PASSIVE MAGNETIC DETUMBLING OF NON-OPERATIONAL SATELLITES IN LEO TO ENABLE ACTIVE DEBRIS REMOVAL

Alain Benoit (ABSpaceConsulting)
Tiago Soares (ESA/ESTEC)
Andrey Kornienko (ESA/ESTEC)
Steeve Kowaltschek (ESA/ESTEC)
David Bakonyvari (ESA/ESTEC)

Clean Space Industrial Days

24 September 2021

Table of contents

1. Introduction to Passive Magnetic Detumbling (PMD)

- **A big challenge driving the complexity of the rendezvous and capture of debris is its tumbling motion**
  - Observations of non-operational LEO satellites often show angular rates above 2 deg/s
- **In case of in-orbit failure, can energy dissipation devices damp the angular rates in advance?**
  - Eddy currents in conductive structures already create some dissipation, however small
  - A potentially faster solution proposed by ESA (patent pending Ref EP19182205) consists in short-circuiting the coils of the Magnetic Torquers (MTQ) already on board LEO satellite.
  - However the accumulated impact of the Solar Radiation Pressure might overcome these damping effects if no mitigation action is taken
- **This paper presents the current status of the investigations done by ESA**
  - Analytical framework by ESA during the phase B1 of the Copernicus Expansion missions, supported by MTQ proof of concept tests by LusoSpace, without Solar Radiation Pressure analyses
  - On-going complements during the present Phase B2, including MTQ detailed characterisation and optimisation by ZARM, Solar Radiation Pressure precursor analyses and simulations and working meetings with Copernicus Expansion primes

2. In-orbit observations of defunct satellites in LEO

- **Ground-based reconstructions by Satellite Laser Ranging (SLR) or photometry**
  - SLR uses the Retro-Reflector Arrays (RRA); being not too close to the Center of Mass, S/C angular rotation creates a modulation of the RRA to Earth distance
- **Envisat**
  - Unexpected mission interruption on 8 April 2012 (altitude 780 km)
    - 3Q 2012: very small residual angular rates (around 0.05 deg/s)
    - First year: spin-up to 3 deg/s
    - Following years: spin down (exponential decay) to 1.7 deg/s (stabilisation?)
- **TOPEX/Poseidon**
  - Planned decommissioning in January 2006 (altitude 1340 km)
    - 1Q 2016: very small residual angular rates
    - Next 10 years: continuous spin-up reaching 33 deg/s in 2017 (and no spin-down)
- **Need to understand and predict the dynamic evolution of defunct satellites in LEO**
  - Operational phase: the AOCS counteracts the following disturbing torques, easy to predict and model for an Earth pointing satellite:
    - Gravity Gradient, Residual Magnetic Dipole,
Solar Radiation Pressure, Aerodynamic
  - Non-controlled space debris: tumbling motion, spin-up, spin-down???
    - Which driving disturbances can explain such in-orbit observations?
Not easy, since the S/C orientation is arbitrary
    - Could the tumbling motion be minimised, in time for an ADR mission?

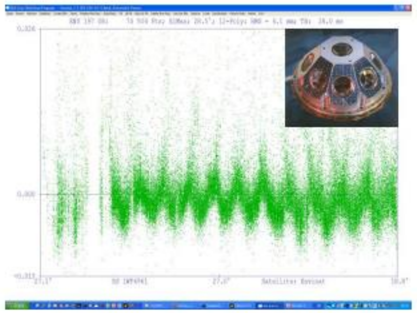
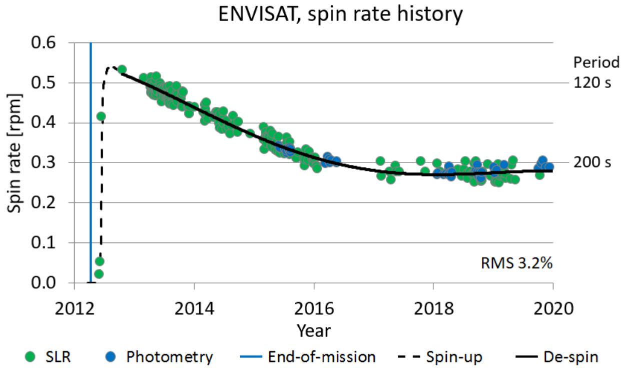
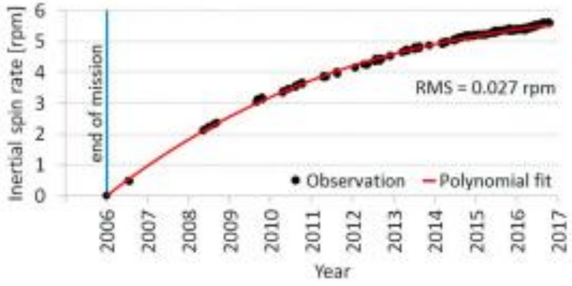


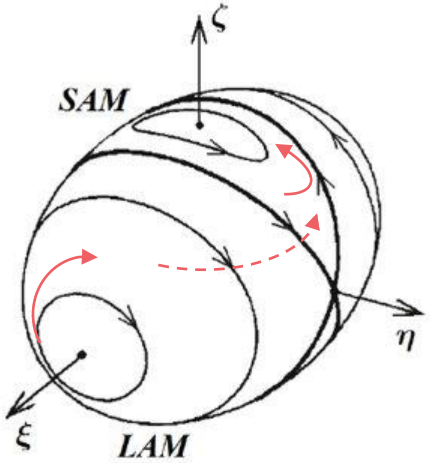
Fig. 5: Each of the 8 retros of the ENVISAT reflector unit slightly changes its distance from the SLR station, as ENVISAT is rotating; 8 'peaks' thus correspond to ONE full rotation of ENVISAT





The history of T/P inertial spin rate: SLR and photometric data combined.

