DETUMBLER SHOWDOWN: A COMPARISON OF 7 CANDIDATE TECHNOLOGIES FOR PASSIVE DETUMBLING

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ABSTRACT

To ward off a full-blown Kessler syndrome eventually rendering low Earth orbits unusable, active removal of large space debris appears imperative. Unfortunately, nothing currently prevents dead spacecraft or derelict launcher upper stages from tumbling uncontrollably. This makes ADR initiatives extremely daunting --and ultimately, costly.

With support from CNES, Airbus has been developing a passive magnetic damping device dubbed the DETUMBLER which ensures passive postmortem stabilization of a host platform, a game-changer for ADR feasibility and affordability. The first model (-M, which weighs 100 grams and is intended for medium platforms up to 1.5 tons) is completing qualification tests, and flight units should be ready for integration into their host platforms by the end of 2025.

Meanwhile, ESA is supporting the development of a larger model (DETUMBLER-L) targeted at bigger satellites (up to 5 tons) or higher orbits (up to MEO). One goal of this study is to confirm our technological choice by pitting the detumbler concept against the whole gamut of alternate candidate technologies and physical phenomena for a detumbling function.

Via a first-principles approach and analytical modelling, we provide an estimate of the mass penalty for each solution to ensure detumbling within a year, for all possible values of satellite inertia and mission altitude. The exercise confirms that the detumbler is indeed the best choice for a wide domain of inertias and altitudes, and especially in the range considered for the new DETUMBLER-L.

1 LIST OF CANDIDATE TECHNOLOGIES

Although removing debris via ADR will become more pressing as time passes, the level of urgency will not be the same for all spacecraft sizes and altitudes. Many derelict spacecraft will remain in orbit a very long time before they are disposed of. This means that a detumbling solution has to remain functional possibly for decades past the operational lifetime of its host satellite. Such long lifetimes are unheard-of for active systems requiring electrical and/or computing power. A detumbling solution will thus have to be 100% passive.

1.1 Existing concepts

Unfortunately, while the literature abounds in technology concepts for *active* detumbling, it is very parsimonious as to solutions that can provide a purely *passive* detumbling capability. After an extensive review of the state of the art, we identified only the following existing solutions:

- Natural eddy currents in the satellite's structure
- Hysteresis rods or strips
- Short-circuited magnetorquers
- Magnetic detumbling device (by Airbus)

1.2 Theoretical concepts, from first principles

In order to make sure that we would not be missing any potential alternative technology in our comparison, we extended the search to 'physically feasible solutions', even ones of a purely theoretical nature. For this, we started from the premise that detumbling is more than just energy damping for spin or attitude stabilization: the total angular momentum must be reduced and therefore the action of an external torque is needed for changing the momentum state of the satellite. In a 'first-principles' approach, we thus looked at the few physical phenomena that can be exploited for creating external torque in LEO:

- Magnetic torque
- Solar or thermal radiation pressure torque
- Aerodynamic torque
- Gravity gradient torque

With the exception of magnetic hysteresis and eddy currents, these phenomena are not dissipative on a rigid body: this strongly suggests that a detumbling function needs mobile parts to ensure dissipation.

We can consider the example of the Airbus detumbler as an illustration. A permanent magnet, if rigidly fixed to the satellite's structure, creates a magnetic torque which tends to align the satellite with the local geomagnetic field like a compass needle. The attitude in which the magnet is aligned with the field is stable, but since the restoring torque is conservative, the oscillations around the equilibrium will be undamped unless additional dissipation is introduced. In the detumbler concept, the magnet is therefore not rigidly fixed, but is left free about an axis of rotation, and it is the viscous torque resulting from the rotation (due to eddy currents in the device's housing) that causes the dissipation.

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For the other physical phenomena, we can imagine a similar (and purely theoretical) design, whereby some mechanical element is responsible for exploiting the external phenomenon and creating a restoring torque, while some sort of viscous articulation or flexibility helps to introduce dissipation. This paper does not go into any technical details of how this might work in the real world.

1.3 Consolidated list

Adding the 3 theoretical concepts to the 4 existing ones leaves us with a total of 7 candidate solutions:

1. Natural eddy currents
2. Hysteresis rods
3. Shorted magnetorquers
4. Magnetic detumbler
5. Solar windvane
6. Aerodynamic windvane
7. Gravity gradient pendulum

2 ANALYTICAL MASS MODELS

To determine a best candidate for passive detumbling, we establish analytical sizing formulas (simplified, scalar) for all candidate solutions. Note that since the equations are simplified, they are not to be used for precise sizing, but for establishing orders of magnitude for comparisons between solutions and identifying broad domains where one solution might be better than others.

