PW-Sat2 deorbit sail effectiveness analysis from the perspective of orbital parameter measurement

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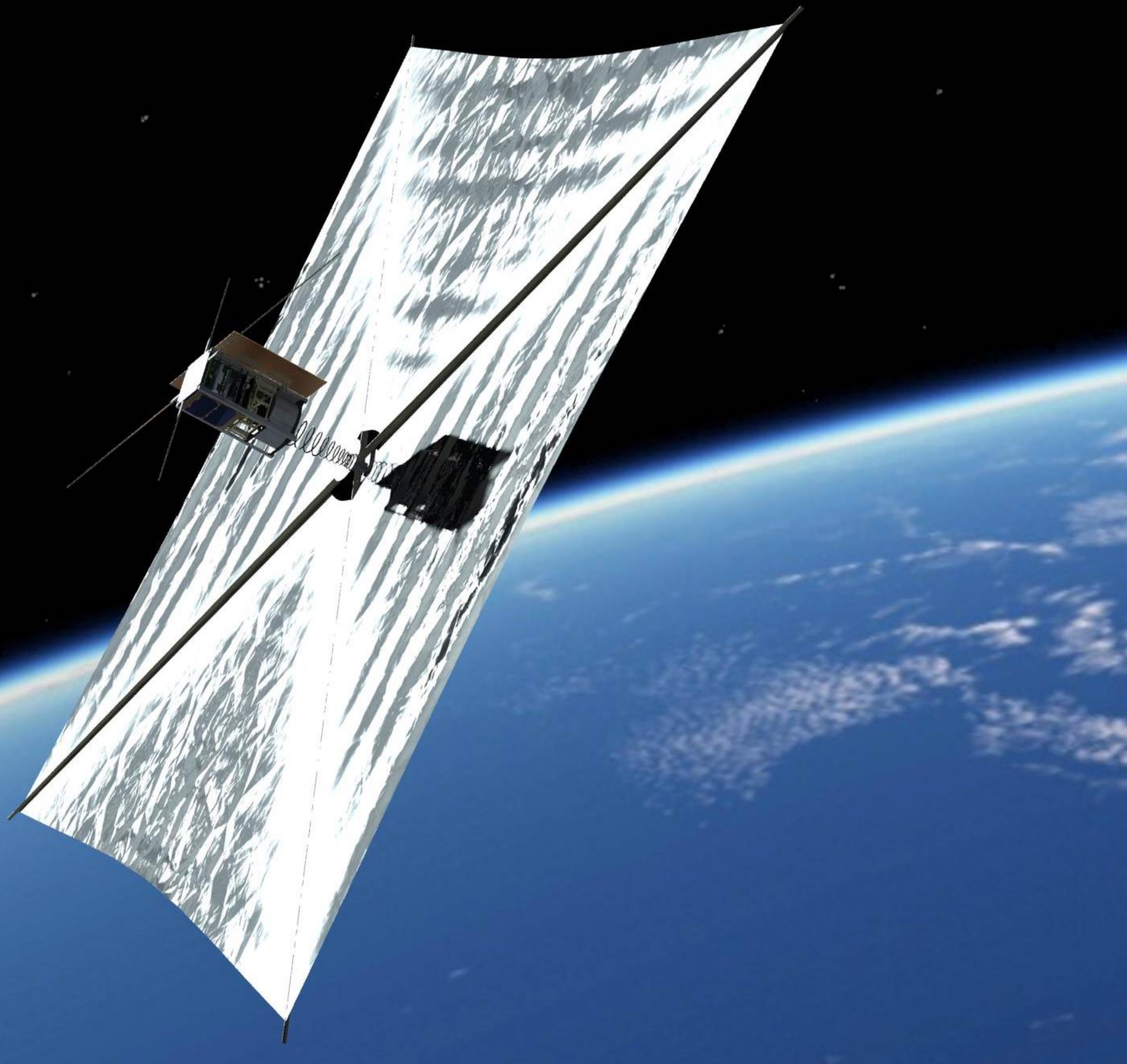
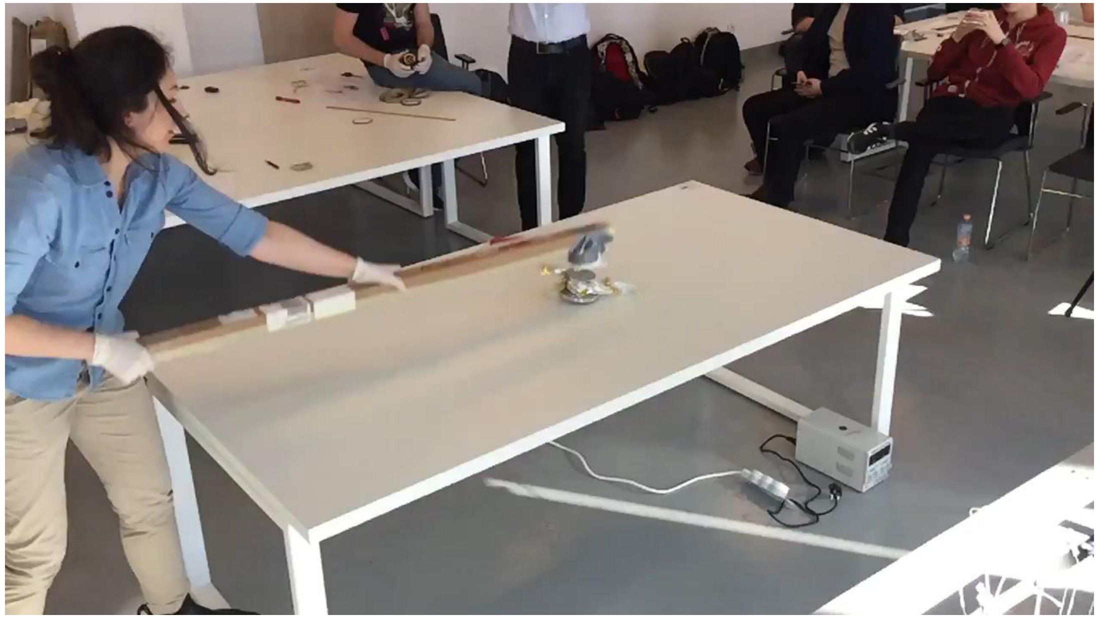
11/10/2022

