# Assessing impacts of Zero Debris approach on CubeSats: A System Analysis

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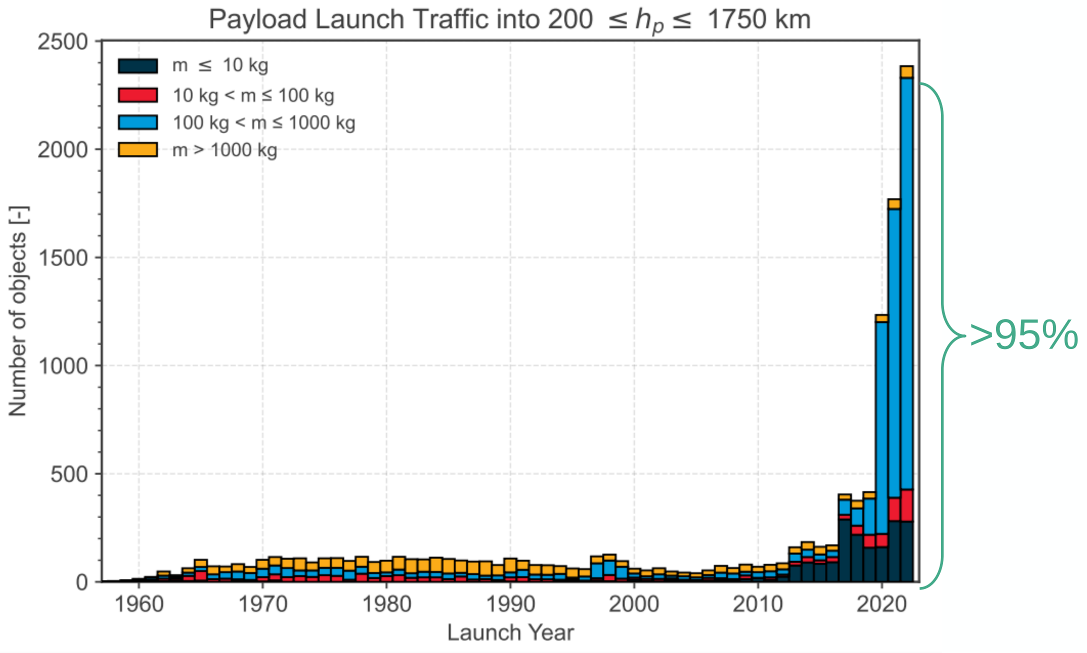
# Numbers: SmallSats in the global picture

## Current

More than **95%** of satellites launched in 2021 were < **1000kg**

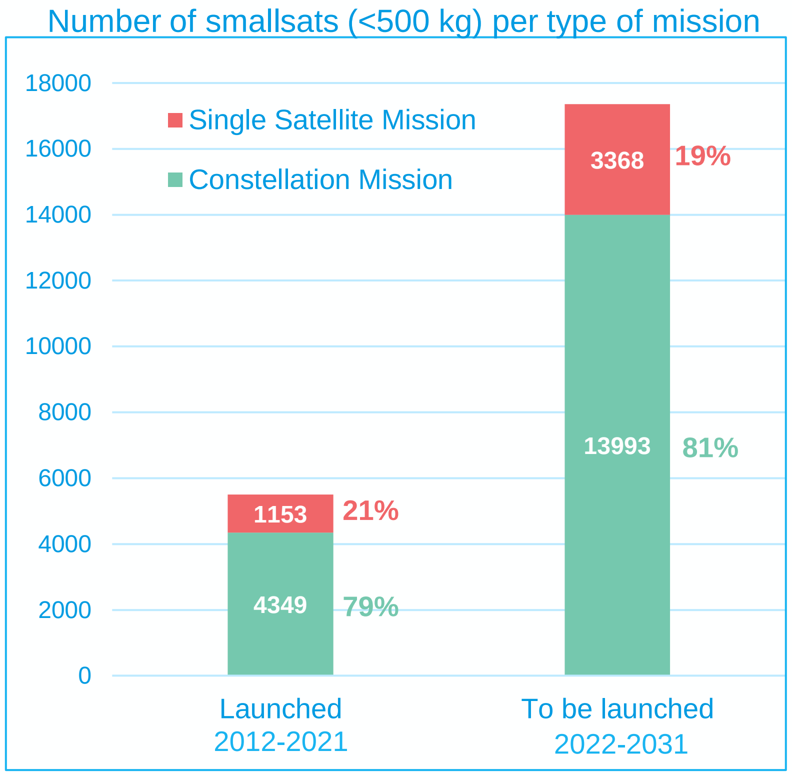



Source: ESA Space Environment report 2023

## Future

"A total of **3,335** smallsats <10kg are expected to launch throughout the next decade, i.e., **more than twice** the **1,656** launched over 2012-2021."

- Euroconsult

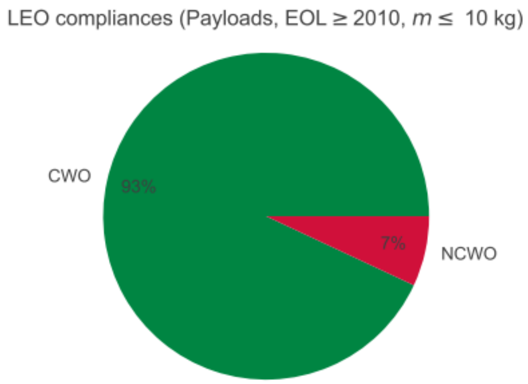



Source: Euroconsult, Prospects for the Small Satellite Market, 8th edition, July 2022