The key comparison criterion is *mass*, as a function of inertia and altitude, with the following assumptions:

- Initial tumbling rate ω_i = 1 deg/s
- final tumbling rate ω_f = 0.1 deg/s
- Satellite inertia $I \in$ [500 50,000 kg.m²]
- Orbit altitude $h \in$ [500 36,000 km]

and the following requirements:

- detumbling time T < 1 year (if the detumbling torque is constant)
- or equivalently a time-constant τ < 4 months (if the detumbling torque is proportional to the tumbling rate)

Both requirements are equivalent to a requirement on the detumbling torque C:

$$C = \frac{I\omega_0}{T} \tag{0.1}$$

and

$$C(\omega_0) = \frac{I\omega_0}{\tau} \tag{0.2}$$

respectively

The dependency to altitude is simply captured by considering that the magnetic field strength decreases as the cube of the distance to the center of the Earth:

$$B(\eta) = \frac{B_0}{(1+\eta)^3} \tag{0.3}$$

Where $\eta = h/R_e$ is the non-dimensional altitude and B_0 is the average strength of the Earth's magnetic field along the ground track (typically B_0 = 45 µT for a polar orbit).

2.1 Natural eddy currents

When a conductive object tumbles in a magnetic field, the variations of the field inside the object cause eddy currents which naturally oppose the rotation. The kinetic energy is dissipated via Joule heating, similar to the operation principle of magnetic brakes onboard heavy ground vehicles.

Since they account for most of the effect, we focus the modelling effort on the structural panels of the spacecraft, which can each be approximated by flat plates.

To simplify further, we consider a 1D model in which a flat plate of width L_x (and length $L_y \gg L_x$) rotates at ω around axis y, within a uniform field B parallel to z.

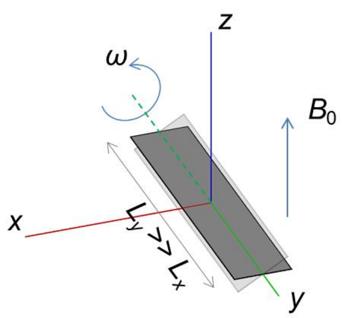

Figure 1. Geometric layout for the simplified problem (Since $L_y \gg L_x$, the problem become 1-dimensional)

The Maxwell-Faraday equations simplify to:

$$\frac{\partial E_y}{\partial x} = \omega B \cos \omega t \tag{1.1}$$

The analytical solution for the electric field is trivial:

$$E(x, y, t) = \omega B x \cos \omega t \tag{1.2}$$

We can then use Ohm's law to get the energy dissipation per unit volume, and integrate along x and y, as well as across the thickness, and then average over time:

$$P = \frac{L_x^3 L_y e}{24} \sigma \omega^2 B^2 \tag{1.3}$$

This can be scaled up from a single flat plate to a full satellite, taking into account a penalty factor κ to represent edge effects (aspect ratio L_y/L_x ~ 1) and the fact that B and ω have random orientations. The value of κ is determined numerically to be (0.8×0.5×0.8 ~ 0.3). This dissipation is then identified with the loss of kinetic energy:

$$P = I\omega\dot{\omega} = \kappa \frac{L^2}{24}\frac{\sigma m}{\rho}\omega^2 B_0^2 \tag{1.4}$$

Where $m = \rho L_x L_y e N_{panels}$ is the mass of the panels contributing to the eddy current dissipation.

Isolating the detumbling time-constant $\tau = \omega/\dot{\omega}$:

$$\tau = \frac{24\,\rho I}{\kappa\sigma B^2 m\, L^2} \tag{1.5}$$

Where σ is the electrical conductivity of the plate's material (typically aluminium) and ρ its specific mass, and L is a typical length of the bus.

Finally, substituting B from (0.3), we get the mass of structural panels for detumbling in the required time τ:

$$m = \frac{24\,\rho}{\kappa\tau\sigma B_0^2}\frac{I(1+\eta)^6}{L^2} \tag{1.6}$$

The dependency in the sixth power of the altitude (term η^6) suggests that the solution's performance will be seriously reduced at higher altitudes.

2.2 Hysteresis rods or strips

Hysteresis rods are sometimes used for detumbling cubesats upon launcher separation. They are made of a high permeability magnetic material, with hysteresis properties such that the residual magnetization in the rod lags behind the Earth's field, to create a resistive torque.