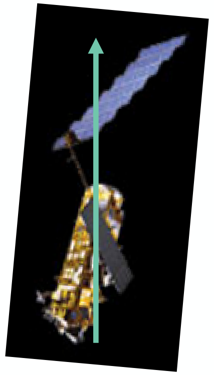
3.1 Basic elements of S/C dynamics



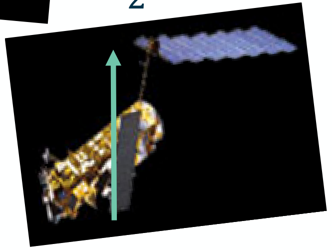
Angular rates in body principal axes for a given angular momentum H
LAM: higher rate if around minor inertia
SAM: smaller rate if around major inertia

- **Free-motion of a non-controlled satellite, without energy dissipation:**
  - A rotation Ω_1 around the minor principal axis $X_P = \xi$
    - pure rotation ω_x or with nutation
  - A rotation Ω_2 around the major principal axis $Z_P = \zeta$
    - pure rotation ω_z or with nutation
  - The intermediate principal axis $Y_P = \eta$ is not stable

Ω_1



Ω_2



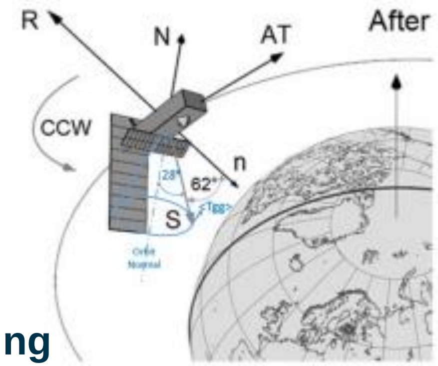
- **A 3-axes stabilised LEO S/L is generally not balanced**
  - Principal axes and Geometrical axes do not coincide: misalignments $\boldsymbol{\varepsilon_x}$ and $\boldsymbol{\varepsilon_y} \sim 10$ deg
- **In presence of energy dissipation, the angular momentum will be transferred to the major principal axis**
  - An initial rotation Ω_1 along the minor principal axis X_P (LAM) will see an increasing nutation (red arrows) and will end up with a pure rotation ω_z of smaller magnitude around the major principal axis Z_P (SAM)
- **This will remain a valid approximation in the short term if the mean external torque (e.g. averaged by a spinning motion $\langle \vec{T} \rangle_{spin}$) is small with respect to the angular momentum $I\vec{\Omega}$**

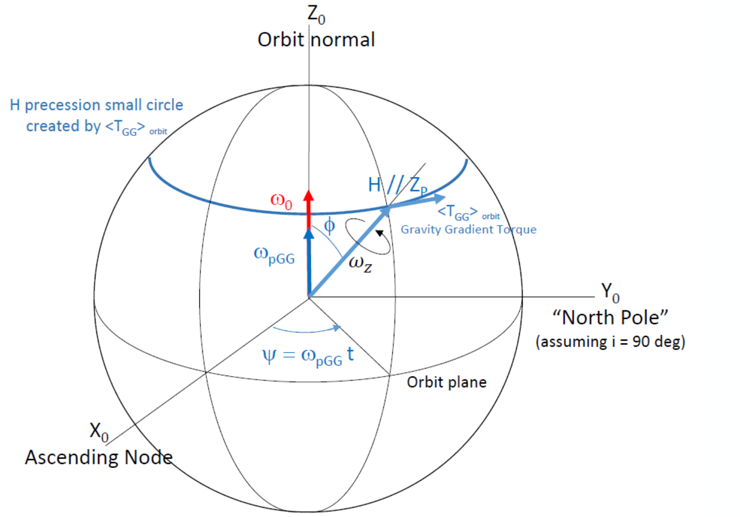
3.2 Impact of Gravity Gradient in LEO

- **ESA started by analysing the impact of the Gravity Gradient torque, known to be the dominant disturbing torque during the operational phase**
  - We assumed a Short Axis Mode (SAM), i.e. spinning around major principal axis $\boldsymbol{Z_P}$ of inertia I_z
  - Spin rate large enough to ensure gyroscopic stiffness => long-term effect $\langle \quad \rangle_{period}$ of the environmental torques: $\langle \vec{T} \rangle_{period} = \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} \vec{T}(t)\ dt$
    - Instantaneous GG torque: $\overrightarrow{T_{GG}}(t) = 3\omega_0^2\, \overrightarrow{R_s} \times \overrightarrow{\bar{\bar{I}} R_s}$
    - Orbit average torque: $\langle \overrightarrow{T_{GG}} \rangle_{orbit} = \frac{3\omega_0^2}{2} \left[I_z - \left(\frac{I_x + I_y}{2}\right)\right] \left(\overrightarrow{Z_0} . \overrightarrow{Z_p}\right)\left(\overrightarrow{Z_p} \times \overrightarrow{Z_0}\right)$
    - Precession motion around the orbit normal

$$\omega_{pGG} = \frac{\langle T_{GG} \rangle_{orbit}}{\text{H} \sin\varphi} = \frac{3\omega_0^2}{2\,H}\left(I_z - \frac{I_x + I_y}{2}\right)\cos\varphi$$

    - Equivalent to lunisolar precession of the Earth (precession of equinoxes – Earth obliquity 23 deg)
    - No energy increase, Obliquity φ remains constant
- **Similar approach for S/C Residual Dipole Magnetic torque**
- **Aerodynamic torque, although a significant contributor at low altitudes <650km (asymmetric case) has insignificant rate damping effect due to low rotation rate of the spacecraft.**





Precession motion of the angular momentum around the orbit normal due to Gravity Gradient

- **References:**

  - Benoit A., et al., *Passive magnetic detumbling to enable Active Debris Removal of non-operational satellites in Low Earth Orbit. CEAS Space Journal* - https://doi.org/10.1007/s12567-021-00354-8
  - Soares T., et al., *Passive Rate Damping of non-operational satellites in LEO to enable Active Debris Removal 11th International ESA Conference on Guidance, Navigation & Control Systems 22 - 25 June 2021,*

3.3 Energy Dissipation by Eddy Currents and Short Circuited Magnetic Torquers

- **Eddy currents recognised as the source of angular rates damping of tumbling satellites or launcher upper stages**
  - Eddy currents in satellite conductive elements: magnetic tensor $\bar{\bar{M}}$ such that $\vec{\boldsymbol{T}}_{\boldsymbol{SC}} = -\left[\bar{\bar{\boldsymbol{M}}}\left(\frac{\boldsymbol{d}\vec{\boldsymbol{B}}_{\boldsymbol{Earth}}}{\boldsymbol{dt}}\right)_{\boldsymbol{sat}}\right] \times \vec{\boldsymbol{B}}_{\boldsymbol{Earth}}$
  - For a typical Copernicus satellite with Aluminum: $\mathrm{M}{\sim}1.5\ 10^4\ \Omega^{-1}\mathrm{m}^4$ to $6.5\ 10^4\ \Omega^{-1}\mathrm{m}^4$ (TBC)
- **ESA proposed to short-circuit the coils of the on-board Magnetic Torquers in case of mission termination**
  - Rod-shaped magnetic core of length l_{core} and area A with a very high intrinsic relative permeability μ_{core} around which one nominal coil and one redundant coil are winded, N_{turn} and resistance R for each coil
  - The rotation of the space debris in the Earth magnetic field will produce a current : $\boldsymbol{i_k} = -\frac{\boldsymbol{\mu_{eff}\ N_{turn}\ A}}{\boldsymbol{R}}\left(\frac{\boldsymbol{d}\vec{\boldsymbol{B}}_{\boldsymbol{Earth}}}{\boldsymbol{dt}}\right)_{\boldsymbol{sat}} . \overrightarrow{\boldsymbol{X_k}}$