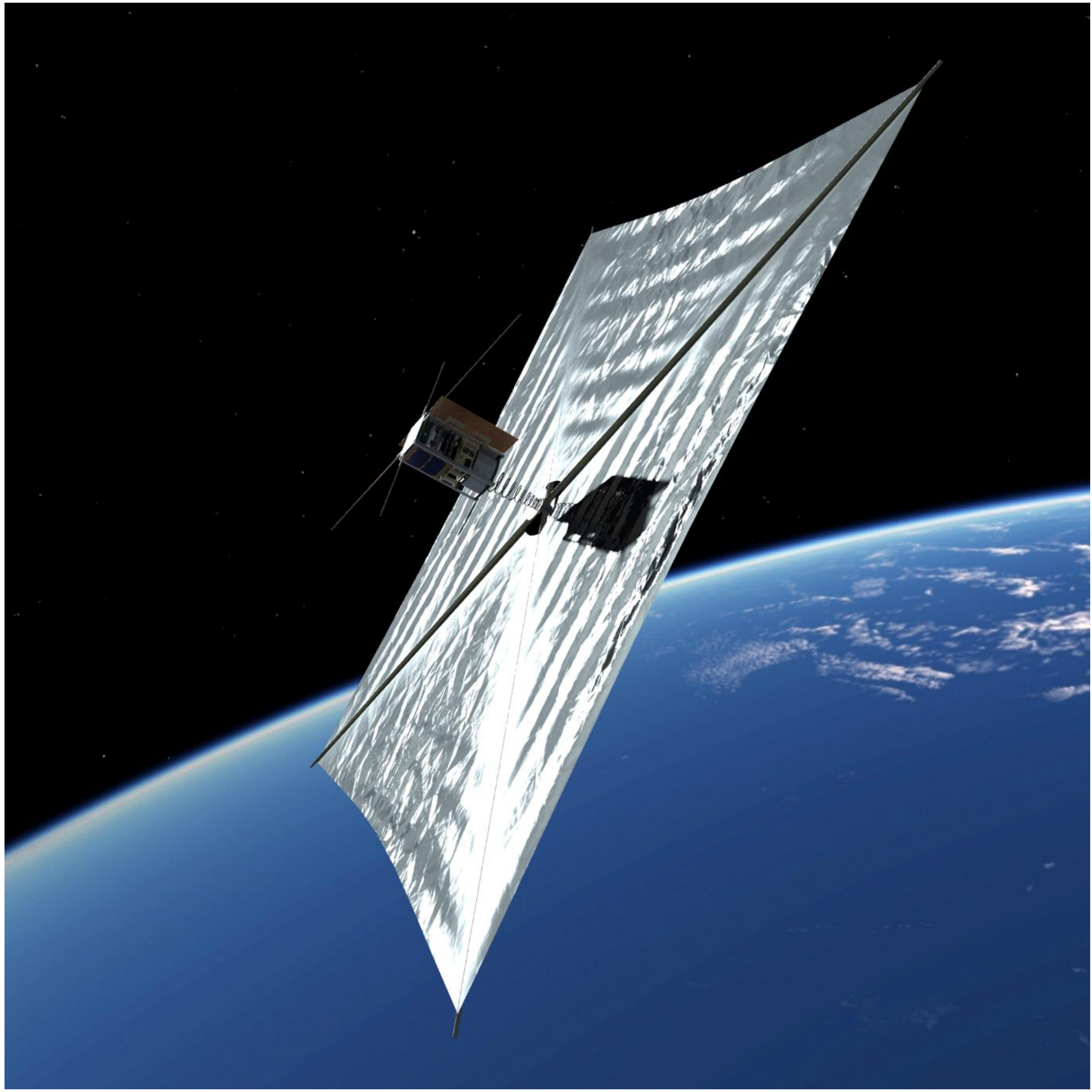


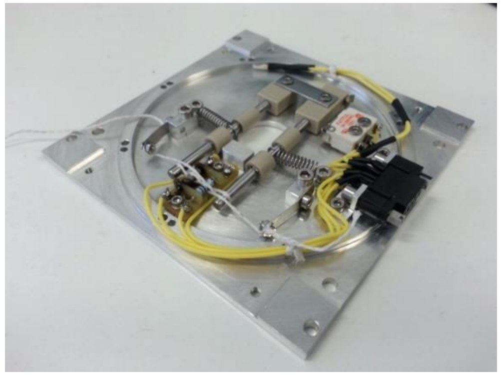
PW-Sat2 satellite

- 4th Polish satellite, 2nd from WUT
- PW-Sat2 – student satellite build by Students’ Space Association, WUT
- Launch 3.12.2018
- Sail deployment 29.12.2018
- Deorbit (atmosphere re-entry) 23.02.2021
- Primary payload - **deorbit sail**
    - Reduction of orbital lifetime
    - Passive deorbit system