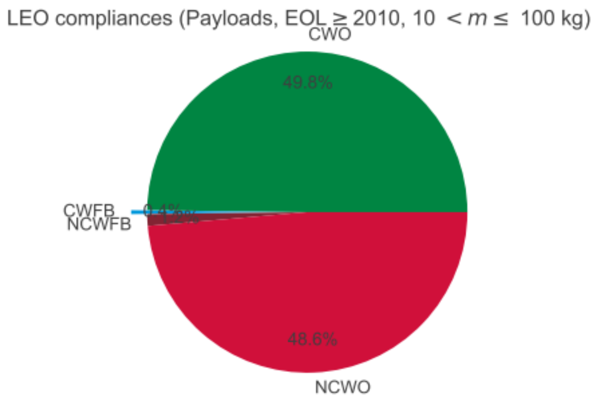
# Numbers: SDM compliance

Breakdown of observed behavioural classes for **disposal at EOL (<25 years)** per satellite mass:

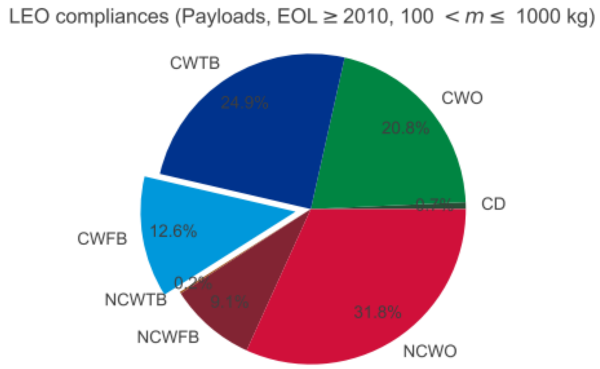
**< 10 kg**




**10 – 100 kg**




**100 – 1000 kg**




- Naturally compliant
- Compliant with disposal action
- Not compliant without attempt
- Not compliant with attempt

Average for EOL after 2010

Source: ESA Space Environment report 2023

- **More than 50%** of satellites in the range of **10-100 kg** not compliant to SDM Requirements
- Around 93% of SmallSats **<10 kg** are operating in **naturally compliant** orbits (i.e. orbital lifetime **< 25 years**)

# The 8 pillars of the Zero Debris Approach

esa

## 1 Applicable orbits

- **Extend space debris mitigation** measures to other earth orbits and lunar orbits.

## 2 Guarantee successful disposal

- Improve probability of successful **self-disposal**
- **Prepare for removal**

## 3 Improve orbital clearance

- **Reduce time** left in protected regions **below 5 years ***
- Improve clearance in **other Earth orbits**

## 4 Avoid in-orbit collisions

- Improve **collision avoidance strategy**
- Cumulative **probability of collisions after EoL < $10^{-3}$ ***
- Share **maneuver data**
- Improve **trackability**

## 5 Avoid internal break-ups

- **Mandatory** passivation features
- **0.95 * probability of successful passivation**

## 6 No intentional release of space debris

- **Prevent release** of launcher related objects and interference with valuable orbits

## 7 Limit on-ground casualty risk

- **Standardize** models and methods to assess demise
- **Improved demise** or controlled reentry of recurrent designs (e.g. launcher stages and constellations,)

## 8 Guarantee dark and quiet skies

- Mitigate impacts on **ground astronomy**

* numerical values subject to change in future updates

**Note**: Dedicated requirements for constellations

# LEO Orbital Clearance Requirements

## General requirements:

- **LEO** clearance in **<5 years** starting from:
  1) The **orbit injection epoch**, if the spacecraft has no manoeuvre capability
  2) The **end of mission epoch**, if the spacecraft has recurrent manoeuvre capabilities
- Recurrent **manoeuvre capabilities** when operating > 5 years
- **Probability of successful disposal >0,9** through to end of life

\+

## Constellations (>10):

- Mandatory **recurrent manoeuvre capability**

## Large constellations (>100)

- Injection into an **initial insertion orbit** with a natural orbital decay duration **< 5 years**
- **Disposal** orbit **apogee < 375 km**
- Probability **of successful disposal >0,95**

# LEO Orbital Clearance

**Orbital Clearance Requirements**
CubeSat in LEO

**Passive compliance**

**Injection** to an **orbit** with a natural decay < **5 years**

Operating **above 5 years**

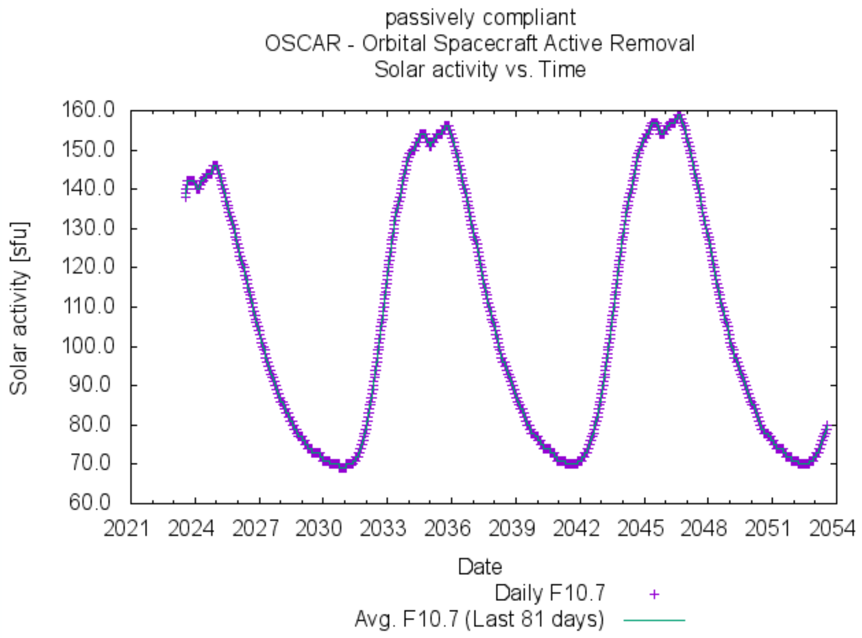
- **Recurrent manoeuvre capabilities**
  - Probability of **successful disposal >90%**
- Orbital clearance at EoL in **< 5 years**