The phenomena governing magnetic hysteresis are quite hard to predict analytically, especially in non-saturated regimes when the magnetic field is weak. We have based the analysis on a 2022 paper by Carletta et al. [6], where the apparent permeability of the hysteresis strip was measured in tests. This value remains constant when resizing the device, as long as the length ratios of the strip or rod are conserved (in the instance of the article, the strip was 0.35 x 9.4 x 65 mm).

Another important aspect of hysteresis rods or strips is that the dissipative torque is constant rather than proportional to angular rate. Indeed, the resistive torque is not caused by back-electromotive force / inductance but by hysteresis, which does not depend on the rate of change of the magnetic field (unless the variations are very fast). The peak dissipative torque is thus simply:

$$C = m_h \times B \tag{2.1}$$

with m_h being the remanent dipole moment due to hysteresis in the rod.

Equation (3) in [6] establishes that:

$$m_h = \frac{\mu_h V B}{\mu_0} \tag{2.2}$$

Therefore:

$$C = m_h \times B = \frac{\mu_h V B^2}{\mu_0} \tag{2.3}$$

Like previously, the dependency in B^2 is consistent with the fact that the Earth's magnetic field intervenes twice:

1. to elicit magnetization in the rod
2. to interact with the magnetized rod to cause the resistive torque

Imposing the required detumbling time in (0.1), and considering that the mass m is proportional to the volume V:

$$m = \frac{\rho_h \omega_0 \mu_0}{T\mu_h B_0^2} I(1+\eta)^6 \tag{2.3}$$

2.3 Short-circuited magnetorquers

The operating principle is similar to the natural eddy currents in the structure: when the satellite tumbles, the variation of the Earth's magnetic flux in the coils of the magnetorquers causes current to flow and creates a magnetic dipole moment that opposes the rotation.

Once again, we expect a dependency in B^2 (and thus a high dependency on altitude), since the geomagnetic field is responsible for both eliciting the dipole moment and torquing it.

Mass model

We start by establishing a mass model: the magnetorquer is made of a soft magnetic core and a coil made of copper wire. We denote L the length and d the diameter of the core. For the coil, we denote λd the average diameter of a loop, and g the diameter of the wire.

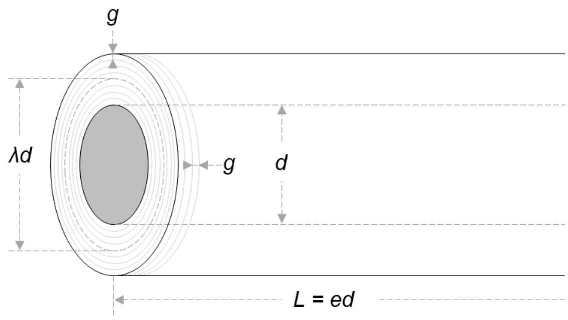

Figure 2. Generic geometric model for the MTQs

The weight of the core is:

$$m_c = \rho_c \frac{\pi d^2}{4} L \tag{3.1}$$

The weight of the wire is:

$$m_w = \rho_w \frac{\pi g^2}{4} \pi \lambda d N \quad (3.2)$$

Replacing the number of turns by its expression in (3.9) (see next subsection), the wire's diameter g cancels out:

$$m_w = \rho_w \frac{\pi^2}{4} \lambda(\lambda - 1) L d^2 \quad (3.3)$$

The total mass can then be formulated as:

$$m = m_c + m_w = \rho_e(\lambda) \frac{\pi}{4} L d^2 \quad (3.4)$$

where $\rho_e(\lambda) \triangleq \rho_c + \pi\lambda(\lambda - 1)\rho_w$ is an 'equivalent' specific mass for both the core and the coil.

We define the elongation ratio $e = L/d$, so that:

$$m = \frac{\pi \rho_e}{4e^2} L^3 \quad (3.5)$$

This can be inverted to express L as a function of m:

$$L^3 = \frac{4e^2}{\pi \rho_e} m \quad (3.6)$$

Expression for the magnetic tensor

Reference [2]) introduces the notion of *magnetic tensor* for determining the dissipative effect of natural eddy currents in a rotating field. A. Benoit (in [3]) extends the notion to shorted MTQs. Here we use a scalar interpretation of the magnetic tensor:

$$\mathcal{M} = \mu_e^2 \frac{N^2 S^2}{R} \quad (3.7)$$

where μ_e is the effective permeability of the magnetic core, N is the number of turns, R the electrical resistance of the whole coil, and S is the cross-section of the *core*. Indeed, only the core contributes significantly to the magnetic flux, due to its high permeability compared to that of vacuum. The physical unit for $\mathcal{M}$ is [$\Omega^{-1}m^4$].