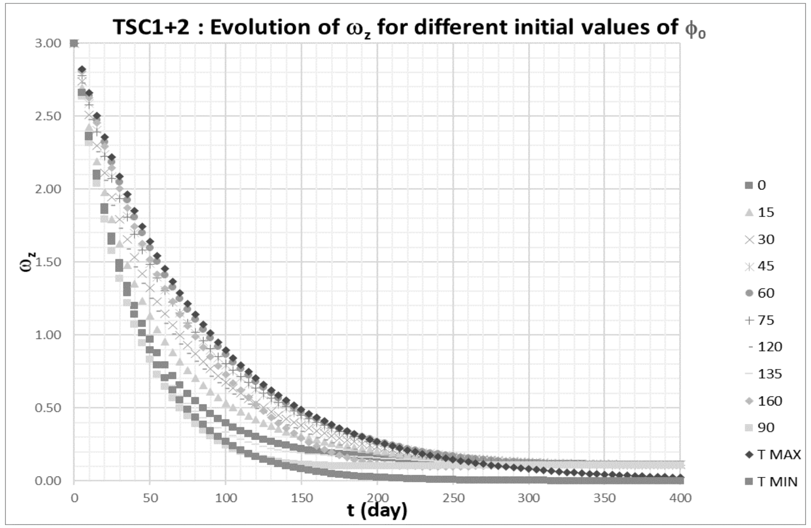
    and energy dissipation by Joule heating $\frac{dE}{dt} = -2R\sum_{k=1}^{3} i_k^2 = -M\left(\frac{d\vec{B}_{Earth}}{dt}\right)^2_{sat}$
  - FOME study with LusoSpace: assuming a linear regime despite the very low magnetic fields: $\boxed{M = \frac{2\ \mu_{eff}^2\ N_{turn}^2\ A^2}{R}}$

    with μ_{eff} the effective permeability of the MTQ (demagnetizing factor due to the finite length of the rod).
- **Next step was to validate these models at very low regime and optimise MTQ's to reach $\mathbf{M{\sim}1.0\ 10^5\ \Omega^{-1}m^4}$**
- **References**

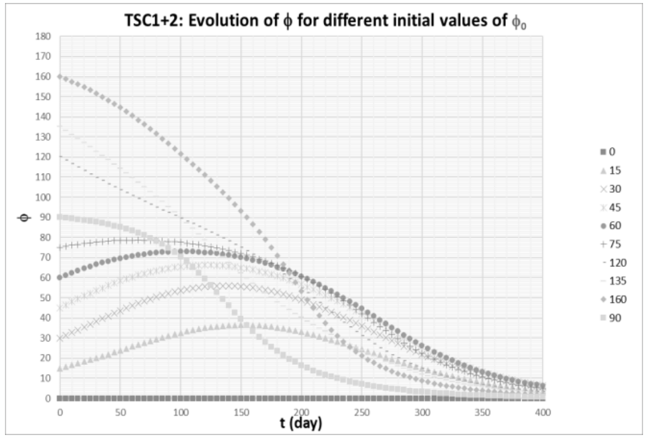
  - Soares, T., Caiazzo A., Wolahan, A., *Magnetic Damping For Space Vehicles After End-of-life.* ESA patent pending EP19182205 https://data.epo.org/publication-server/rest/v1.0/publication-dates/20201230/patents/EP3757021NWA1/document.pdf
  - *Final Report D4R - Feasibility of Magnetic Damping after End of Life (FOME) - LS-MAD-REP-0001 - 25/09/2019*

3.4 Dynamic Evolution with PMD and no SRP

- **The torque created by the Magnetic Tensor can be split into two components**
  - $\vec{T}_{SC} = -\left[M\left(\frac{d\vec{B}_{Earth}}{dt}\right)_{sat}\right] \times \vec{B}_{Earth} = \overrightarrow{T_{SC1}} + \overrightarrow{T_{SC2}}$
    - A rotational torque, predominant at high angular rates: $\overrightarrow{T_{SC1}} = -\left[M(-\vec{\omega} \times \vec{B})\right]$
    - An orbital torque, due to a non-inertial $\vec{B}$: $\overrightarrow{T_{SC2}} = -\left[M\left(\frac{d\vec{B}}{dt}\right)_{inertial}\right] \times \vec{B}$
- **The rotational torque itself can be split into two components**
  - A damping torque $\overrightarrow{T_{SC1D}} = -M\left\|\vec{B}_{\perp}\right\|^2 \vec{\omega}$
    and a tilting torque $\overrightarrow{T_{SC1T}} = M\left(\vec{B}.\vec{\omega}\right)\vec{B}_{\perp}$
  - $\langle\overrightarrow{T_{SC1D}}\rangle_{long\ term} \cong -M\frac{5}{2}B_{eq}^2(1 - 0.5\sin^2\varphi)$ with arbitrary obliquity Tapez une équation ici.
    - Instantaneous damping time constant $\tau(\varphi) = \frac{I_z}{M\frac{5}{2}B_{eq}^2(1-0.5\sin^2\varphi)}$
    - It varies only between τ_0 and $2\tau_0$, with $\boxed{\boldsymbol{\tau_0} = \frac{\boldsymbol{I_z}}{\boldsymbol{M\frac{5}{2}B_{eq}^2}}}$
- **When ω_z decreases, the orbital torque $\overrightarrow{T_{SC2}}$ modifies the final evolution**
  - $\varphi \to 0°$ instead of $90°$, erecting the spin axis perpendicular to the orbital plane and ω_z converges towards $\omega_{limit} = \pm\frac{9\omega_0}{5}$ instead of 0



Evolution of the spin rate (w/o SRP, Residual Dipole, AERO)