PW-Sat2 Sail







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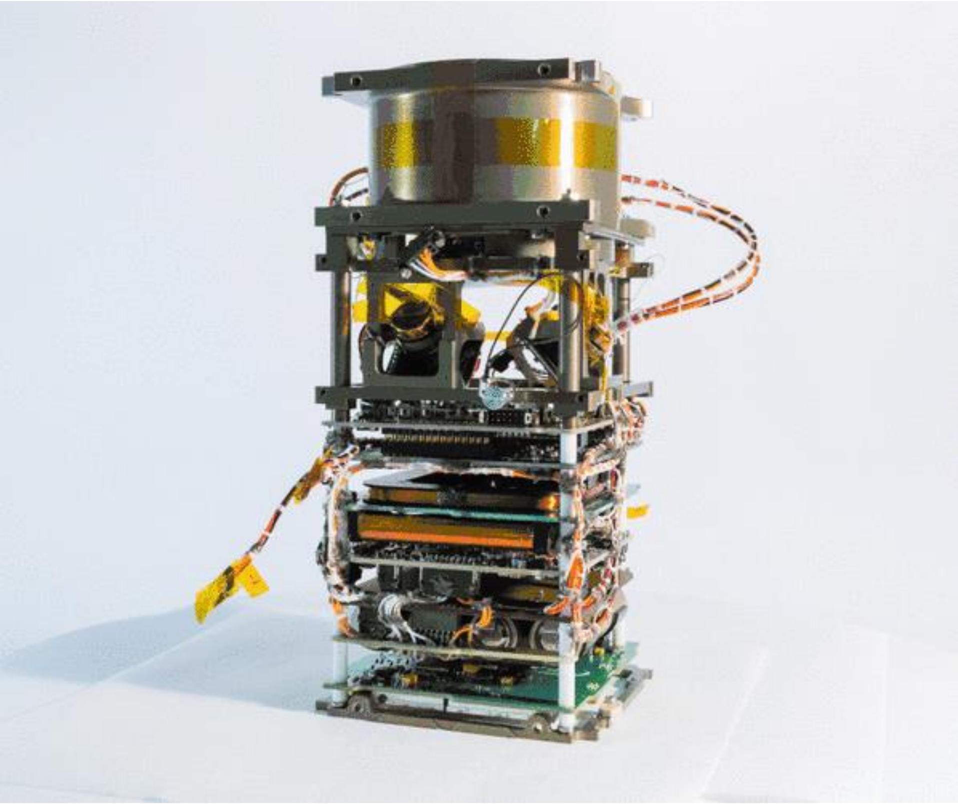
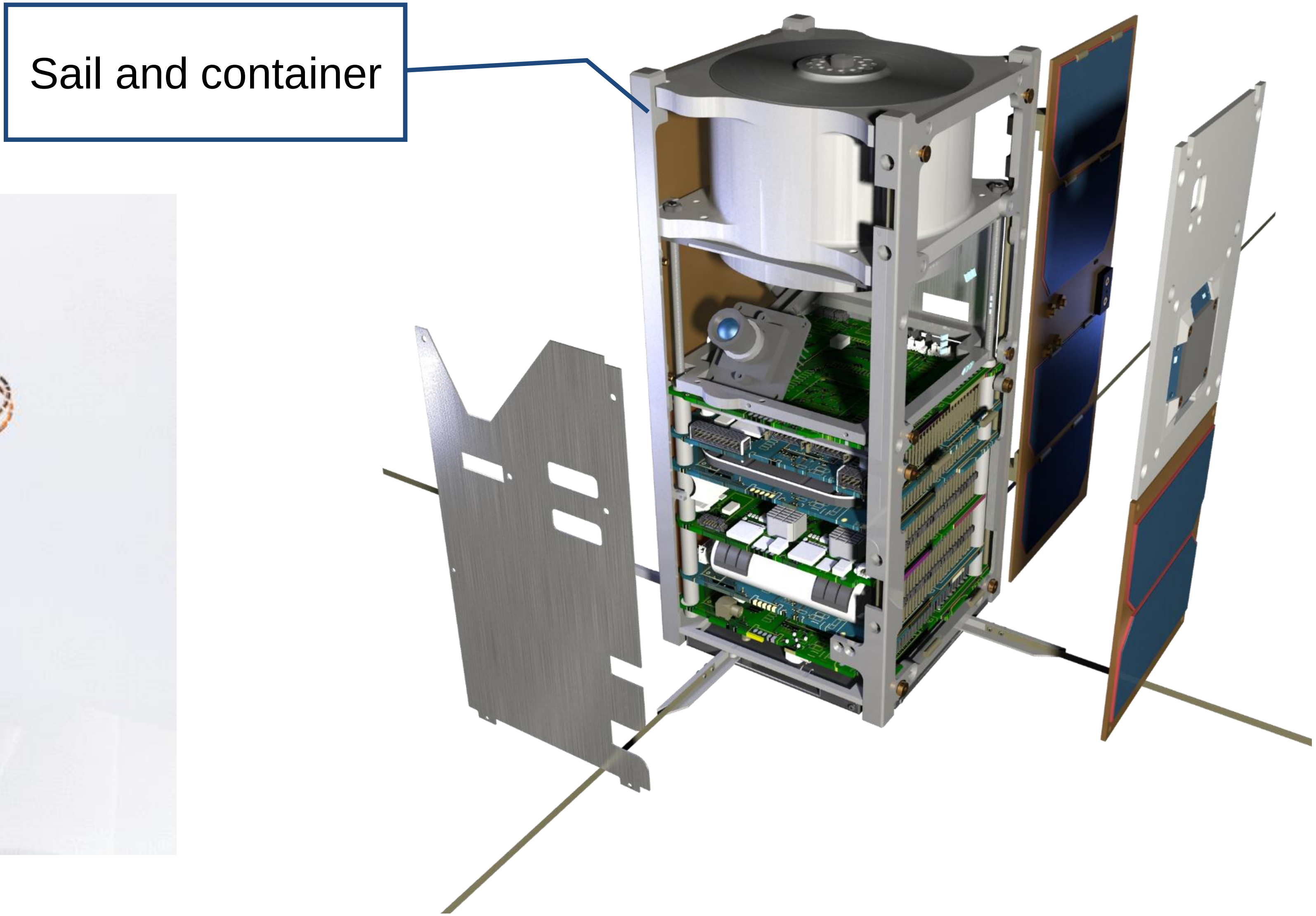




International regulations

- Regulations introduced by ESA, NASA, CNES, suggested by UN/UNOOSA
  - 25 years or less on orbit after mission end
  - In practice collision probability decrease is the crucial outcome
  - Traditionally for spacecrafts with propulsion: orbit lifetime $\propto$ collision probability
  - No longer satisfied for spacecrafts which area changes significantly during mission (deployable sail, baloon, tail, ribbon etc.)

