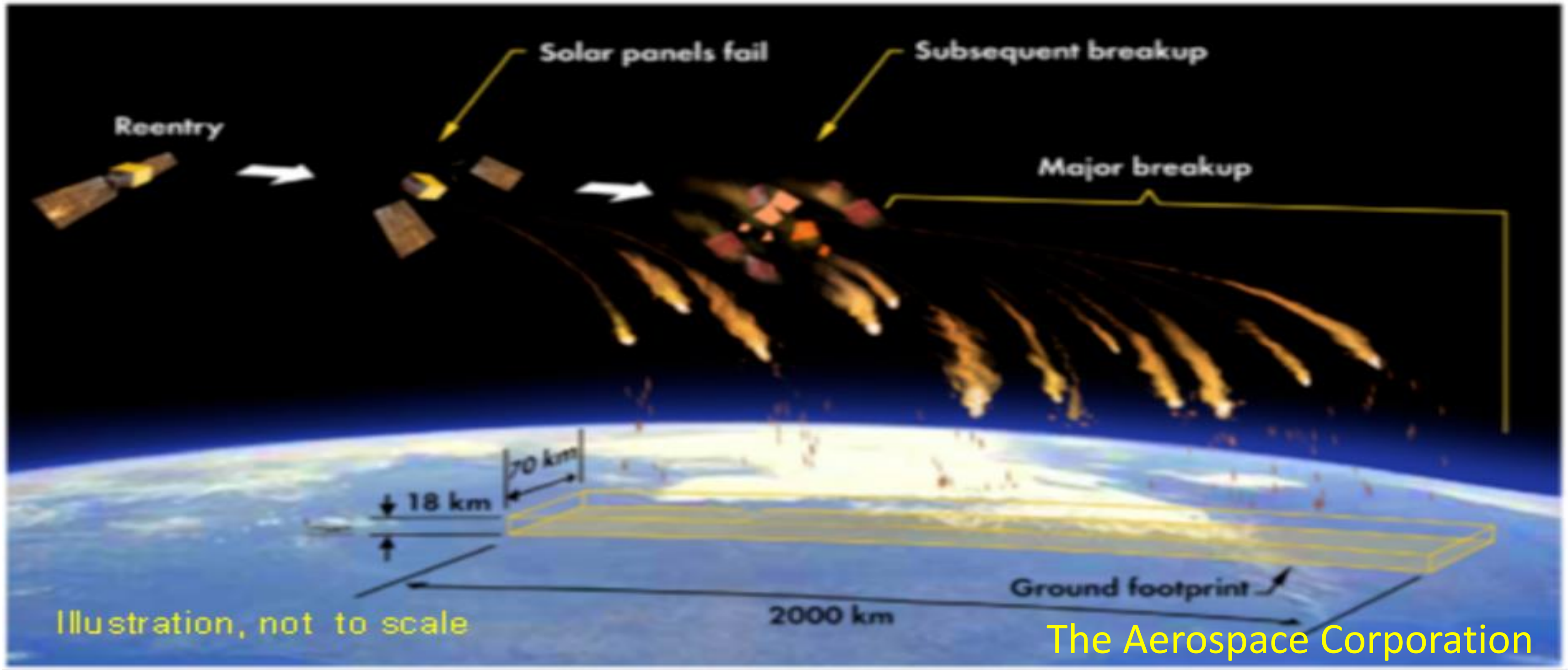
✓ **Meet 25-year threshold in LEO: circular below ~625km or perigee below ~400km**

✓ **Effect of increased area increasing drag is evident…**

Re-entry Survival

- Four primary characteristics that drive re-entry survival:
  - ✓ Material: typically aluminum and circuit boards
  - ✓ Mass: under 100kg (for microsats and smaller)
  - ✓ Construction: no hardened or especially densely-packed components
  - ✓ Re-entry Trajectory: due to contraction from atmospheric drag