Evolution of the obliquity

4. Characterisation and optimization of Magnetic Torquers for Passive Magnetic Detumbling (1/2)

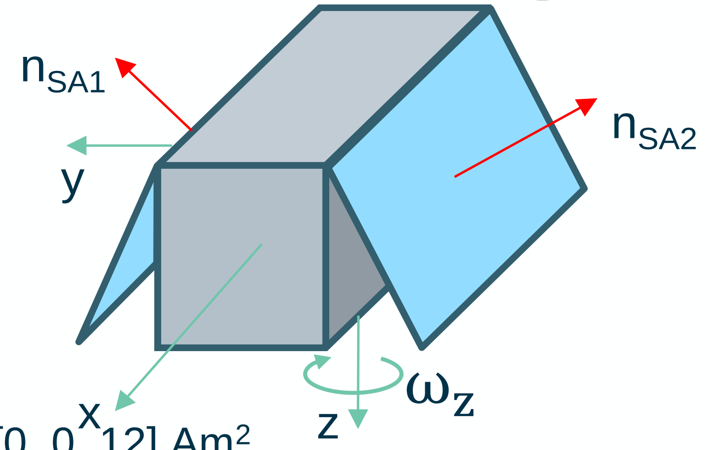
- **A number of precursor characterization tests of short circuited Magnetic Torquers have been ran by LusoSpace (PT).**
- **After the down-selection of ZARM Technik (DE) for all 6 HPCMs, an activity was conducted focusing on the hardware (Magnetic Torquers) to be delivered for the 6 missions.**
  - In an Helmoltz setup, as many as 13 different MTQ have been short-circuited to measure the induced current in presence of an angular rate.
  - One of the challenges was to measure accurately the low current generated (in the range of 100 µA).
  - Conditions with the two (nominal & redundant) coils short-circuited in series and in parallel were tested. As expected, they will have the same consequences.
  - The magnitude of the induced current was coherent with the preliminary analyses, showing the magnetic core was behaving in its linear regime, even close to the zero.
- **After confirming the induced current on the short-circuited magnetic torquer, the investigation focused on « optimising » a MTQ for the detumbling phase**
- **The analytical work performed at ESA & ABSpaceConsulting pointed to a number of ways to improve the magnetic tensor.**
  - Lengthening the MTQ is by far the most effective improvement (power 3).
  - Enlarging the electrical time constant improves M linearly
  - Relaxation of maximum length and acceptable time constant by the AOCS are two very important aspects to be agreed on each satellite.

4. Characterisation and optimization of Magnetic Torquers for Passive Magnetic Detumbling (2/2)

- **Interactions with Zarm has helped to translate the analytical improvements into physical and « manufacturable » MTQ respecting constraints of each satellite manufacturer**
  - Need to respect the linear dipole achievable, constraints on the number of layers, acceptable Resistance & Inductance varying between the avionics architectures
- **Fully analytical ESA MTQs « designs » are now in complete accordance with Zarm MTQs « designs » generated via their internal tools.**
  - For example, MT 250 magnetic tensor can be doubled with a mass increase of 15%
  - Manufacturing of such MTQs are feasible with no further R&D: they remain in the family of MTQs produced.
- **An efficient way to optimize MTQ for detumbling while maintaining acceptable electrical time constant for the AOCS is to move from Aluminum housing to Carbon Fiber (to avoid mutual inductance). Qualification model is being started to secure future projects on time.**
- **This table gives optimization results when relaxing driving parameters (length, elec. time constant, mass)**
  - Further increased efficiency of 20% is expected due to low temperature of defunct satellites (lower resistance)

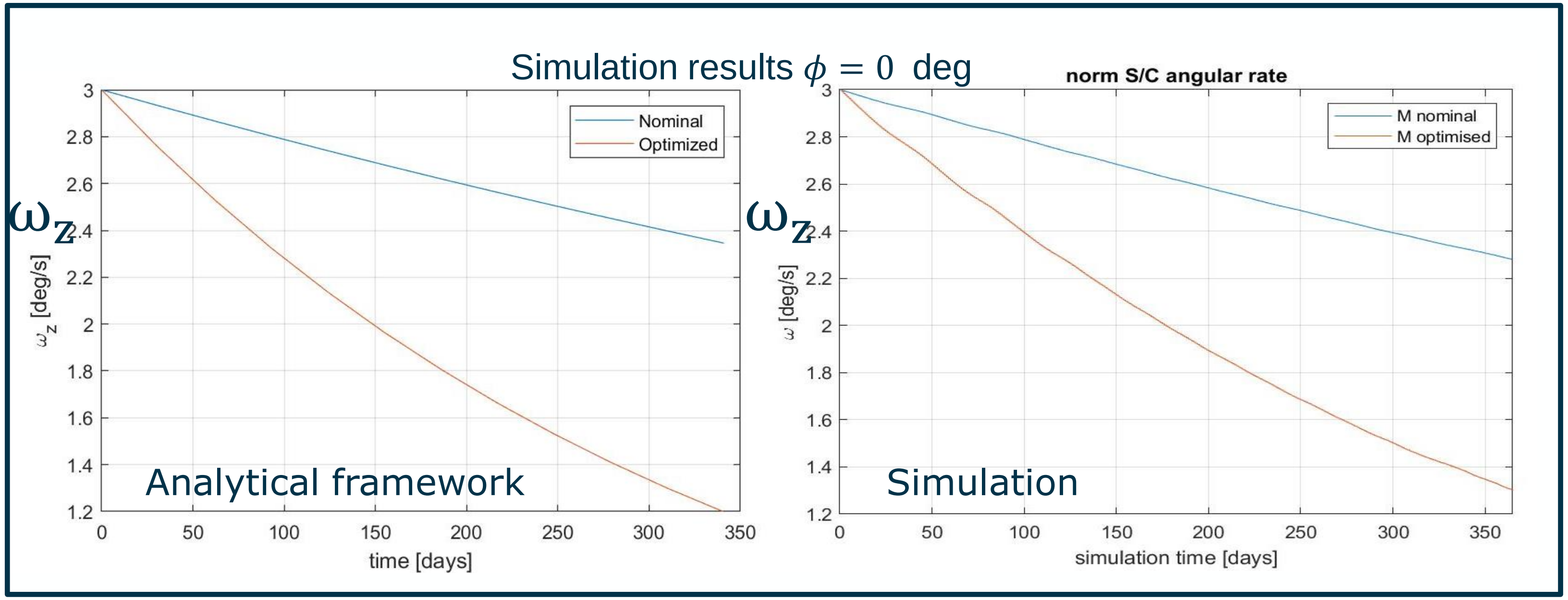
MT Am^2 - Housing	MT 250 - Alu	MT 250 - CFRP	MT 250 - CFRP	MT 400 - Alu	MT 400 - CFRP
Length/elec tau/mass	0.85m/200ms/5 kg	1m/235ms/5.7 kg	1m/330ms/7.4 kg	1m/350ms/8.9 kg	1m/350ms/11.1 kg
Magnetic Tensor @ 20° C	$\mathbf{2.7\ 10^4\ \Omega^{-1}m^4}$	$\mathbf{5.5\ 10^4\ \Omega^{-1}m^4}$	$\mathbf{7.8\ 10^4\ \Omega^{-1}m^4}$	$\mathbf{6.9\ 10^4\ \Omega^{-1}m^4}$	$\mathbf{9.3\ 10^4\ \Omega^{-1}m^4}$