For a satellite with an across-track cross-section **annual collision probability** with objects of size from the range: could be expressed as:

$$ACP = \sum_{j=1}^{n} F_j \, \pi \left(R_{SC} + r_j\right)^2$$

Where:

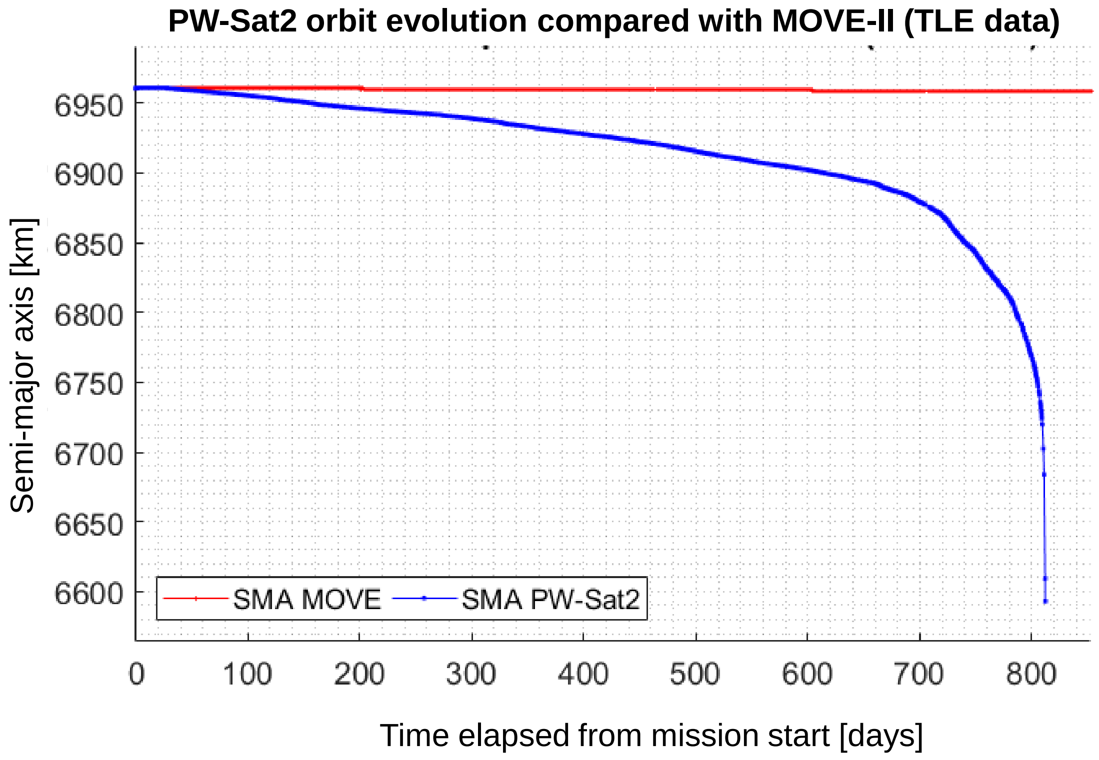
- n - numer of impactor size bins
- j – particular impactor size bin
- ACP – annual collision probability
- F_j – stream of impactors from the *j* bin – numer of objects from size bin *j* intersecting the orbit of satellite in question during a single year
- R_{SC} – representative radius of the satellite for which the ACP – is determined (modelled as a sphere for simplicity)
- r_j – impactor radius

Deorbit sail effectivness for sails - definitions

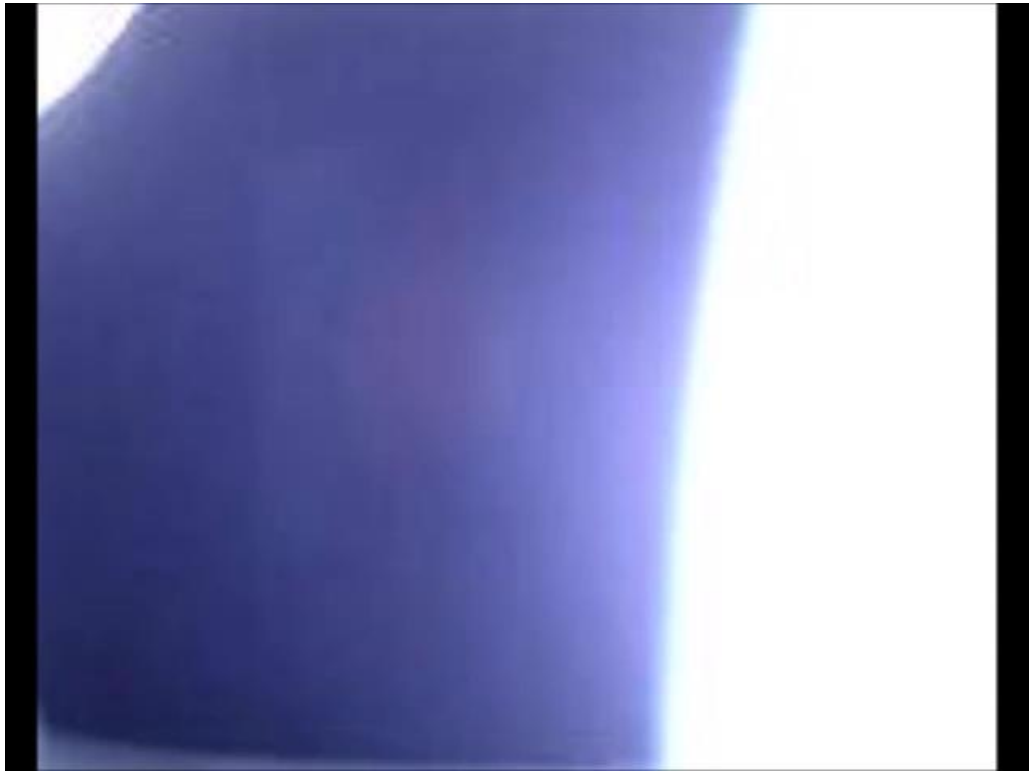
- (Regulations) Deorbit in < 25 years
- (Narrow definition) Sail effectivness in preventing the space debris issue – **collision probability decrease**
- (Wider definition) Effectiveness of deorbit system in systems engineering perspective
  - Is the deorbit sail a good alternative to other deorbit systems (e.g. thrusters)
  - Cost, mass, volume, reliability, attitude control, power usage, thermal aspects, pre-launch storage, communication, operational aspects