Material	**Mass**
Construction	**Re-entry Trajectory**



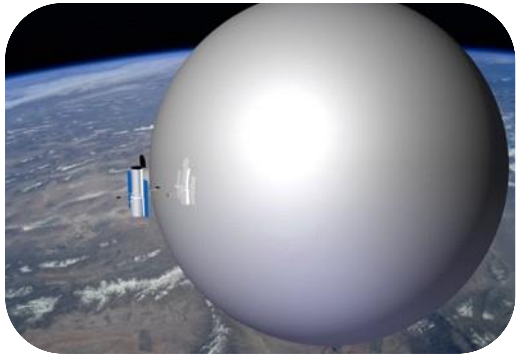
- Microsats and smaller satellites will pose little air or ground impact risks

- Beware of densely-built components such as control moment gyros and batteries

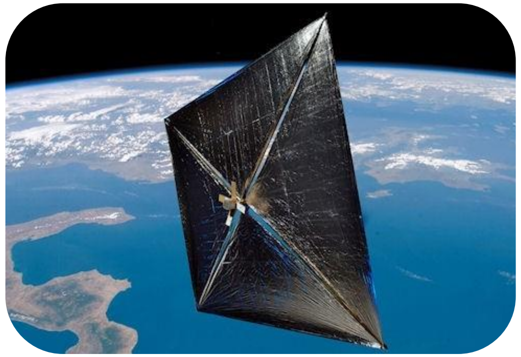
PMD Options

$$\Delta V = V_e \ln\left(\frac{m_o}{m_f}\right)$$