With the notations established previously and assuming that $\lambda - 1 \ll 1$, we can replace S, N and R with expressions depending only on the geometry:

$$S = \frac{\pi d^2}{4} \quad (3.8)$$

$$N = N_d N_L = \frac{dL(\lambda - 1)}{g^2} \quad (3.9)$$

Where N_d and N_L correspond respectively to how many wires can fit within d (radially) and L (longitudinally).

$$R = 4 \frac{\lambda d N}{\sigma_w g^2} \quad (3.10)$$

where σ_w is the conductivity of the wire.

Substituting the terms above into (3.7), we get:

$$\mathcal{M} = \frac{\pi^2}{64} \sigma_w \frac{(\lambda - 1)}{\lambda} \frac{\mu_e^2}{e^4} L^5 \quad (3.11)$$

Taking into account effective permeability

In the expression above, a dependency in the elongation ratio e is hidden in the effective permeabilityμ_e. Indeed, literature on designing electromagnets and magnetorquers shows that it is only when the core's elongation tends to infinity that the effective permeability approaches the permeability of the core's material.

Reference [4] supplies an empirical chart showing the relationship between the effective permeability and the material's permeability, for various elongation ratios. Assuming that the core material has a very high permeability, we can infer an empirical rule of the form below:

$$\mu_e \approx e^a \quad (3.12)$$

with $a \approx 1.5$ (as long as $e < 100$, which is reasonable)

Replacing μ_e in the expression of the magnetic tensor:

$$\mathcal{M} = \frac{\pi^2}{64} \sigma_w \frac{(\lambda - 1)}{\lambda e} L^5 \quad (3.13)$$

Finally, replacing L with its expression in (3.6) and isolating m on the left-hand side, we obtain:

$$m = \left(\frac{256}{\pi}\right)^{1/5} \left(\frac{\mathcal{M}}{\sigma_w} \frac{(\lambda - 1)}{\lambda}\right)^{3/5} \frac{\rho_e}{e^{7/5}} \quad (3.14)$$

Final expression for the mass

In parallel, we can determine the required value for the magnetic tensor, from (0.2) and the relationship between the torque and the magnetic tensor:

$$C = \frac{I\omega_0}{\tau} = \mathcal{M}\omega_0 B^2 \Rightarrow \frac{I}{\tau B_0^2} (1 + \eta)^6 \quad (3.15)$$

To simplify the notations, we define the auxiliary constant L_* (same units as a length) as:

$$L_*^5 \triangleq \frac{I(1 + \eta)^6}{\tau \sigma_w B_0^2} \quad (3.16)$$

Finally, replacing $\mathcal{M}$ in (3.14), we obtain:

$$m = \left(\frac{256}{\pi}\right)^{1/5} \left(\frac{\lambda}{\lambda - 1}\right)^{3/5} \frac{\rho_e L_*^3}{e^{7/5}} \quad (3.15)$$

Baseline mass of MTQs in LEO

The above result computes the mass required for a magnetorquer-based detumbling capability. Since LEO satellites already need magnetorquers for initial acquisition and momentum management, the weight of the 'nominal' magnetorquers should be subtracted from the determination of the mass penalty.

The rationale for computing the baseline mass of magnetorquers is the following:

- they are sized for initial detumbling after separation
- they need to dump the initial angular momentum, from the initial rate at separation Ω_0 = 3 deg/s
- the initial rate reduction should last less than 2 orbits
- the corresponding requirement for the dipole moment of the MTQs is proportional to the inertia (we assume that the magnetic field in LEO is 40 µT)
- a scatterplot based on MTQ datasheets allows to fit a linear approximation for the mass of MTQs as a function of their dipole moment specs
- the baseline MTQ mass is capped at the mass of the largest MTQs in the catalog (i.e. larger satellites use thrusters for detumbling)

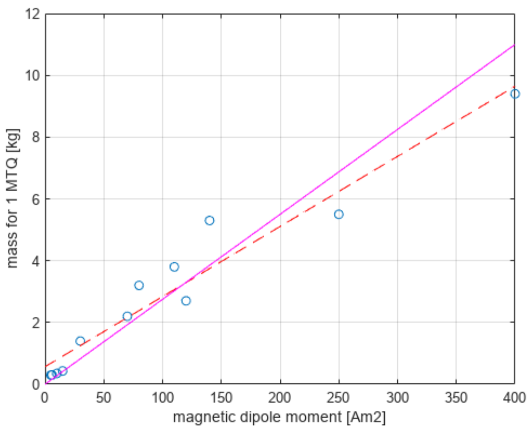

Figure 3. Fitting an affine (--) or linear (—) mass model onto MTQ datasheet design points (from Zarm data)

For simplicity, the analysis considers that all satellites have a baseline weight of LEO magnetorquers, including non-LEO satellites. This is optimistic in the overall approach but will not change the results too much, since the mass penalty grows much faster.