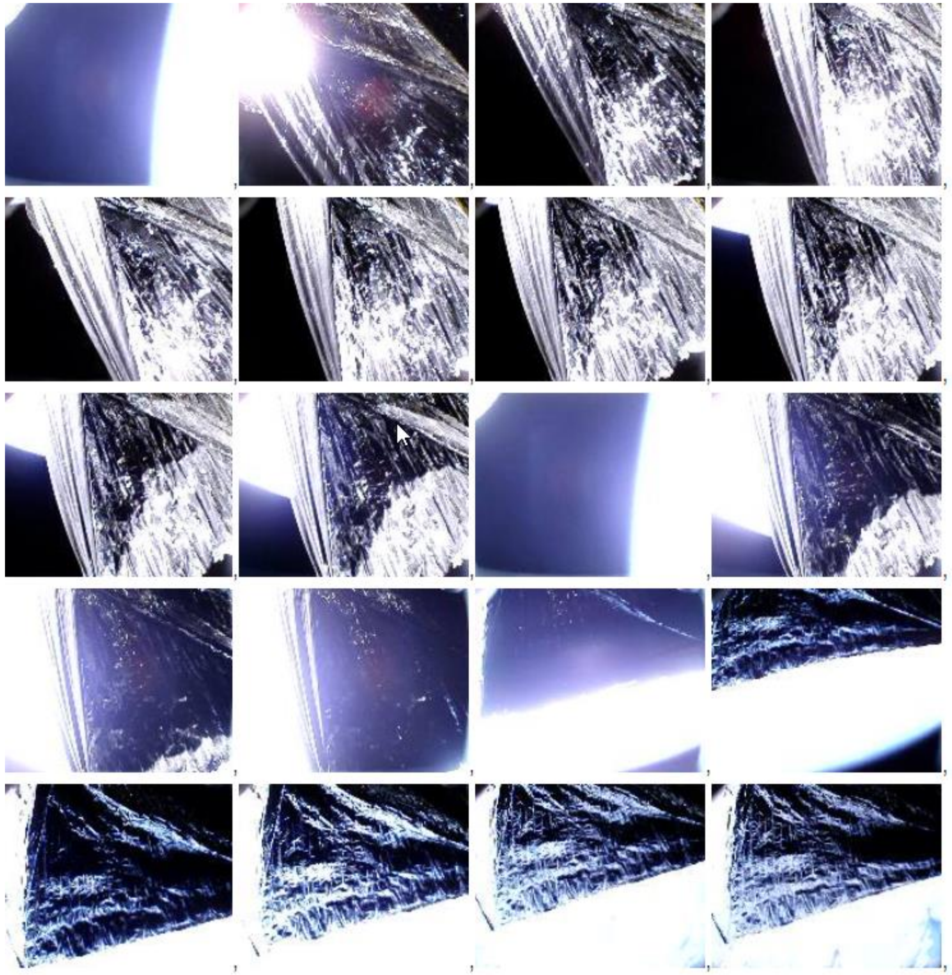
Experimental data used for analysis and how it was acquired

- Orbital parameters (ephemeris) from TLE
  - TLE –Two Line Elements, publicly available orbital parameters shared by NORAD
  - Comparison with MOVE II – the same launch container, the same time of release as PW-Sat2 – the same initial orbit
- Photos of the deployed sail taken by the on-board camers