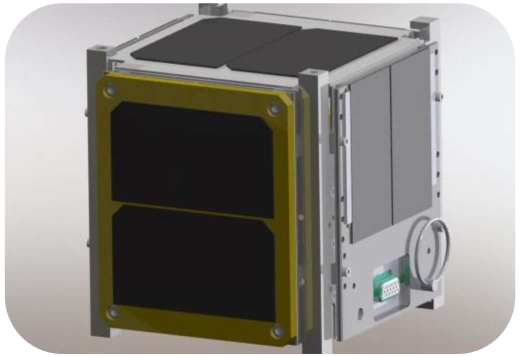
Propulsive



Drag Augmentation



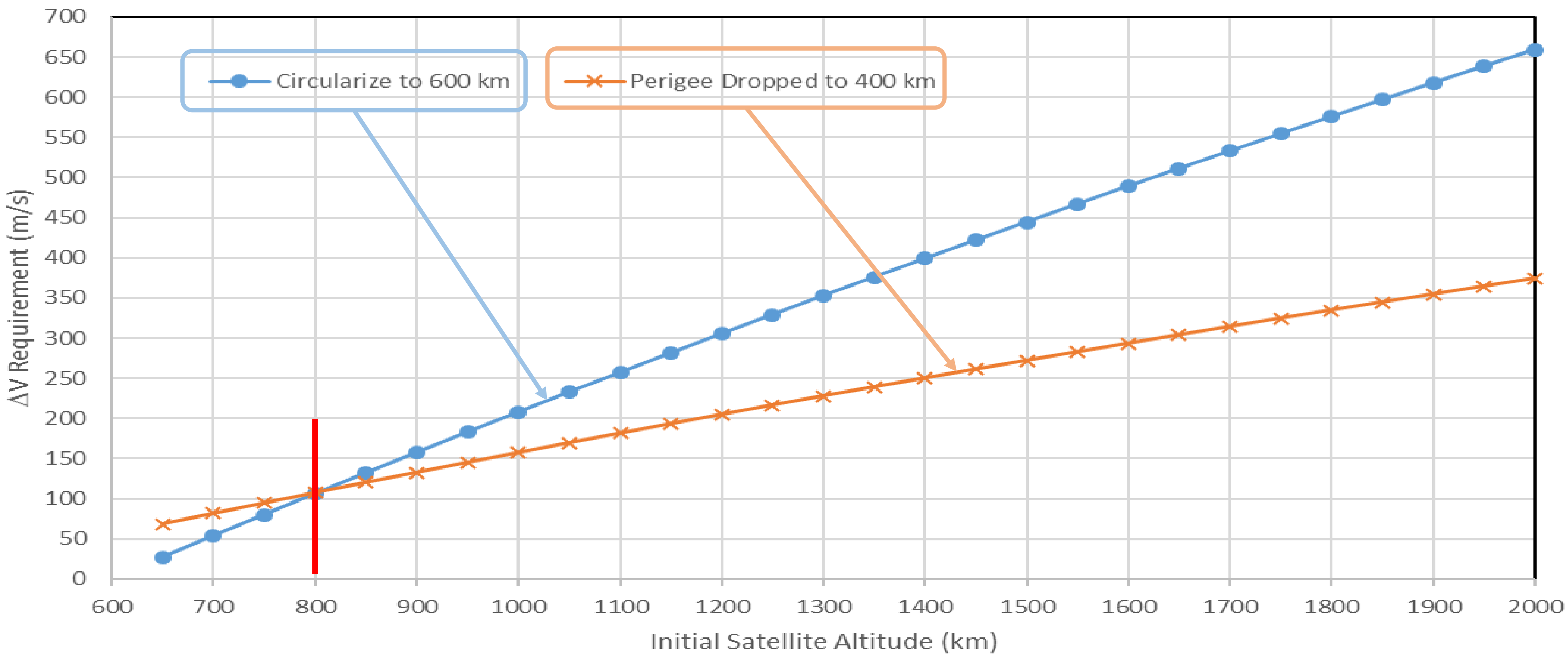
Solar Sail



Electrodynamic Tether

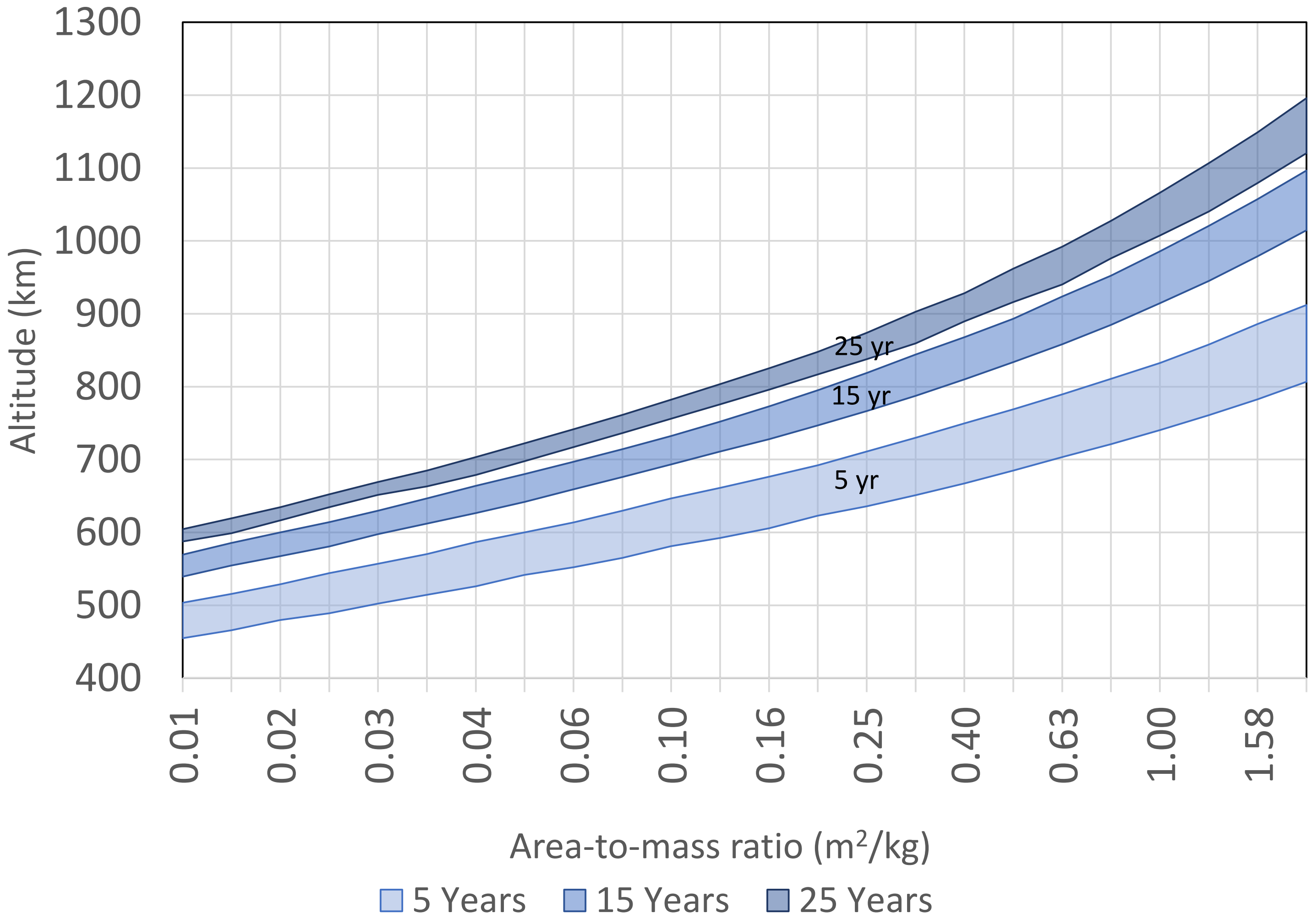
Reduce Lifetime by Propulsion

✓ Strategy varies across LEO: requires 10s to 100s m/s of delta velocity depending on altitude and strategy to meet the 25-year rule