# Injection altitude for passive compliance

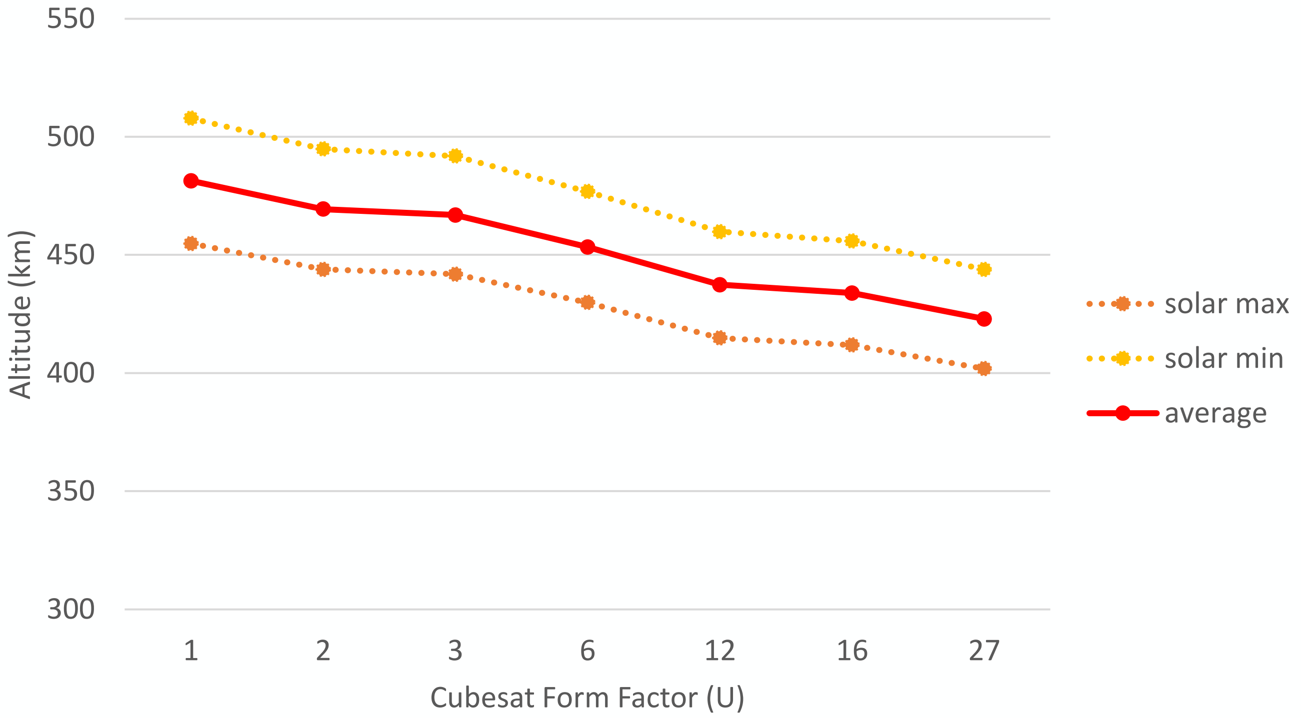
Residual lifetime computation is very sensitive to the model assumptions, in particular:

- **Solar activity –** variability depending on the starting epoch of the propagation and on the model
- Different **atmosphere density** models