PW-Sat2 Sail deployment





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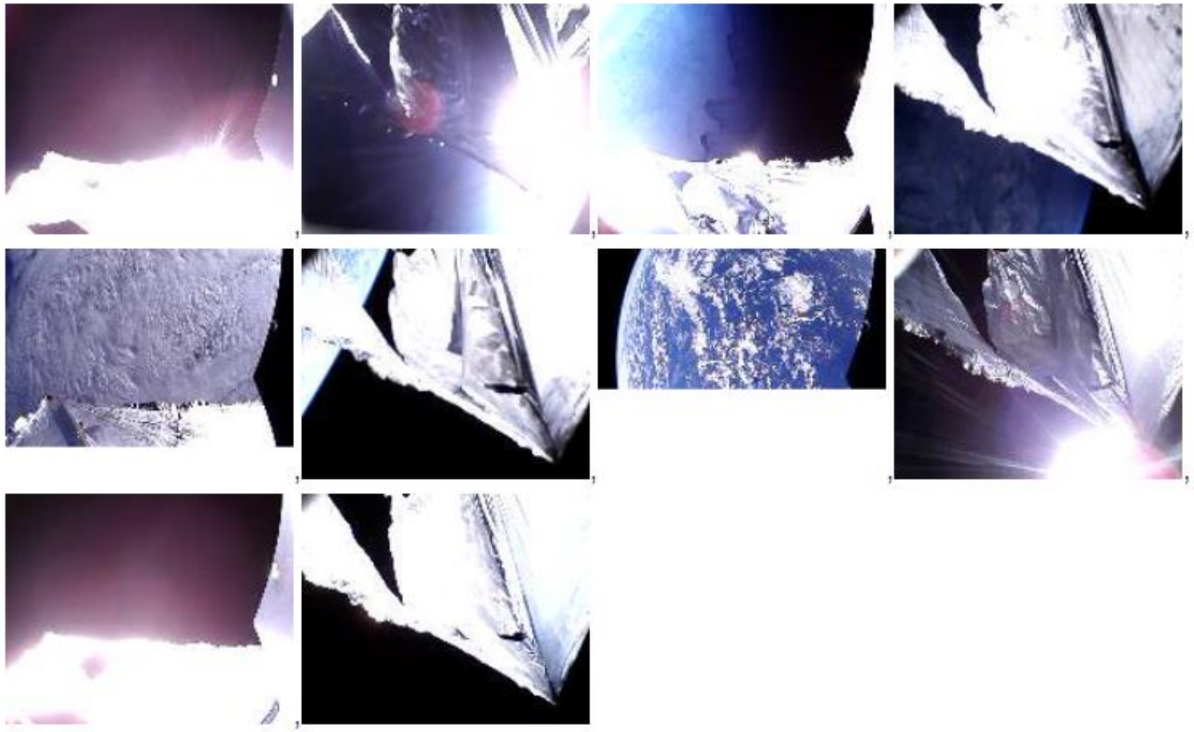
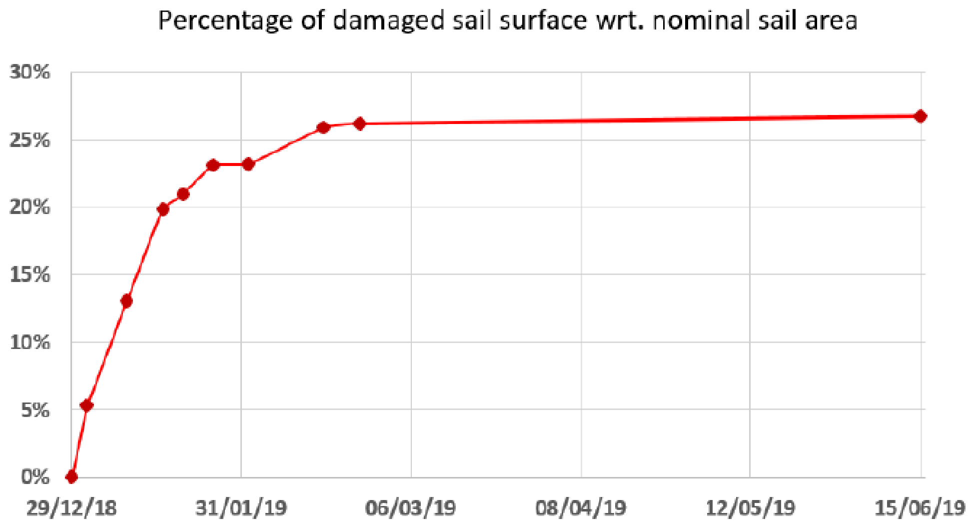
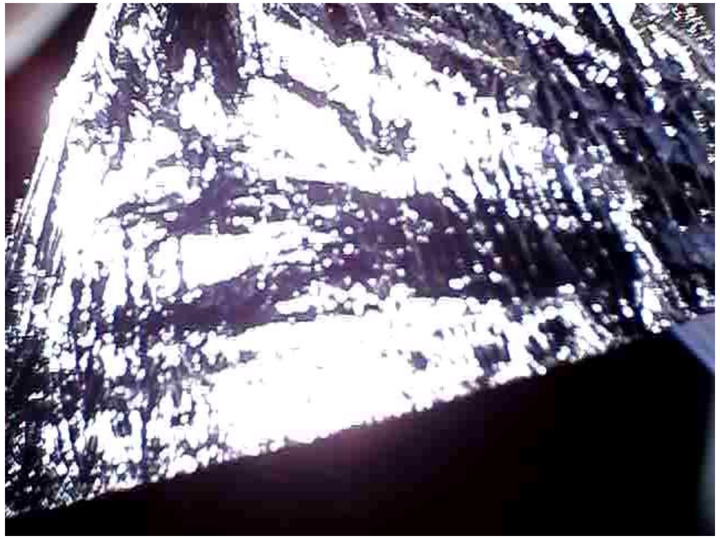
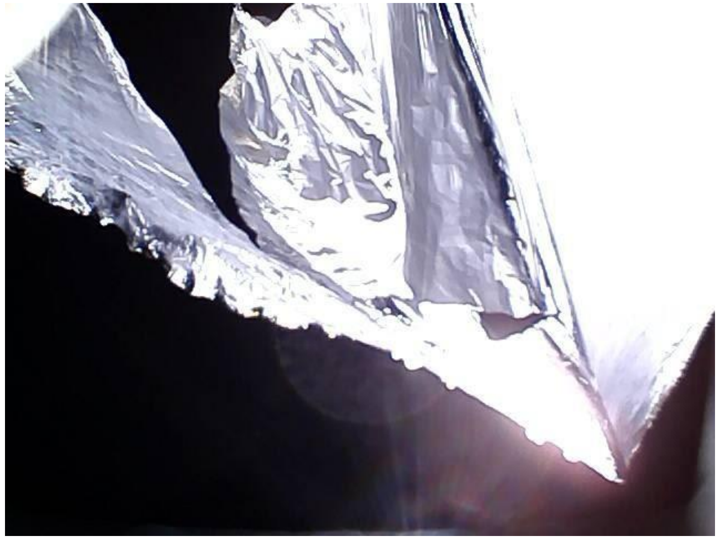


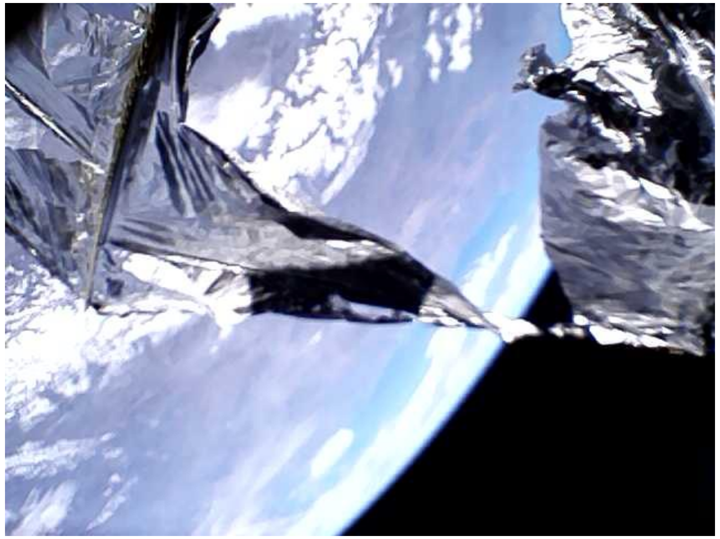
Experimental data used for analysis and how it was acquired