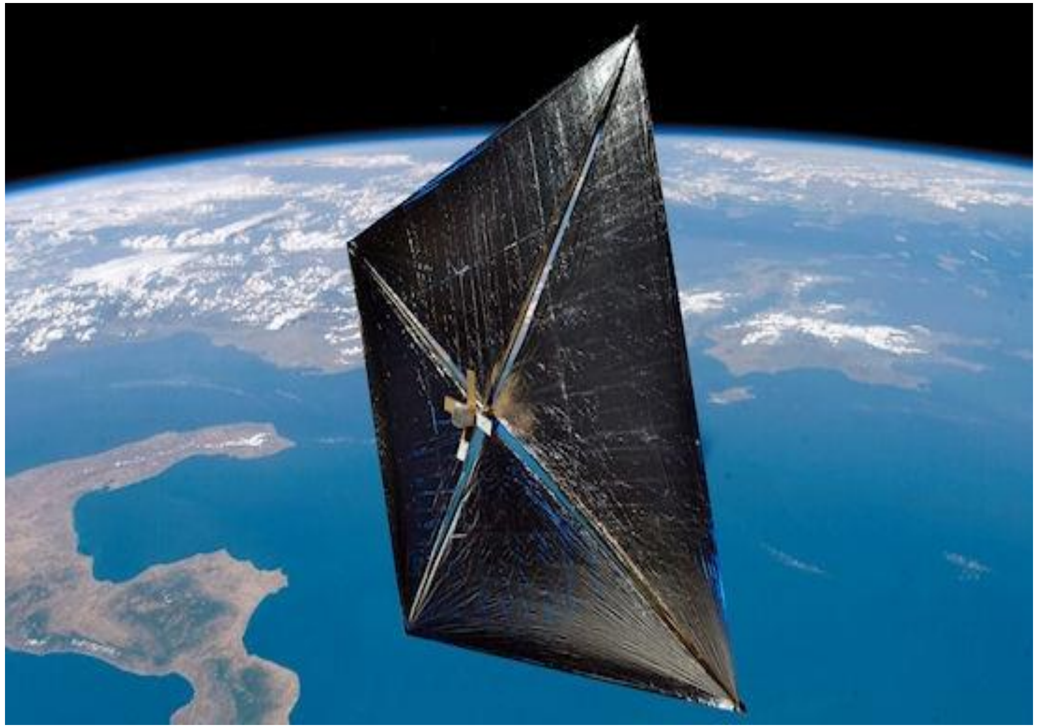
Altitude vs Time to Deorbit

As Function of Area-to-Mass Ratio

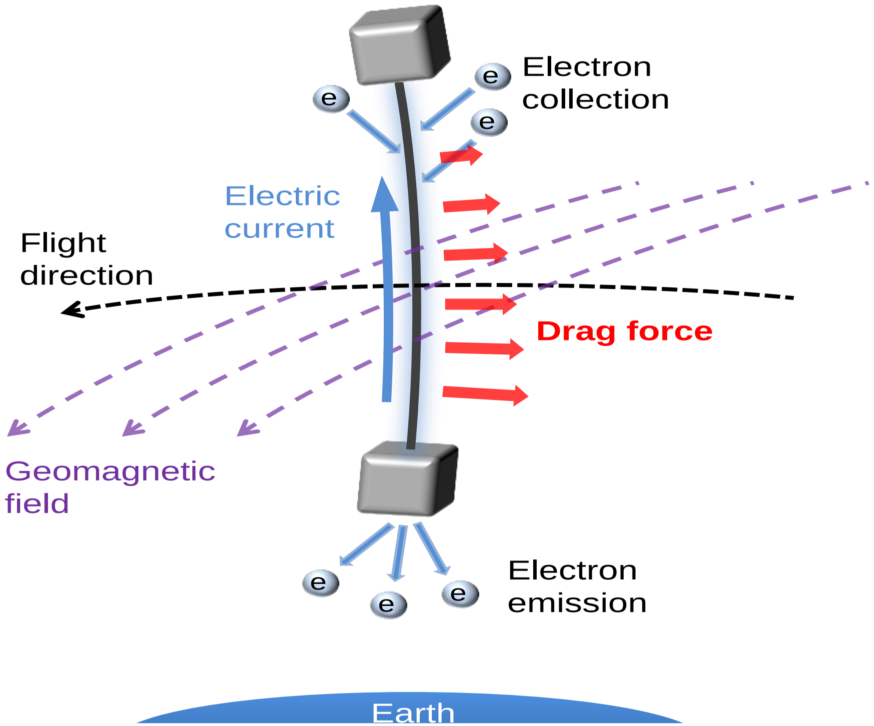


Reduce Lifetime by Non-Drag Forces

- Solar Radiation Pressure



- Electrodynamic Tether (EDT)