ESA latest prediction model



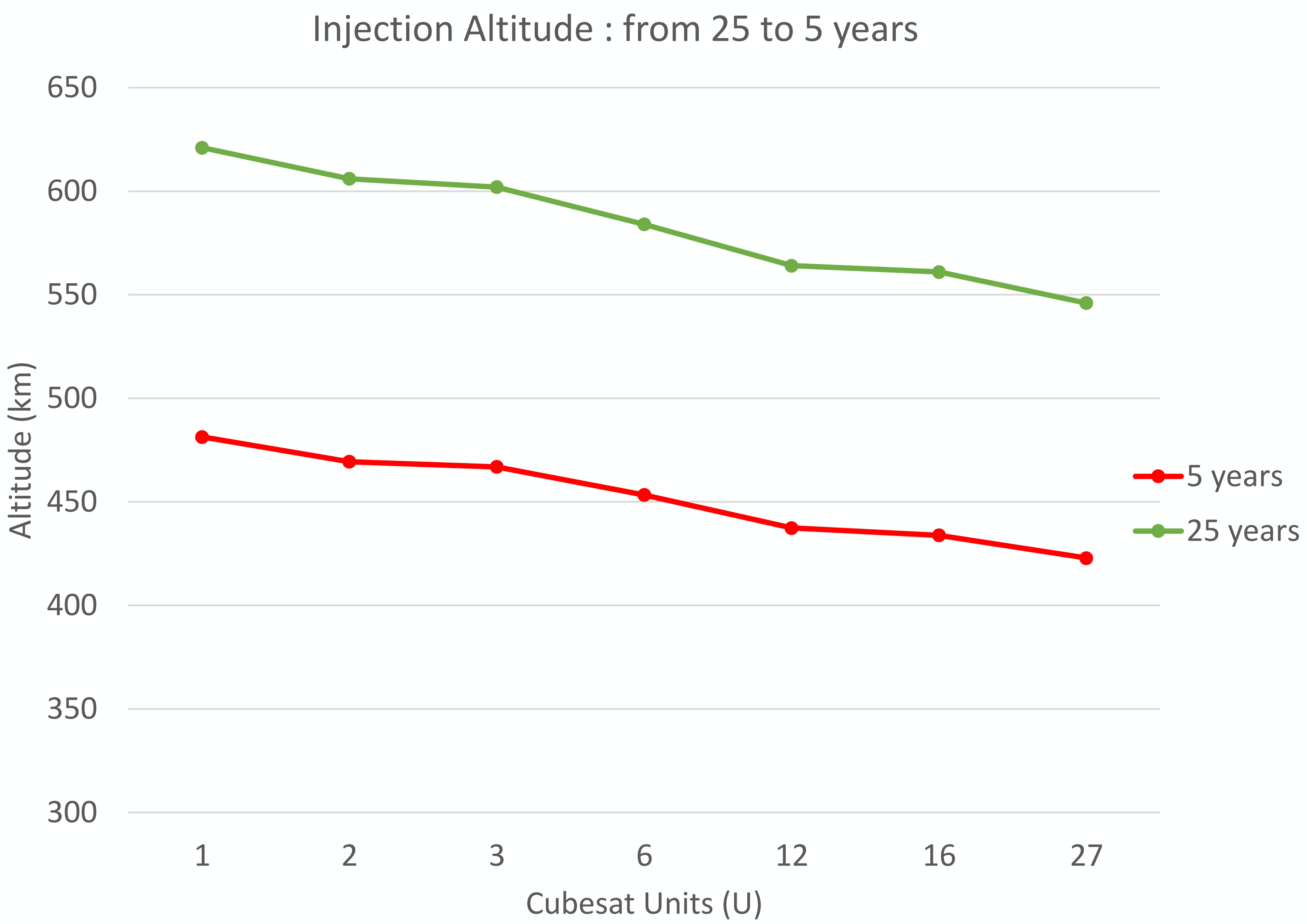

Injection Altitude for 5 years compliance



# Injection altitude for passive compliance

Injection altitude for **circular polar orbit**

- Computed for different CubeSat Form Factors with **no deployed surfaces**
- **Median value** varying the starting epoch throughout a full **solar cycle**
- **5% margin** on the 5 years lifetime (according to ISO 27852:2011)

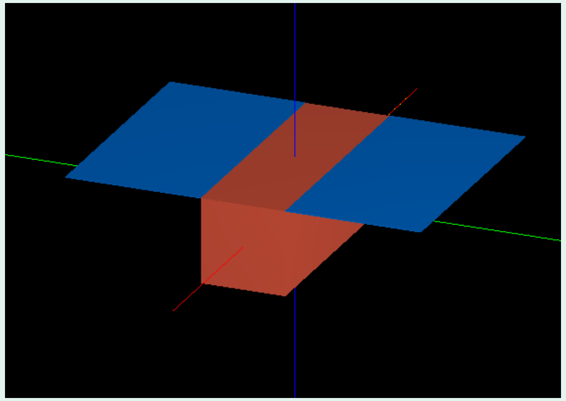


# Passive compliance - Reduction of mission lifetime

**5 years compliance** to be computed for:

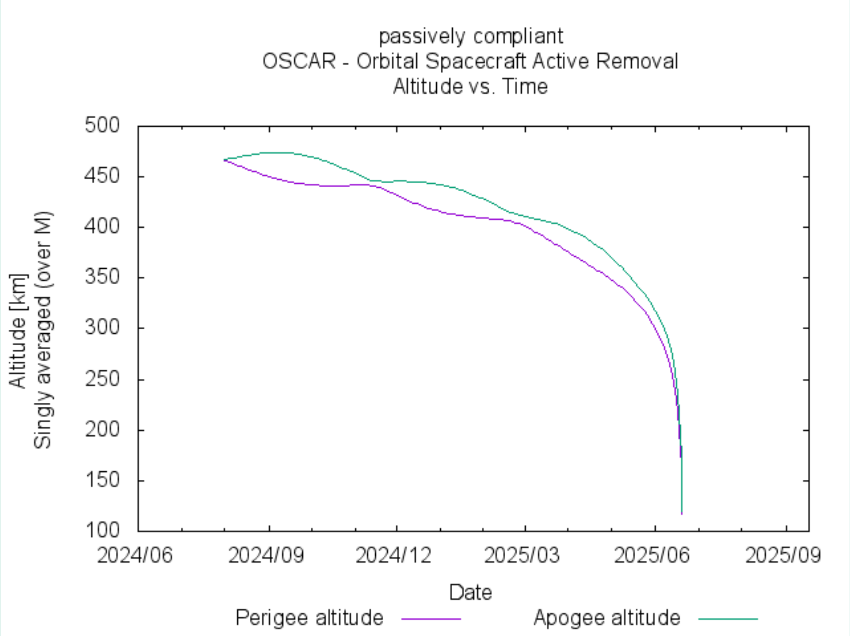
- **Dead-on-arrival scenario** (randomly tumbling, no deployed surfaces)
- **Operational configuration** (average surface, deployed solar panels)

Injection altitude **@460 km** - **compliance in the dead-on arrival scenario**



- **Solar panels deployment** after injection → Increase of the cross-section area