- Visual assessment of the sail surface conditio after deployment
- 28% of Surface material became loose as a results of appearing tears (2 months after sail deployment)





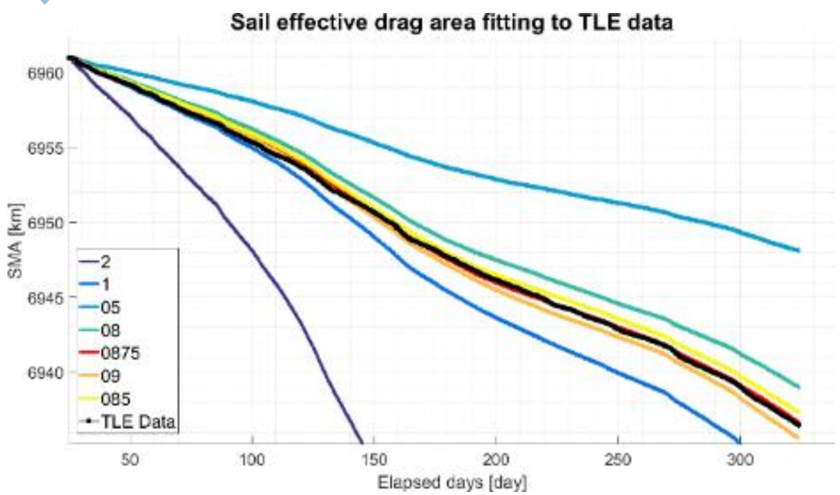


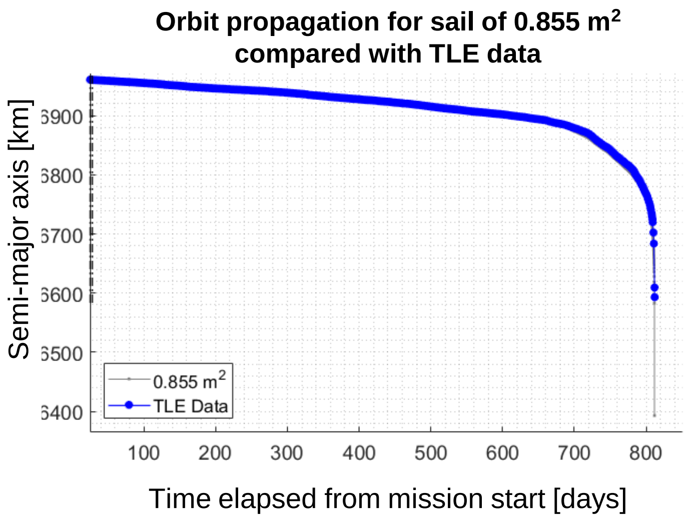


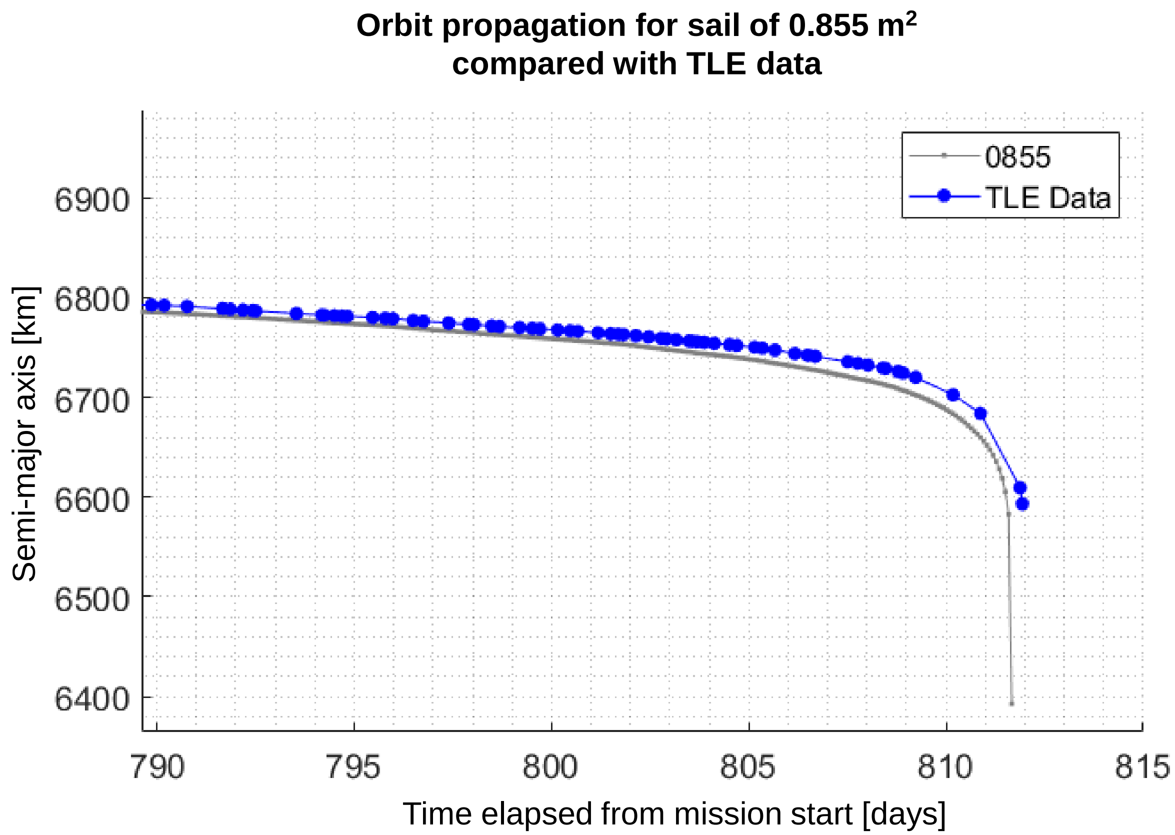
Photos analysis and lost surface estimation kindly shared by PW-Sat2 mechanical team.