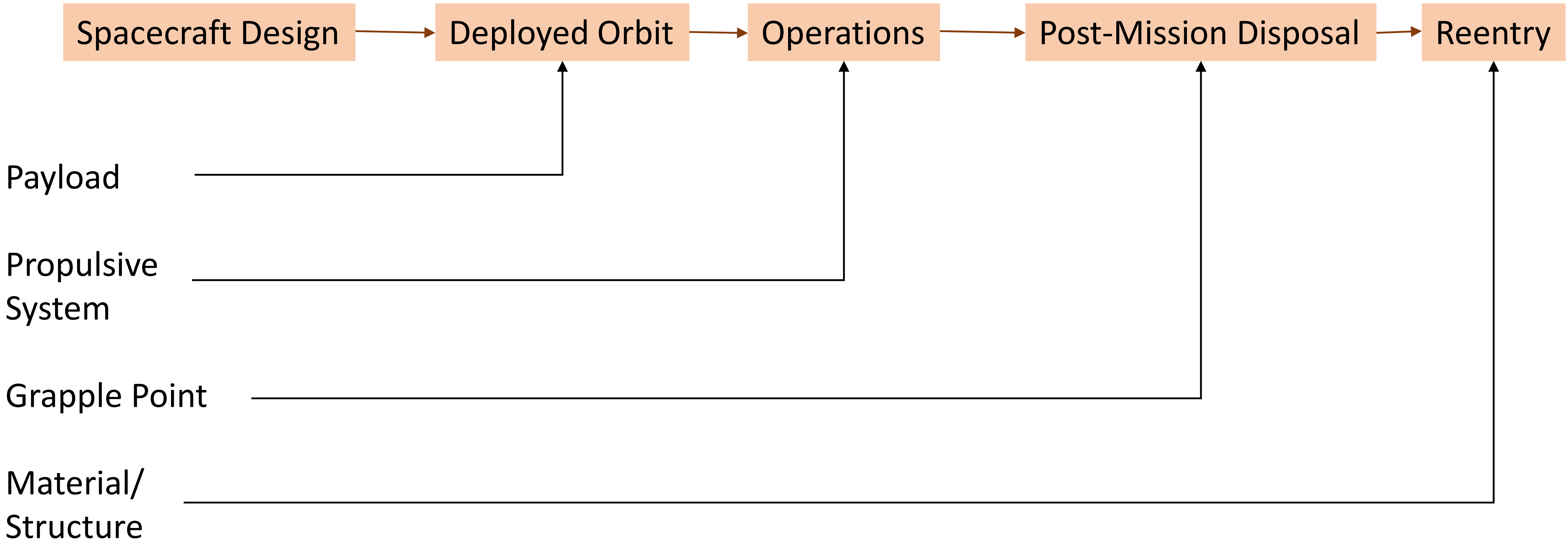


✓ **Solar - simple, slow**; deal with stability, durability, & collision cross-section issues

✓ **EDT - flexible, fast**; deal with stability, durability, & collision cross-section issues

Trade Study – What is Best for you?

- What can you control and what will provide greatest effects?



Key PMD Design Observations

- Satellite missions below 800 km have more available options since drag can help removal and the distance needed to move the system is less.
  - ✓ Circularize to 600 km is most efficient
- Between 800-1,000 km altitudes, there are several PMD approaches that can assist in the reduction of orbital lifetime with varying SWAP and operational complexity burdens.
  - ✓ Drop perigee to 400 km is most efficient
- Above 1,000 km altitude, only propulsive systems and solar sails are viable.
  - ✓ Drop perigee to 400 km is most efficient

- While there have not been any detailed reliability discussions in the tradeoff analysis it may be reasonably assessed that approaches that have been used often and reliably in the past will be more reliable.
- The most used to least used for orbit moving are:
  - ✓ First, <u>propulsion</u> then <u>drag augmentation</u> then <u>solar sail</u> and, lastly, <u>EDT</u>.

Trade Study Results

		3U / 5 kg @700 km, 65° inclination	100 kg/1 m² @700 km SSO	100 kg/1 m² @800 km SSO	100 kg / 1 m² @1000 km, 90° inclination