5.1 Solar Radiation Pressure: Symmetric Satellite



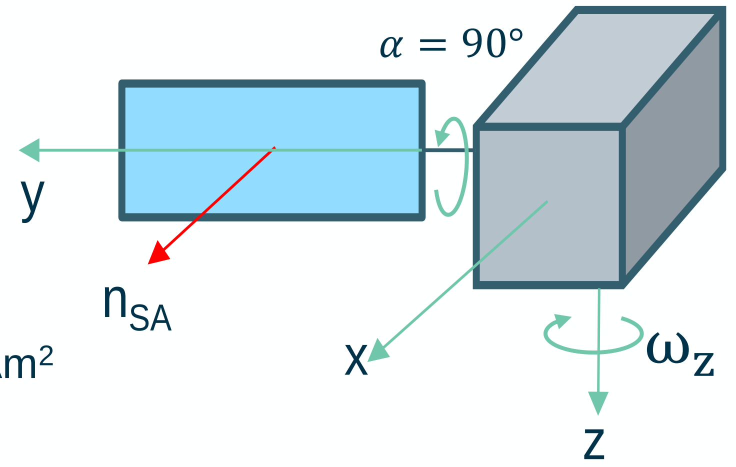
- **SAT1: Symmetric Configuration**
  - LEO spacecraft at polar orbit at 760km altitude
  - Symmetric configuration with two Solar Arrays 2x12m^2
  - MoI [I_{xx}, I_{yy}, I_{zz}] = [900, 3000, 3250] kgm^2
  - Nominal and optimized Magnetic Torquers
  - Disturbance effects: SRP (w/o shadowing), GG, Aero, Residual Magnetic Dipole [0, 0, 12] Am^2
- **Simulation results (no shadowing)**
  - Good agreement between analytical framework and simulations (e.g., for $\phi = 0$ deg) :

Time constant τ (years)	Nom. M 2.7×10^4 $(\Omega^{-1}\mathrm{m}^4)$	Opt. M 9.2×10^4 $(\Omega^{-1}\mathrm{m}^4)$
Analytical $\tau_0 = \frac{I_z}{M \frac{5}{2} B_{eq}^2}$	3.26	0.97
Simulation	3.63	1.18

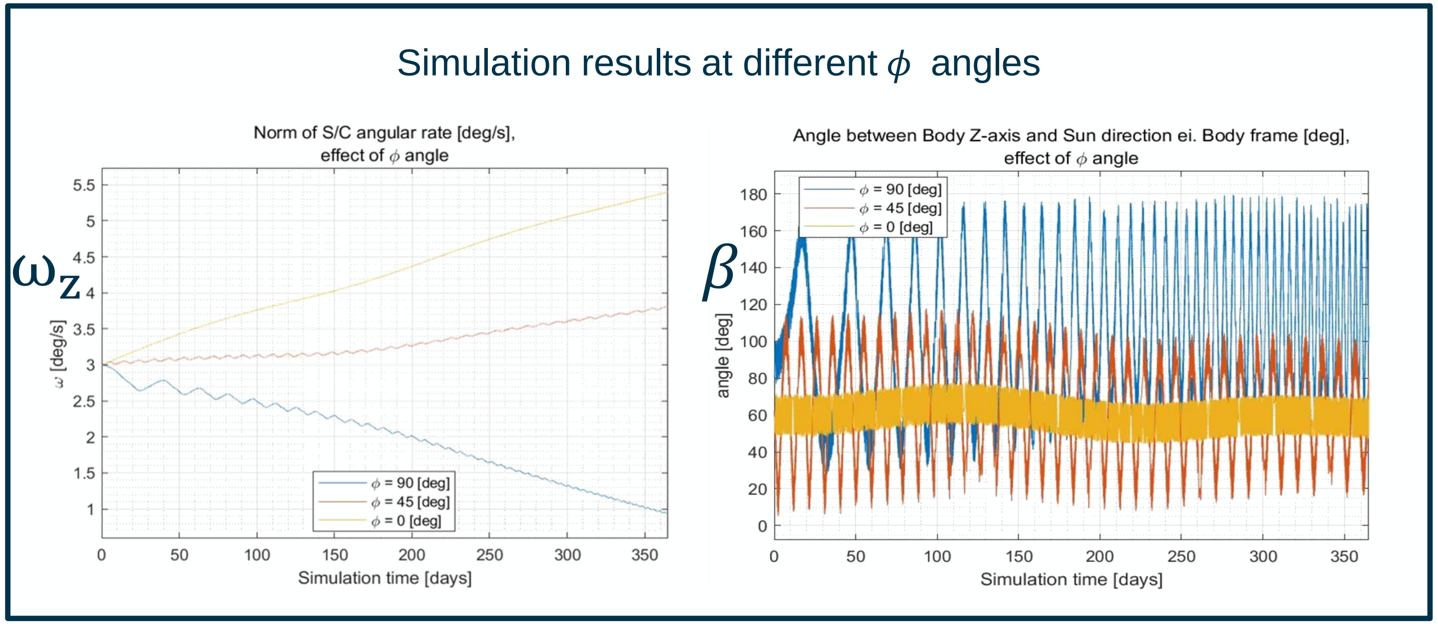


5.2 Solar Radiation Pressure: Asymmetric Satellite

- **SAT2: Asymmetric Configuration**
  - LEO spacecraft at polar orbit at 750km altitude
  - Single lateral Solar Array 12m^2
  - MoI [I_{xx}, I_{yy}, I_{zz}] = [1500, 2000, 2600] kgm^2
  - PoI [I_{xy}, I_{xz}, I_{yz}] = [70, 130, -80] kgm^2
  - Disturbance effects: SRP, GG, Aero, Residual Magnetic Dipole [0, 0, 12] Am^2