  Average cross section ~730 cm^2




**Remaining lifetime** of **0.9**

For orbit injection during a solar max

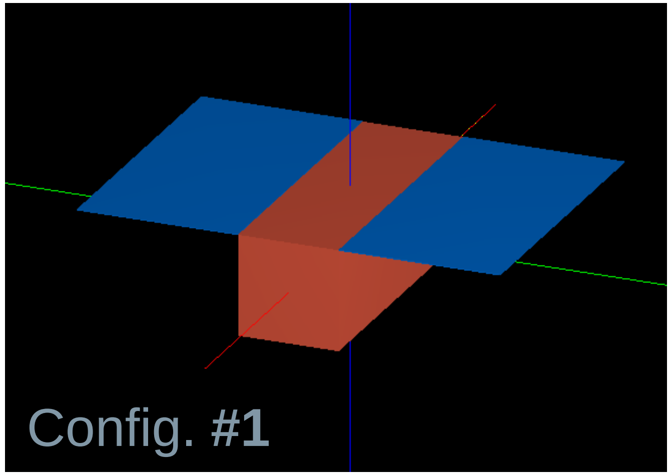
# Passive compliance - Reduction of mission lifetime

Attitude minimizing the cross section increases mission's lifetime

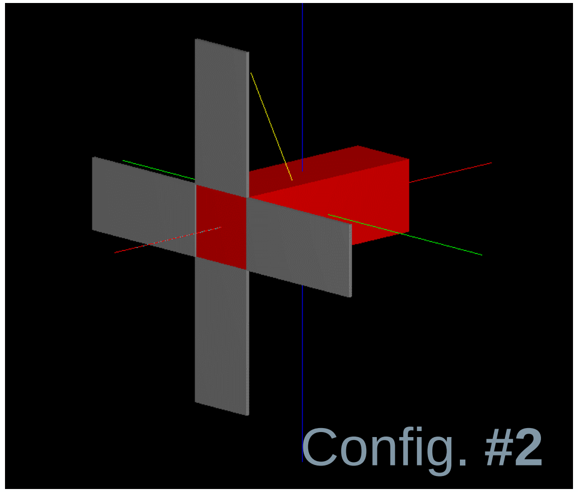
**Injection @460 km**

**Average** cross section (~730 cm^2) → **0.9** to **3.7 years** – Remaining lifetime

**Minimized** cross section (~104 cm^2) → **~11 years** – Max Remaining lifetime




… when compatible with mission constraints




**Average** cross section (700 cm^2) → **0.9** to **4 years** - Remaining lifetime

**Minimized** cross section (322 cm^2) → **2.7** to **6 years** – Max remaining lifetime

...and with the adopted solar panel configuration

# Orbit maintenance with EP - use case (3U with FEEP)

EP system for **3 years** orbit maintenance (for high solar activity case)

| **460 km**<br>**Injection for compliance in the dead-on- arrival scenario** | **510 km**<br>**Injection for compliance in the operational configuration** |
|---|---|

$\Delta a_{lim} = 200\ m$

**Average cross section**

460 km:
- **Δa ~ 860 m** per day
- manoeuvre every **5.5 hours**
- Daily manoeuvre time **~ 97 min**

$\Delta V_{TOT}$=493 m/s

510 km:
- **Δa ~ 420 m** per day
- manoeuvre every **11.5 hours**
- Daily manoeuvre time **46 min**

$\Delta V_{TOT}$=245 m/s

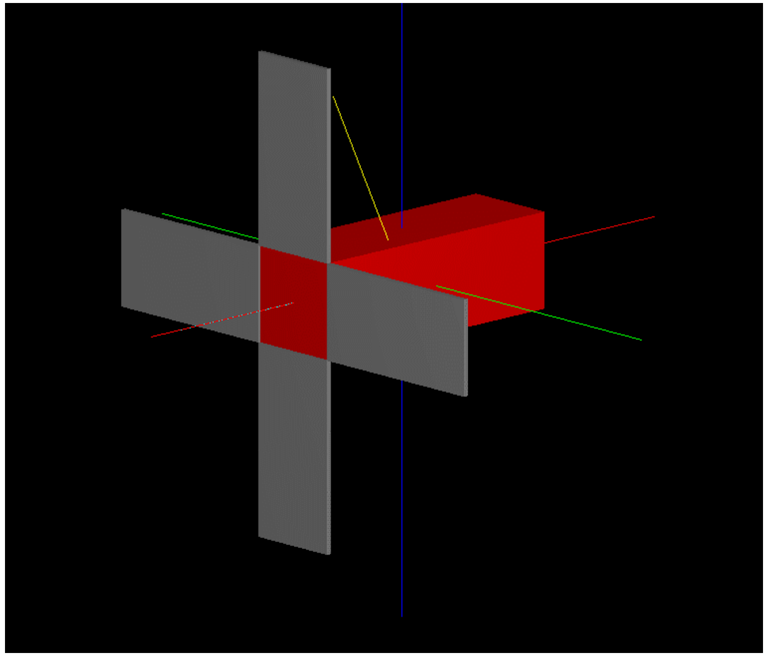
**Minimized cross section**

460 km:
- **Δa ~ 370 m** per day
- manoeuvre every **12 hours**
- Daily manoeuvre time: **41 min**

$\Delta V_{TOT}$= 219 m/s

510 km:
- **Δa ~ 180 m** per day
- manoeuvre every **26 hours**
- Daily manoeuvre time **~ 20 min**

$\Delta V_{TOT}$=106 m/s



| Electrical | Size [U] | Thrust [mN] | ISP [s] | Wet mass [kg] | total impulse [N*s] |
|---|---|---|---|---|---|
| **FEEP** | < 1 U | 0.33 | 6000 | 0.9 | **5000** |