No deorbit	Lifetime	80 yr	50 yr	>150 yr	>800 yr
	Integrated Collision Risk	1.70E-05	4.00E-04	2.30E-03	1.00E-02
Cold Gas Lower Perigee Specific Impulse = 60 s	Lifetime	25 yr	25 yr	25 yr	25 yr
	ΔV [m/s]	42	28	67	133
	Consumed Mass [kg]	0.35	4.7	11	20
	Integrated Collision Risk	3.00E-06	1.60E-04	1.80E-04	2.20E-04
Electric Propulsion Specific Impulse = 1600 s Total Thrust = 40 mN	Lifetime	25 yr	25 yr	25 yr	25 yr
	ΔV [m/s]	47	30	82	182
	Thrust Duration [h]	1.63	21	56	125
	Consumed Mass [kg]	0.015	0.20	0.52	1.15
	Integrated Collision Risk	3.00E-06	1.60E-04	1.70E-04	2.00E-04
Drag-Augmentation Device Gossamer Device	Lifetime	25 yr	25 yr	25 yr	25 yr
	Cross sectional surface [m²]	0.1	2	6	40
	Integrated Collision Risk	1.60E-05	4.00E-04	8.00E-04	1.30E-02
Drag-Augmentation Device Stabilized Drag Sail	Lifetime	25 yr	25 yr	25 yr	25 yr
	Cross sectional surface [m²]	0.1	2	6	40
	Integrated Collision Risk	1.60E-05	4.00E-04	8.00E-04	1.30E-02
Drag-Augmentation Device Tumbling Drag Sail	Lifetime	25 yr	25 yr	25 yr	25 yr
	Cross sectional surface [m²]	0.1	2	6	40
	Drag sail surface [m²]	0.25	4	12	81
	Integrated Collision Risk	1.60E-05	4.00E-04	8.00E-04	1.30E-02
Passive EDT	Lifetime	25 yr	25 yr	25 yr	25 yr
	Tether length [m]	12	120	320	340
	Tether width [mm]	10	25	25	100
	Increment of drag surface [m²]	0.12	3	8	34
	Integrated Collision Risk	2.46E-05	8.43E-04	1.19E-03	1.14E-02