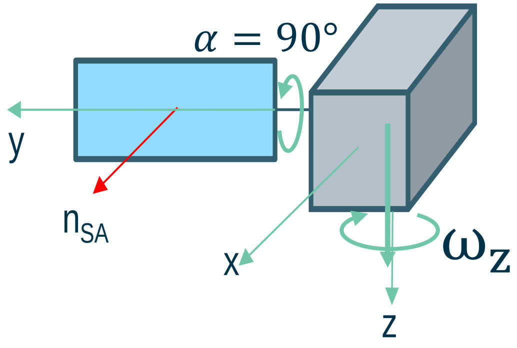


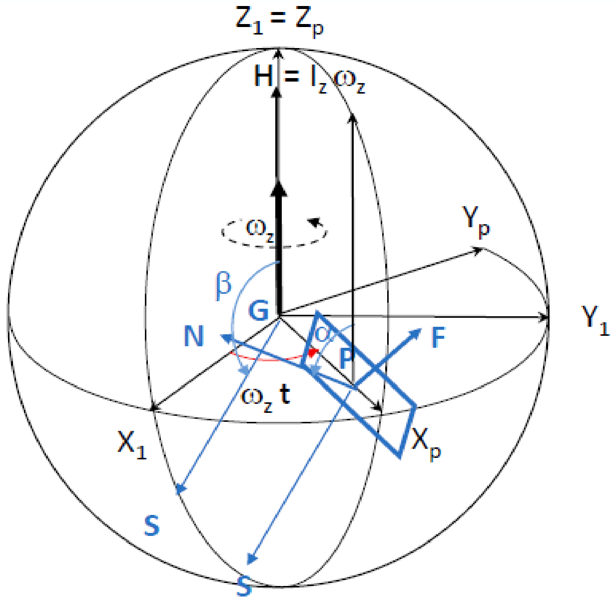
- **General Simulation Results over 1 year**
  - Sensitivity analysis of the key parameters
    - Obliquity angle ϕ and therefore β (sun aspect angle)
    - Solar Array reflectivity coefficients c_s, c_d (specular and diffuse)
    - Solar Array Angle α
  - In the simulation on the right with $\alpha = 90°$ SRP dominates spin dynamics
    - SRP torque much powerful than PMD
    - SRP may cause spin-up or spin-down



5.3 Understanding the impact of SRP on an Asymmetric Satellite (1/2)

- **Effect of the Solar Radiation Pressure (SRP) average torque**
  - Although its instantaneous value is small, it has the potential to spin-up space debris, if some unbalance creates a repetitive non-null average torque over one spin period
  - This effect, first identified for asteroids around 1901, was called the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect
- **Impact of non equal reflectivity coefficients of the single Solar Array**
  - If $\alpha = 90°$ (figure), the sun illuminates successively the front side when $0 \leq \omega_z t \leq 180°$ and the back side between $180°$ and $360°$ with different reflectivity coefficients, which create a long-term torque
  - If $\alpha = 0°$, the orbit-average torque seems negligible because both half rotations compensate each other (the sun always illuminates the same side of the Solar Array).
  - However, this is not true in presence of spin axis misalignment