# LEO Orbital Clearance

**CubeSats EOL compliance**

**Passive compliance**

**Fast orbital decay**
- **Drag minimization attitude**

**Drag compensation**

**Operating above 5 years**

- Recurrent manoeuvre capabilities
- Probability of successful disposal **> 90%**
- Orbital clearance at EoL **< 5 years**

**Passive de-orbiting**

**Active de-orbiting**
with propulsion

# De-Orbiting - Drag sail

**Drag sails** for passive de-orbiting

- Effectiveness depends on altitude, solar activity and ballistic coefficient

**De-orbiting time (years) with a 5 m^2 stabilized sail**

| units (U) | Initial orbit (km) | | | |
|---|---|---|---|---|
| | **800** | **700** | **600** | **500** |
| **1** | 2.188 | 0.55 | 0.147 | 0.029 |
| **2** | 4.761 | 1.314 | 0.262 | 0.055 |
| **3** | 5.741 | 2.234 | 0.374 | 0.08 |
| **6** | 7.124 | 4.861 | 0.802 | 0.149 |
| **12** | 9.3 | 6.218 | 1.909 | 0.264 |
| **16** | 13.313 | 6.687 | 2.784 | 0.339 |
| **27** | 20.448 | 7.753 | 5.106 | 0.598 |

**Pros:**

- Low volume and mass required
- **No active telecommand** necessary → solutions with clocks triggering the deployment in case of loss of communication

**Cons:**

- **Propulsion** system still needed to perform **CAMs**
  → Available CAM modules <0.5U
- Increase of **collision risk** and risk of **debris release**

**Commercial Drag Sail Datasheet**

| | |
|---|---|
| **mass [kg]** | <1 kg |
| **Module size [U]** | 1 U |
| **sail area [m^2]** | 5 |