Note that since we are working in 1D, the expression is computing the required weight for only 1 MTQ. Like for the detumbler, it's probably acceptable even for the 3-axis case to have only one large MTQ for passive detumbling, and keep the baseline units on the other 2 axes. As a consequence, the mass penalty considers the added mass for only one oversize MTQ.

2.4 Detumbler

The detumbler comprises a small rotor which behaves like a compass needle thanks to 2 permanent magnets on its rim. When the satellite tumbles, there is a difference in angular rate between the rotor (which wants to stay aligned with the local geomagnetic field) and the housing (which is attached to the satellite's structure). This rate difference causes the rotor magnets to travel tangentially near the inner wall of the conductive housing, and the resulting eddy currents create a viscous torque opposing the satellite's tumbling motion. More details on the detumbler itself can be found in [1].

In contrast to the other magnetic solutions presented above, the detumbler manages to break away from the dependency in B^2: thanks to the use of permanent magnets, the resistive torque is only proportional to B.

Efficiency model

The major element in the sizing exercise is the dipole moment M required to produce the necessary magnetic torque (we implicitly assume that designing the rotor for achieving the right amount of viscous friction is secondary). This dipole moment directly determines the weight of the rotor magnets, and thus the mass of the device.

We also assume that the detumbler is designed so that its saturation rate (the rate at which the viscous torque is equal to the maximum magnetic torque) is ω_0.

At saturation, we know that the viscous torque is:

$$C(\omega_0) = M \times B \tag{4.1}$$

Plugging in (0.2), we can derive the requirement for the rotor's magnetic dipole moment:

$$M = \frac{C}{B} = \frac{I\dot{\omega}}{B} = \frac{I\omega_0}{B\tau} = (1+\eta)^3 \frac{I\omega_0}{B_0\tau} \tag{4.2}$$

Mass equation

The mass of magnets is directly proportional to the magnetic dipole moment M through:

$$m_m = \rho_m V_m = \rho_m \frac{\mu_0 M}{B_r} \tag{4.3}$$

where ρ_m is the magnet's specific weight and B_r is the remanence of the magnet's material.

Pending detailed design, we assume that the total mass of the detumbler is the sum of an incompressible mass (50 grams) + 3 times the mass of the magnets themselves.

Combining all of the above, we get the following expression for the device's mass:

$$m = m_0 + 3\frac{\rho_m \omega_0 \mu_0}{B_r B_0} I(1+\eta)^3 \tag{4.4}$$

2.5 Solar windvane

The (purely theoretical) operating principle is similar to the detumbler, except that the restoring torque is not magnetic torque but solar radiation pressure torque from some sort of solar ‘empennage’ comprising a solar sail at the end of a boom: there is a stable attitude when the boom and sail are aligned with the sun’s direction, and energy dissipation is introduced by some sort of viscous angular deflection of the boom.

Efficiency model

The sizing for the solar windvane is quite straightforward, using the following (crude) model for the SRP torque:

$$C = \epsilon PSL = \frac{I\omega_0}{\tau} \tag{5.1}$$

where P is the solar radiation pressure, S is the area of the sail, L the length of the boom, and $\epsilon = \theta/2\pi$ is a penalty factor representing the fact that the angular motion of the windvane's boom is limited in range, limiting its effect to a portion of each revolution.

Requirement for sail surface area

Assuming that an optimum design would probably have a boom length somewhat longer that the side length of the sail, we can (arbitrarily) consider that $L = 3\sqrt{S}$

$$3S^{1.5} = \frac{I\omega_0}{\epsilon\tau P} \Rightarrow S = \left(\frac{I\omega_0}{3\epsilon\tau P}\right)^{2/3} \tag{5.2}$$

Mass model and mass equation

Deriving a weight budget from a required length and area is not trivial, since most of the weight is in the booms or stiffeners and the deployment mechanism and not the sail membrane itself. But since the length of the booms and stiffeners is probably proportional to $\sqrt{S}$, we can expect a law in square root of the area. Looking at various datasheets, we can indeed fit such a simple empirical law $m = b\sqrt{S}$ (see next Figure), with $b \approx 1.14$ kg/m

This allows to reach the final result:

$$m = b\sqrt[3]{\frac{I\omega_0}{3\tau\epsilon P}} \tag{5.3}$$

Note that the mass requirement is predictably– independent from the orbit’s altitude, since the solar radiation pressure is the same for all Earth orbits.