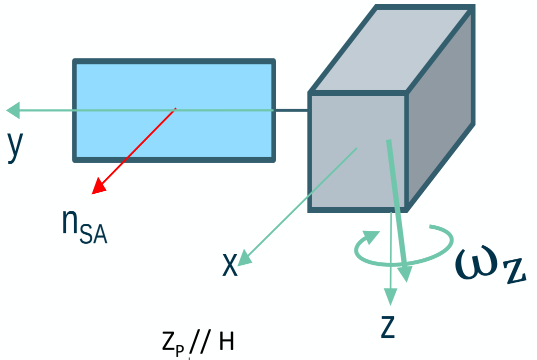


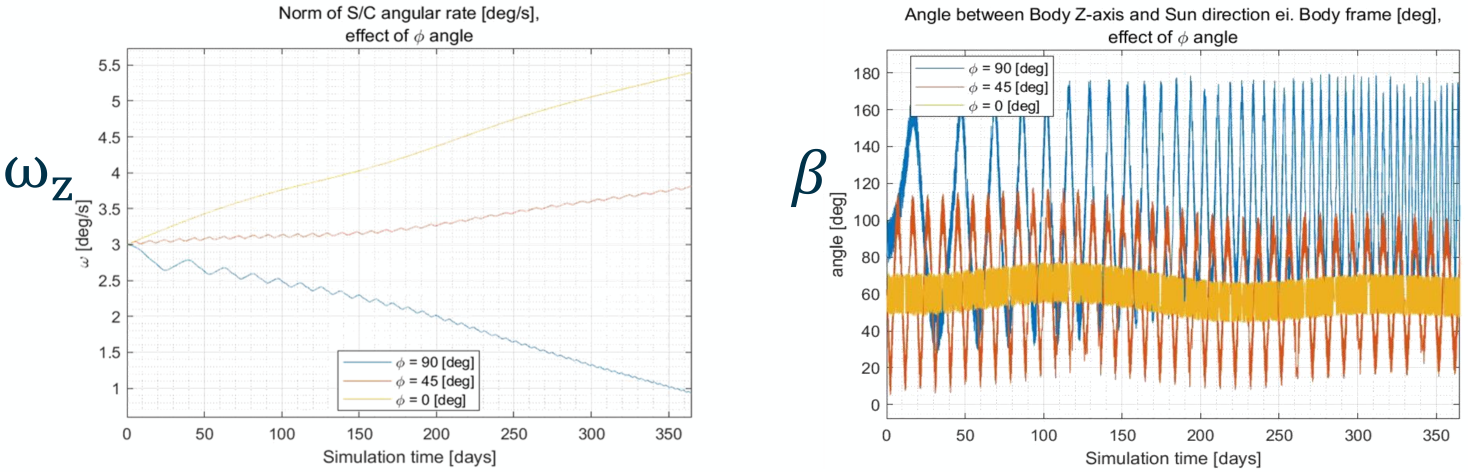


Sun and Solar Array geometry

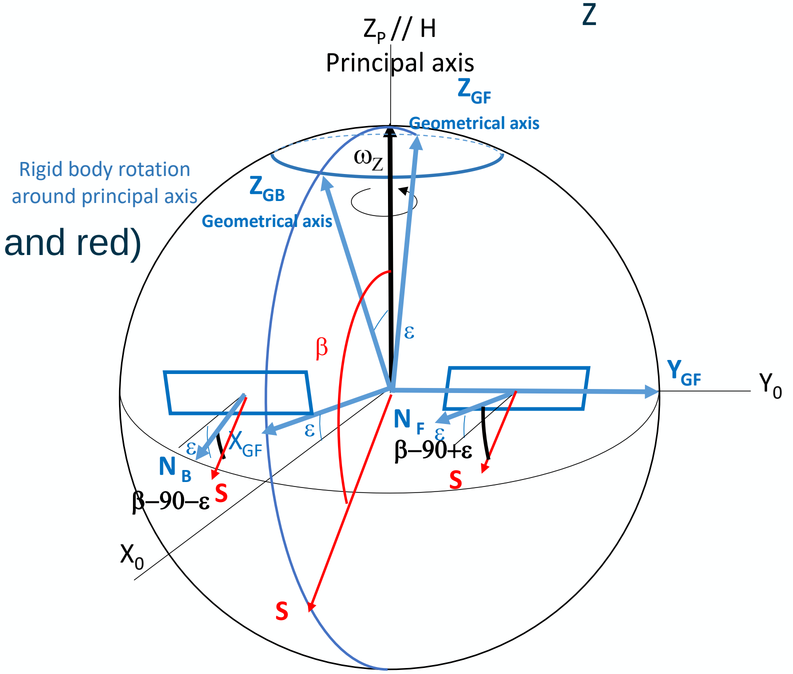
5.3 Understanding the impact of SRP on an Asymmetric Satellite (2/2)

- **The misalignment angles ε_x and ε_y between the spin axis and body Z_G axis create different sun incidence angles during a spin rotation**
- **A secular spin-average torque appears which may dominate the spin dynamics**
  - SRP may cause spin-up or spin-down
    - With $\langle\beta\rangle_{spin} > 90°$ (figure right and blue plots),
      $\Rightarrow$ left half more illuminated than right half $\Rightarrow$ $\langle T_z \rangle < 0$ and spin down
    - With $\langle\beta\rangle_{spin} < 90°$ (orange and red plots)
      $\Rightarrow$ right half more illuminated than left half $\Rightarrow$ $\langle T_z \rangle > 0$ and spin up
    - And complex evolution of the sun aspect angle β due to SRP tilting torque (blue and red)





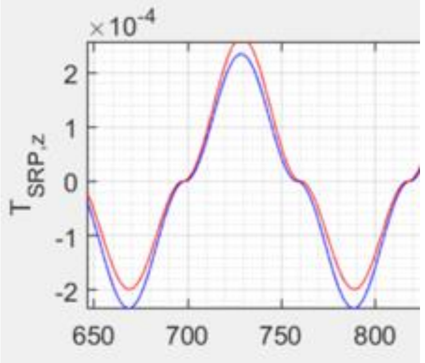
Simulation results at different ϕ angles



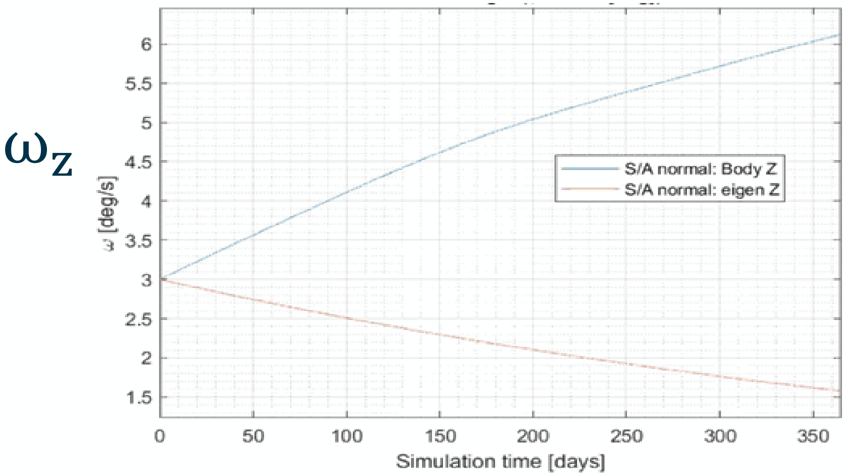
Sun and Solar Array geometry

5.4 Proposed mitigation action to minimize SRP (1/2)

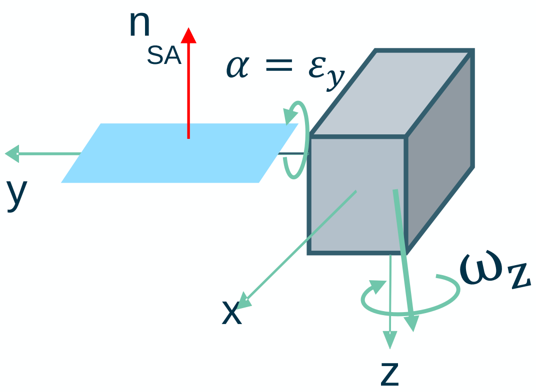
- **1. Solar Array normal parallel and not perpendicular to the geometrical axis Z_G ($\alpha = 0°$),**
  ⇒ the sun will illuminate either the front side or the back side
  - No issue from having different reflectivity coefficients
  - But the spin axis misalignment results in a non-null average torque over one spin period
- **2. Additional offset ε_y applied to the SADM to minimize this unbalance torque**
  - The figures below right show that the sun incidence has been re-balanced by this Solar Array angle compensating the principal axis misalignment $\boldsymbol{\varepsilon_y}$
  - The simulation below shows that the SRP which was dominating the spin dynamics (blue plot) loses its authority to the profit of PMD (red plot) thanks to this mitigation action
  - Next question: which accuracy is required?