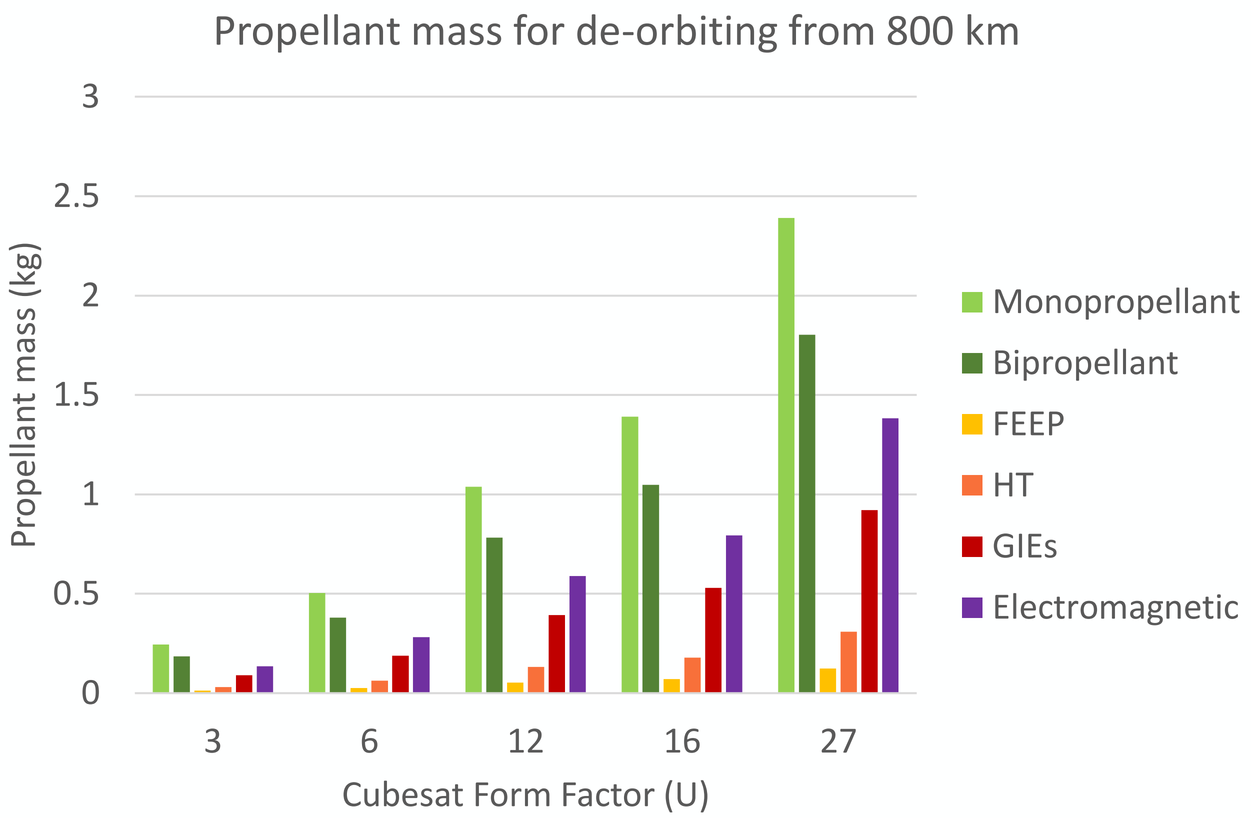
# Propulsion – Chemical vs Electrical

## Chemical

Single impulse to lower perigee

**Pros:**
- Fast de-orbiting
- Low power demand

**Cons:**
- Higher volume
- High propellant mass




## Electrical

Low thrust manoeuvre

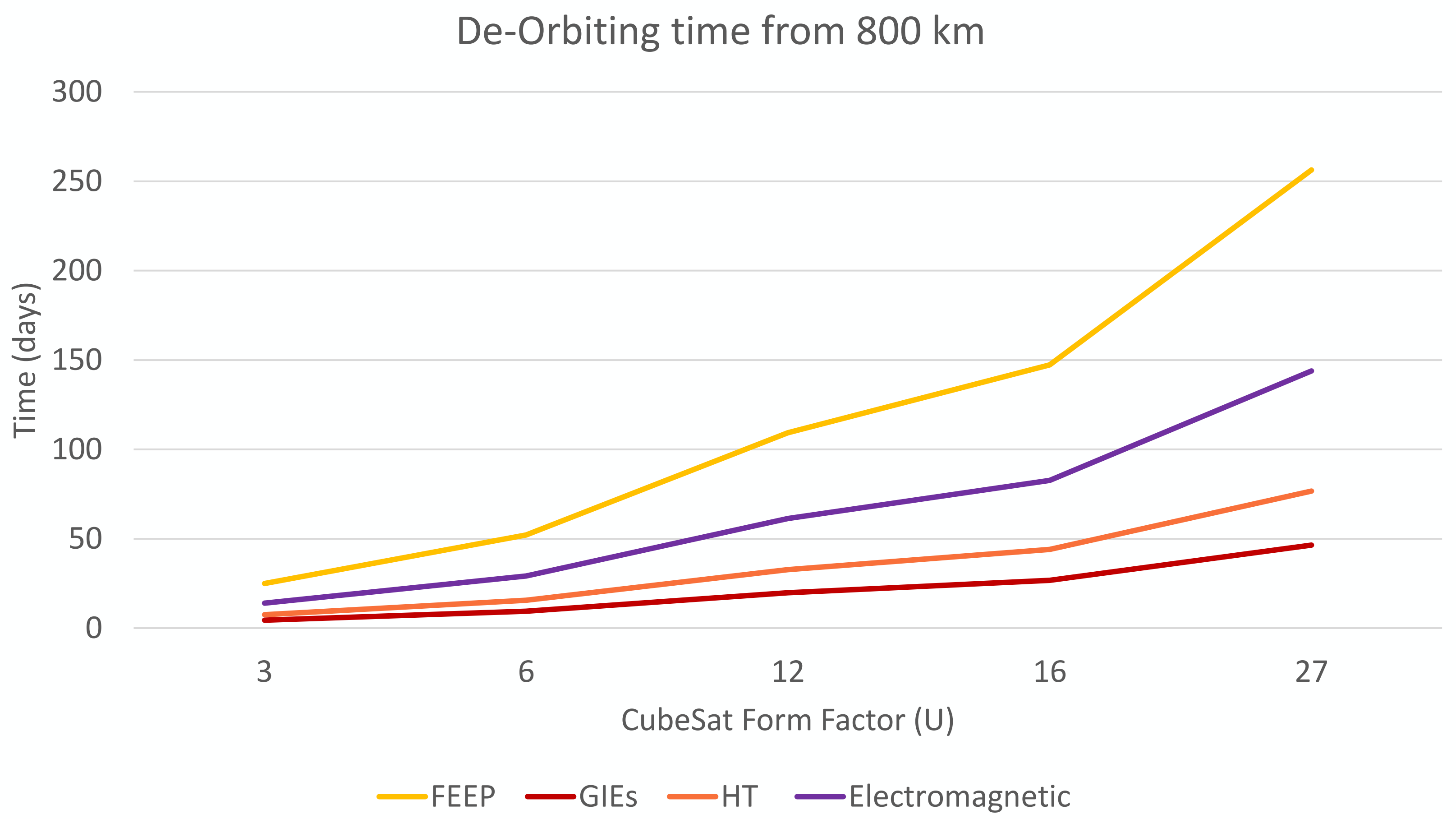
**Pros:**
- Low propellant mass

**Cons:**
- Long manoeuvre times
- High power demand

| Chemical | Size [U] | Thrust [N] | ISP [s] | Power [W] | Dry mass [kg] | Prop mass [kg] | Total impulse (N*s) |
|---|---|---|---|---|---|---|---|
| **Monopropellant** | 2 | 1 BOL-0.25 EOL | 213 | 1.7 | 1.8 | 0.8 | 1700 |
| **Bipropellant** | 1 | 0.5 | 285 | <12 | 1.1 | 0.3 | > 850 |

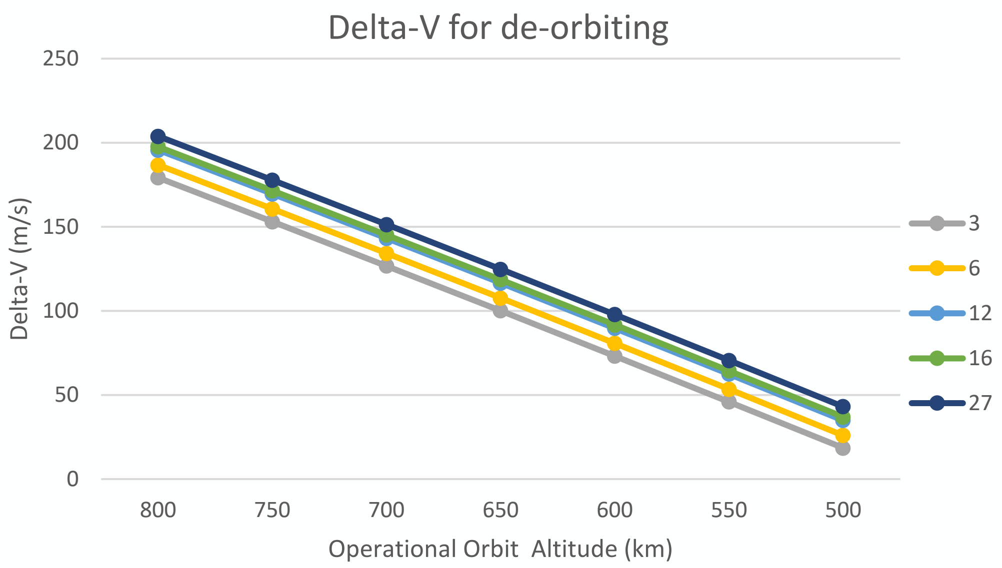
| Electrical | Size [U] | Thrust [mN] | ISP [seconds] | Power [W] | Wet mass [kg] | Total impulse [N*s] |
|---|---|---|---|---|---|---|
| **FEEP** | <1 | 0.33(0.01 - 0.4 ) | 2000-6000 | 35 (8-40) | 0.9 | 5000 |
| **GIEs** | 1U + tuna can | 1.8 (1-2) | 800 (300-800) | 60 (30-70) | 1.9 | 1000 |
| **HT** | 1 | 0.3 - 1.1 | Up to 2400 | 35-65 | 1.2 | 5500 |
| **EM** | 1.5 | 0.55(0.25-0.65) | 550 (650) | 50 (30-60) | 2.5 | 3000 |