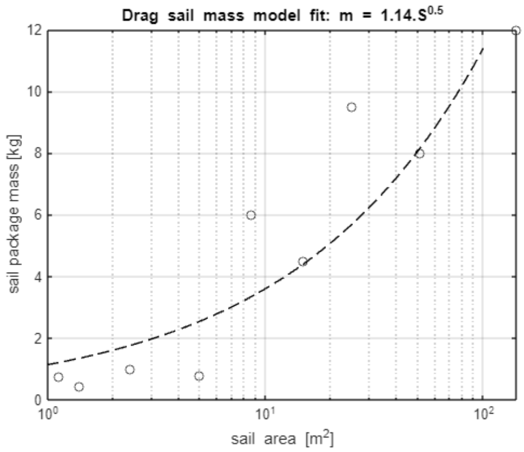

Figure 4. drag/solar sail mass model fit, from datasheets in references [7], [8] and [9]

2.6 Aerodynamic windvane

The principle is the same as the solar windvane described previously: the dynamic pressure acting on a drag sail at the end of a boom causes a restoring torque that tends to align the boom downwind from the main bus. If the boom is allowed to flex or rotate, and if that deformation or motion causes dissipation through damping or friction, some kinetic energy will be converted to heat and the satellite will detumble.

Efficiency and mass models

The process for computing the mass model is the same, replacing solar radiation pressure by dynamic pressure:

$$C = \epsilon P_a C_D SL = \frac{I\omega_0}{\tau} \tag{6.1}$$

Assuming drag sails rely on the same technology than solar sails, the mass model for the solar windvane can be reused as-is:

$$m = b\sqrt[3]{\frac{I\omega_0}{3\tau\epsilon P_a C_D}} \tag{6.2}$$

The dynamic pressure depends on air density and orbital speed, which both depend on the altitude:

$$P_a = \frac{1}{2}\rho_a(h)v^2(h) \tag{6.3}$$

$$v^2 = \frac{\mu_E}{R_E(1+\eta)} \tag{6.4}$$

For the atmospheric density model, we can use a simple exponential model:

$$\rho_a = \rho_0 \exp\left(-\frac{h}{h_s}\right) \tag{6.5}$$

By choosing ρ_0 = 1.7×10^{-9} kg/m^3 and h_s = 62.4 km, the exponential model is a good fit for the standard US76 atmosphere model in the altitude range [400 - 600 km] we are most interested in.

Mass equation

The mass equation in (6.2) becomes:

$$m = b\sqrt[3]{(1+\eta)\frac{2I\omega_0 R_E}{3\tau\epsilon C_D \rho_0}}\exp\left(-\frac{\eta R_E}{h_s}\right) \quad (6.6)$$

The dependency in $\exp(-\eta)$ shows how such a solution is extremely sensitive to altitude (and in fact only performs suitably at altitudes where air drag brings the satellite down spontaneously, i.e. detumbling is not needed).

2.7 Gravity-gradient pendulum

The principle is similar to the previous 3 concepts: a pendulum which is left free to rotate will naturally want to align vertically due to gravity gradient. If the attachment point exhibits friction when then pendulum rotates, the libration oscillations of the satellite will be damped.

We assume that the pendulum has inertia $J = mL^2$

Efficiency model

The peak value for the gravity-gradient torque is:

$$C = \frac{3}{2}n^2 J \quad (7.1)$$

Where n is the orbital pulsation:

$$n = \sqrt{\frac{\mu_E}{\left(R_E(1+\eta)\right)^3}} \quad (7.2)$$

And we need the torque to detumble the satellite with a time-constant τ :

$$C = \frac{3}{2}n^2 J = \frac{I\omega_0}{\tau} \quad (7.3)$$

Mass equation

From (7.2) and (7.3), we can derive:

$$m = \frac{2I\omega_0 R_E^3(1+\eta)^3}{3\tau\mu_E \epsilon L^2} \quad (7.3)$$

3 COMPARISON CHARTS

We can finally combine all these developments into a single comparison chart.