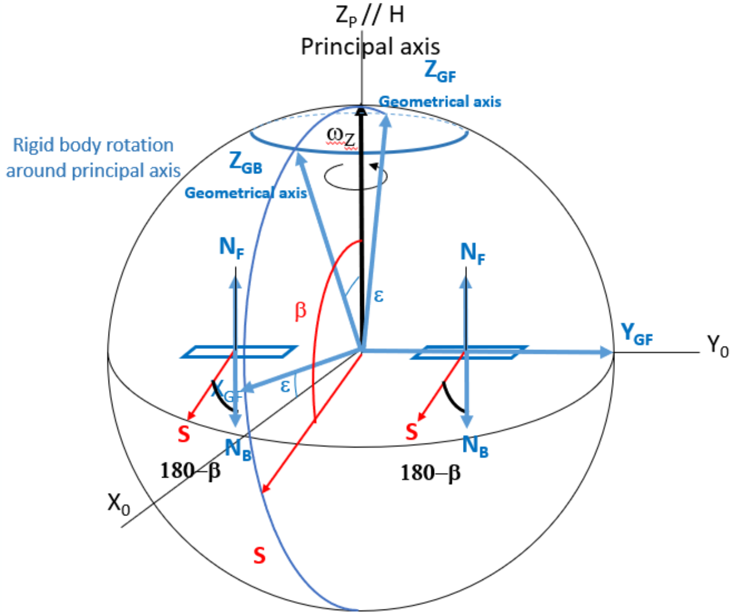


Torque profiles over one spin period
blue: w/o spin axis unbalance $\langle T_z \rangle = 0$
red: with spin axis unbalance $\langle T_z \rangle \neq 0$



Simulation results with $\alpha = 0$ (blue) and $\alpha = \varepsilon_y$ (red)

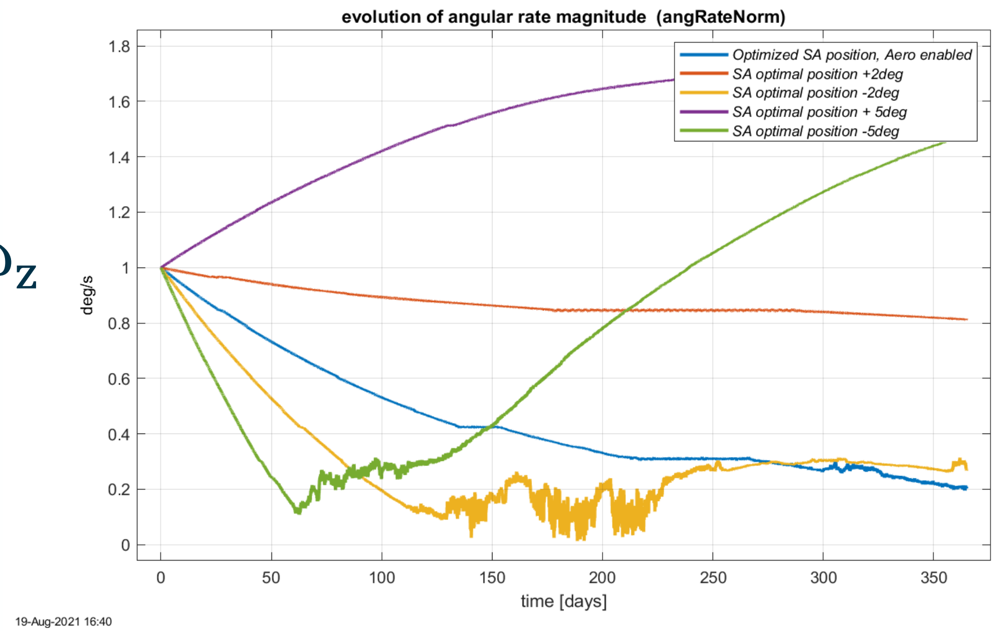




5.4 Proposed mitigation action to minimize SRP (2/2)

- **This long-term simulation of an asymmetric satellite includes all disturbances:**
  - Gravity Gradient, Solar Radiation Pressure, Residual Magnetic Dipole, Aerodynamic torques
  - The rate evolution with the optimised Solar Array position $\boldsymbol{\varepsilon_y}$ = 7.14 deg (blue plot) is consistent with the analytical framework
  - However, this offset needs to be precisely estimated and applied (in-orbit calibration)
    - 2 deg inaccuracy can create a non negligible spinning torque, positive (orange, $\alpha = 9.14°$) or negative (yellow, $\alpha = 5.14°$)
    - 5 deg inaccuracy creates a significant spinning torque, with SRP overruling PMD authority (purple and green)

ω_z



6. Application to Copernicus Expansion Sentinels

- **Six new Copernicus Expansion Sentinels developed to address European Union policy and Copernicus user needs and to expand the current capabilities of the Copernicus space component:**
  - CO2M, CHIME, CIMR, CRISTAL, LSTM and ROSE-L.
- **ESA has adopted a proactive and innovative approach for their End-of-Life management**
  - If the nominal de-orbit manoeuvres do not happen, additional requirements have been added in the ESA SSRD to facilitate a combined VEGA mission which would at the same time bring the replacement satellite and capture and de-orbit the defunct satellite
  - Several technology developments are currently on-going to address each of these new functions.
  - For the tumbling motion damping function, based on the promising evaluations of the use of Passive Magnetic Detumbling, the following requirements have been created:
    - *D4R-U-001. The Spacecraft shall be able to automatically “short circuit” the Magnetorquers to allow passive rate damping after power voltage is lower than a threshold to be agreed with the Agency.*
      Note 1: The short circuiting of the magnetorquers aims to damp residual rates starting from up to 3 deg/sec down to 0.75 deg/sec within 12 months.
    - *GD4R-U-003. In case the spacecraft has a SADM, after power voltage is lower than a threshold to be agreed with the Agency, the Spacecraft should automatically reorient the Solar Panels to a position minimising the misalignment between the Normal direction of the Solar Panels and the major axis of inertia of the Spacecraft, such that the residual misalignment, in the plane perpendicular to the SADM rotation axis, is smaller than 1 deg (TBC).*

7. Conclusions

- **Short-circuiting of the Magnetic Torquers at the End-of-Life is a promising method to dissipate kinetic energy from the satellite tumbling motion and damp the angular rates.**
  - MTQ optimisation consists in maximising the length and the electrical time constant and preferably selecting a CFRP housing instead of Aluminum
- **The analytical framework developed by ESA during the Phase B1 of the six new Copernicus Sentinels helps to predict the long-term dynamic evolution of the spin rate and assess detumbling durations**
  - Reference time constant τ_0 derived from the spin inertia of the satellite, the orbit radius and the Magnetic Tensors of the 3 short-circuited Magnetic Torquers and Eddy currents, assuming no dominant Solar Radiation Pressure torque
  - Proof of concept tests performed by ESA and LusoSpace during the ESA FOME study
  - Characterisation of MTQ's at very low regime and optimisation process on-going at ZARM
- **Further work necessary**
  - Refining the estimation of Eddy currents in Copernicus Expansion satellites conductive structures
  - Understanding and mitigating the Solar Radiation Pressure impact for asymmetric satellites
  - Avionics implementation and High-Fidelity simulations by Copernicus Expansion primes

Contacts: tiago.soares@esa.int, andrey.kornienko@esa.int, steeve.kowaltschek@esa.int, alain@abspaceconsulting.com