# De-orbiting time




- Transfer time can be even higher depending on the **power availability** (thrust to power ratio) and for use of thrusters for **other operations** (e.g. RW desaturation)

# De-orbiting – Electrical Propulsion




Total **delta-v** accounting also for:

- **Drag compensation** (from ~15 m/s/yr @500 km to 0.6 m/s/yr @800 km)
- **Collision avoidance** (~0.1 m/s per collision, max of 5/10 collisions in 3/5 years of mission lifetime)

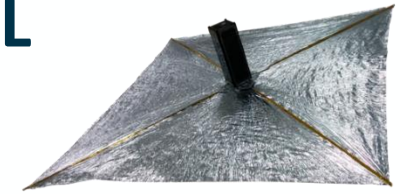
## Total impulse required (de-orbiting + 3 years orbit manteinance)

| Units (U) | Operational Orbit (km) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 800 | 750 | 700 | 650 | 600 | 550 | 500 |
| **3** | 722.5396 | 621.9764 | 525.9088 | 430.0202 | 349.9794 | 273.756 | 255.252 |
| **6** | 1505.215 | 1304.084 | 1111.957 | 920.1192 | 759.8815 | 607.126 | 568.533 |
| **12** | 3153.43 | 2751.183 | 2366.929 | 1983.253 | 1662.778 | 1357.268 | 1280.082 |
| **16** | 4246.375 | 3710.046 | 3197.707 | 2686.14 | 2258.839 | 1851.493 | 1748.578 |
| **27** | 7389.682 | 6482.759 | 5618.186 | 4754.916 | 4033.847 | 3346.450 | 3172.781 |

| Electrical | Size [U] | Thrust [mN] | ISP [seconds] | Power [W] | Wet mass [kg] | total impulse [N*s] |
|---|---|---|---|---|---|---|
| **FEEP** | < 1 U | 0.33(0.01 - 0.4 ) | 2000-6000 | 35(8.0-40) | 0.9 | **5000** |
| **GIEs** | 1U + tuna can | 1.8 (1-2) | 800 (300-800) | 60 (30-70) | 1.9 | **1000** |
| **HT** | 1U | 0.3 - 1.1 | Up to 2400 | 35-65 | 1.2 | **5500** |
| **Electromagn** | 1.5 | 0.55(0.25-0.65) | 550 (650) | 50 (30-60) | 2.5 | **3000** |

# Trade-off between disposal strategies

## DRAG SAIL



**PROS:**

- Low complexity
- Simple implementation
- Can be triggered even in case of telecommunication failure

**CONS:**

- Limited orbit applicability
- Stability problems
- An additional CAM module has to be considered

## EP MODULE

**PROS:**

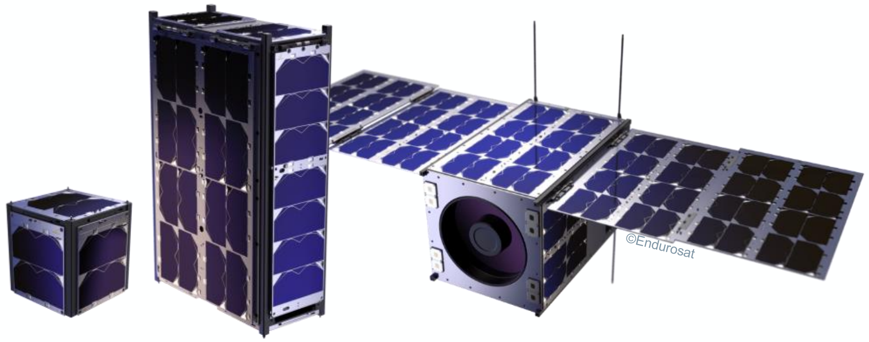
- Deorbit from up to 800 km could be achieved with a **1U** EP module
- Clustered EP solutions are possible for bigger CubeSats (16-27 U)

**CONS:**

- Higher complexity
- High power needed
- Needs the spacecraft to be active

# Conclusions

- **Small CubeSats < 3U** still able to operate at lower altitude and with **shorter mission lifetim**e
- **State of the art technologies** allows to comply with Orbital Clearance requirements with flight proven technologies
- **Increase** in **launch mass** (and in **cost )** is foreseen
- **More constraining requirements** apply to **constellations** → adapted technology roadmaps
- Most challenging aspect is **reliability** → **90% probability of successful disposal** very difficult to prove
    - Variability between batches
    - COTS components
    - Dead-on- arrival scenario



# BACK-UP SLIDES