Key Issues Addressed by the PMD Handbook

- EFFECTIVE: Will it work?
  - ✓ Can the change in altitude be made by the approach selected? The higher the altitude, the more change is needed.
- SWAP: What size, weight, and power (SWAP) is required to implement this approach?
  - ✓ Certain approaches have greater engineering requirements that require additional hardware, software, and controls to be deployed. Clearly, the smaller your satellite the more likely that these requirements will be demanding.
- RELIABILITY: How reliable is the PMD option?
  - ✓ The reliability required for PMD execution is at least 90% but evolving discussions are pushing likely reliability levels to 95% and even to 99%.
  - ✓ This may limit PMD options for your use even further. This metric is even more challenging when it is likely that many of these PMD devices will be activated after having been on-orbit for many years.
- ORBITAL COLLISION RISK: Did you create more risk by executing your PMD?
  - ✓ This is examined as the area-time-product for collision risk but also includes the potential for debris generation during a PMD deployment (e.g., tether release or deployment of a drag-augmentation device).
- GROUND IMPACT RISK: Does your system pose a hazard above the suggested 10^{-4} probability of casualty on the ground?
  - ✓ If you have to execute a controlled re-entry due to the potential of some of your hardware posing an impact risk to people on the ground, this will likely limit your PMD option to a propulsive system with assured attitude control until re-entry.

Closing Thoughts

- Responsible behavior in space is important for all users

- Everything related to orbital debris is moving quickly…
  - ✓Collision risk
  - ✓Regulatory activities
  - ✓Engineering options

- This handbook provides valuable snapshot of issues but any space operator will need to be proactive and persistent in keeping up on the evolving situation

Contributors

- ***Editors***

Rei Kawashima, UNISEC-Global & Darren McKnight, Centauri Corporation

- ***Primary Authors***

Darren McKnight, Centauri Corporation	Chapter 1&3
Christophe Bonnal, CNES	Chapter 2
Daniel Oltrogge, AGI	Chapter 2
Martha Mejía-Kaiser, IISL	Chapter 2
Alim Rüstem Aslan, Istanbul Technical University	Chapter 3
David B. Spencer, Penn State University	Chapter 4
Fabio Santoni, Sapienza University of Rome	Chapter 5
Norman Fitz-Coy, University of Florida	Chapter 5
Lourens Visagie, Stellenbosch University	Chapter 5
Alfred Ng, CSA	Chapter 5
Aaron Q. Rogers, SSL	Chapter 5
Satomi Kawamoto, JAXA	Chapter 6
Sergey Trofimov, KIAM RAS	Chapter 6
Juan-Carlos Dolado Perez, CNES	Chapter 7
Marlon Sorge, The Aerospace Corporation	Chapter 7

- ***Reviewers***

Vladimir Agapov, Keldysh Institute of Applied Mathematics RAS
Alex da Silva Curiel, SSTL
George A Danos, Cyprus Space Exploration Organisation (CSEO)
Laurent Francillout, CNES
Livio Gratton, Colomb Institute
Akira Kato, JAXA
Toshiya Hanada, Kyushu University
Scott Hull, NASA Goddard Space Flight Center
Mohammed Khalil Ibrahim, Cairo University
Heiner Klinkrad, TU Braunschweig
Rene Laufer, Baylor University
Peter Martinez, Secure World Foundation
Barnaby Osborne, ESA
Mikhail Ovchinnikov, Keldysh Institute of Applied Mathematics RAS
Luca Rossettini, D-Orbit
Rainer Sandau, IAA
Hanspeter Schaub, University of Colorado
Thomas Schildknecht, University of Bern
Klaus Schilling, Julius-Maximilians-University Wuerzburg
Craig Underwood, University of Surrey
Benjamin Bastida Virgili, ESA/ESOC
Carsten Wiedemann, TU BraunschweigTetsuo Yasaka, iQPS Inc.