In addition to the common requirements mentioned before, we add (or recall) a few specific assumptions for some of the technologies:

- for eddy currents, we consider that the allocated length of the structural panels is the complete bus length. Note: a simple empirical fit on a few satellite design points provides a simple relationship $I = 35L^{4.5}$ between satellite inertia and a typical bus length
- the hysteresis devices have the same proportions (and thus the same apparent permeability μ_e) as in the cited article
- for magnetorquers, the average diameter of the coil is 25% greater than that of the core.
- for magnetorquers, the effective permeability of the core follows the empirical power law
- for the detumbler, the total mass of the device is three times the mass of the rotor magnets (+ a penalty of 50 grams)
- for the gravity gradient pendulum, the allocated length is the complete bus length

The goal of the chart is not to perform an accurate prediction of the performances of any specific design point but to compare orders of magnitude between technologies, and especially how those orders of magnitude scale with altitude and satellite size. As a consequence, the chart uses logarithmic scale, and the inaccuracies resulting from some of the assumptions and modelling simplifications will have only a modest effect on the overall picture.

3.1 Mass vs altitude

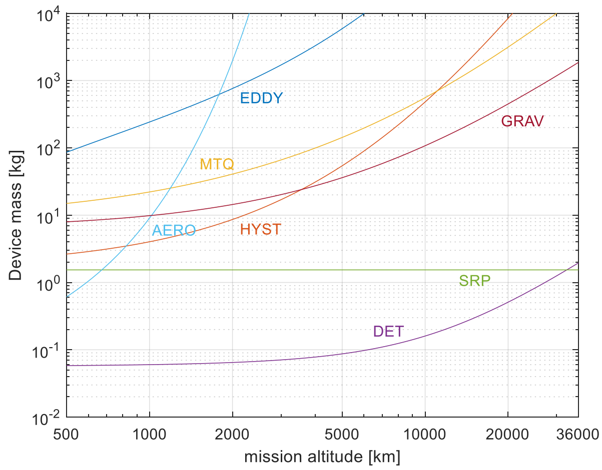

Figure 5. Comparison between detumbling concepts: mass vs altitude for an inertia of 5000 kg.m²

3.2 Mass vs inertia

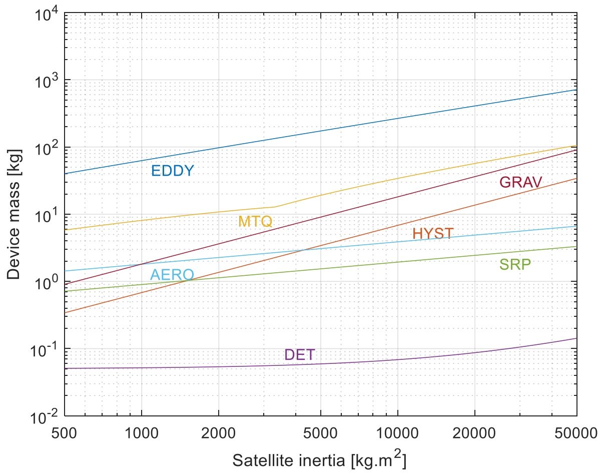

Figure 6. Comparison between detumbling concepts: mass vs inertia for altitude = 800 km

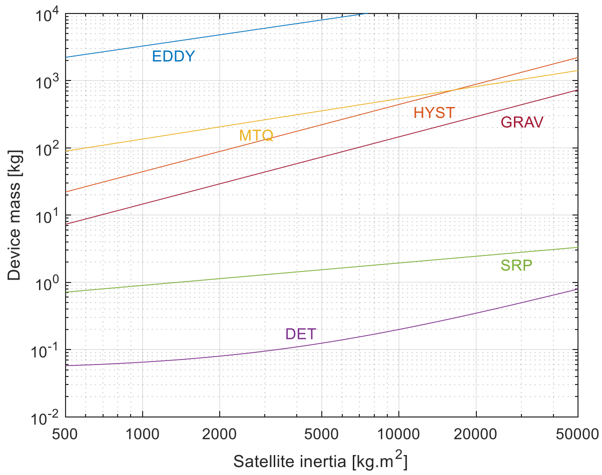

Figure 7. Comparison between detumbling concepts: mass vs inertia for altitude = 8000 km

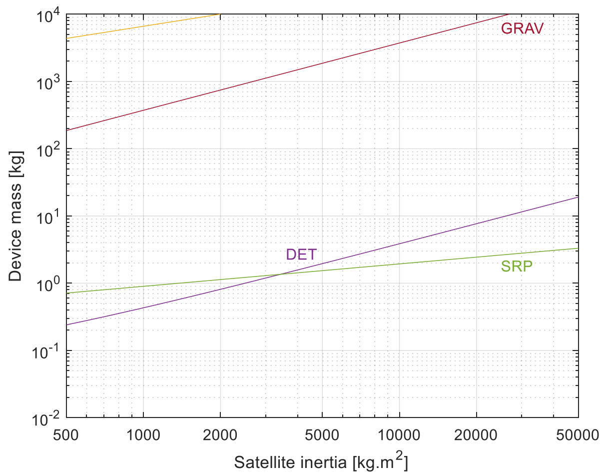

Figure 8. Comparison between detumbling concepts: mass vs inertia for altitude = 36000 km

3.3 Best candidate in inertia/altitude domain

We can summarize the results by showing the regions where each solution has the lowest mass budget.

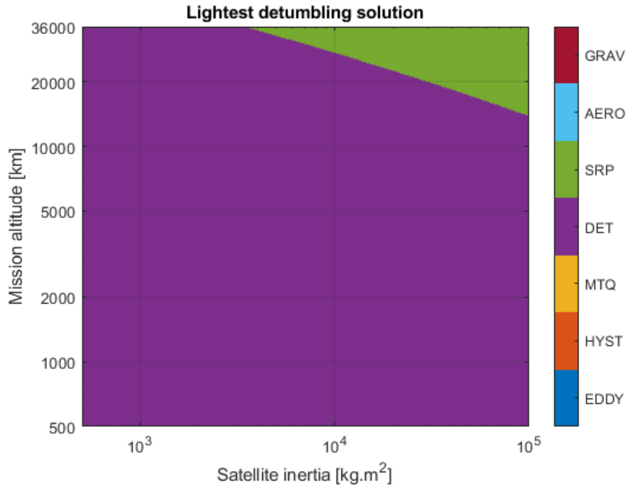

Figure 9. Comparison between detumbling concepts: best solution in inertia/altitude space

The chart confirms that the detumbler solution is the most efficient way (in terms of mass) to ensure detumbling, except for the very heaviest satellites on the very highest orbits (typically, telecom platforms).

And just for the sake of completeness, if we extend the range of inertia values down to much lower values, we show that the hysteresis rods might be an interesting solution for very small satellites.

This could be an artefact of the choice of 50 grams as an incompressible mass for a detumbler, but this is also in line with the fact that hysteresis rods are indeed used on some cubesats. In any case, the differences here are less than 50 grams.

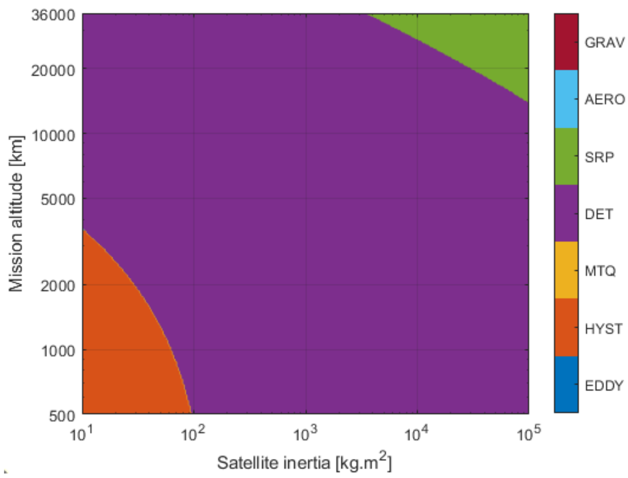

Figure 10. Comparison between detumbling concepts: best solution in inertia/altitude space (wider range for satellite inertia values)

4 CONCLUSIONS

The analysis clearly demonstrates that in terms of mass, the detumbler is a better solution than all other candidate concepts. The only exception is the theoretical contraption we called the *solar windvane*, which –if it existed-- would start to be competitive above typically 20,000 kgm² inertia and 20,000 km altitude.

Since the issue of space debris build-up is most pressing on LEO orbits around 800 km, Figure 6 is the most relevant result, and it shows that the detumbler solution is at least 5 to 10 times more weight-efficient than all other solutions.

We can acknowledge two key reasons for this higher efficiency:

- Magnetic torque is quite powerful compared to other external torque phenomena. This is the reason why LEO attitude control systems use magnetorquers for momentum dumping.
- Having permanent magnets only relies on the Earth's magnetic field once (to create the torque), compared to the other magnetic solutions, which exhibit a dependency to B^2.

This analysis has allowed to firmly justify the technology choice for the current detumbler development (DETUMBLER-M), as well as for the ongoing, ESA-funded, predevelopment of a larger unit targeted at larger hosts and/or higher orbits (DETUMBLER-L).

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