Propagated orbit fitting to actual orbit parameters

- Actual orbit fitting to propagations with different effective drag areas – sail area lower than expected by 42.43%
- Difference resulting from unfavourable sail attitude (no precise AOCS)







Collision probability analysis - assumptions

- DRAMA ARES (ESA)
  - Annual collision probability
  - Constant orbit around the year
- Normalized to daily collision probability
- Ephemeris changing for each day
  - **Actual orbit from TLE**
  - Propagation with nominal sail 2.015 m^2
  - Propagation with no sail 0.0267 m^2
- Satellite model sphere (ARES)
  - Conservative – great circle of 4 m^2
  - Nominal – great circle of 2.015 m^2

Scenario	**NS**	**TN**	**TC**	**SN**	**SC**
Orbit	Propagation with 0.0267 m^2	**Actual orbit (TLE)**	**Actual orbit (TLE)**	Propagation with 2.015 m^2	Propagation with 2.015 m^2
Orbit lifetime [days]	4891	786	786	427	427
Sphere	Nominal	Nominal	Conservative	Nominal	Conservative
Sphere radius [m]	0.092	0.8	1.14	0.8	1.14
Max P_d	1.72E-07	1.15E-06	2.21E-06	1.16E-06	2.24E-06
Total P_m	2.88E-04	6.52E-04	1.24E-03	5.96E-04	3.14E-04

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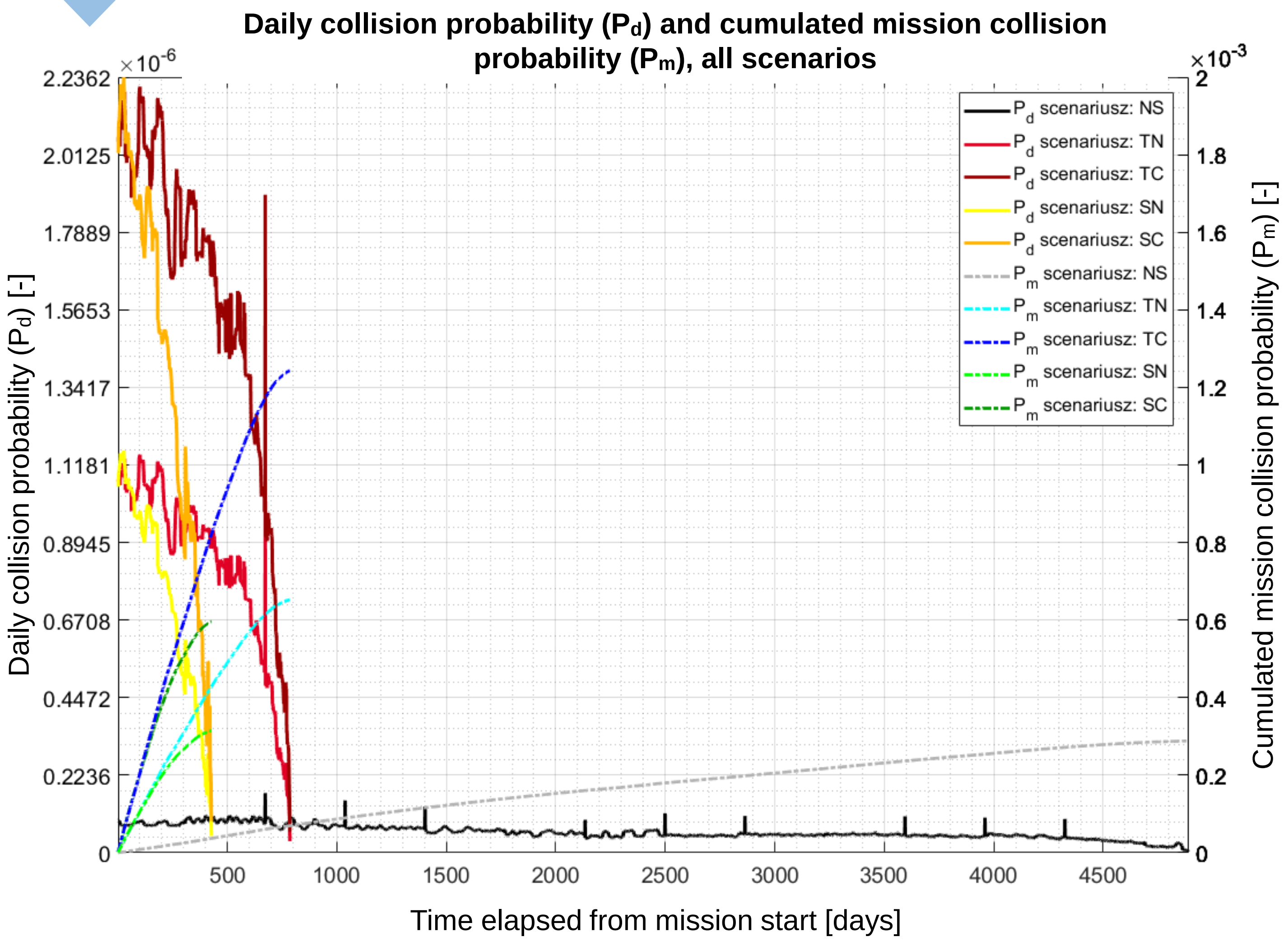
Results
P_m – cumulative collision probability during lifetime

Results of the collision probability analysis



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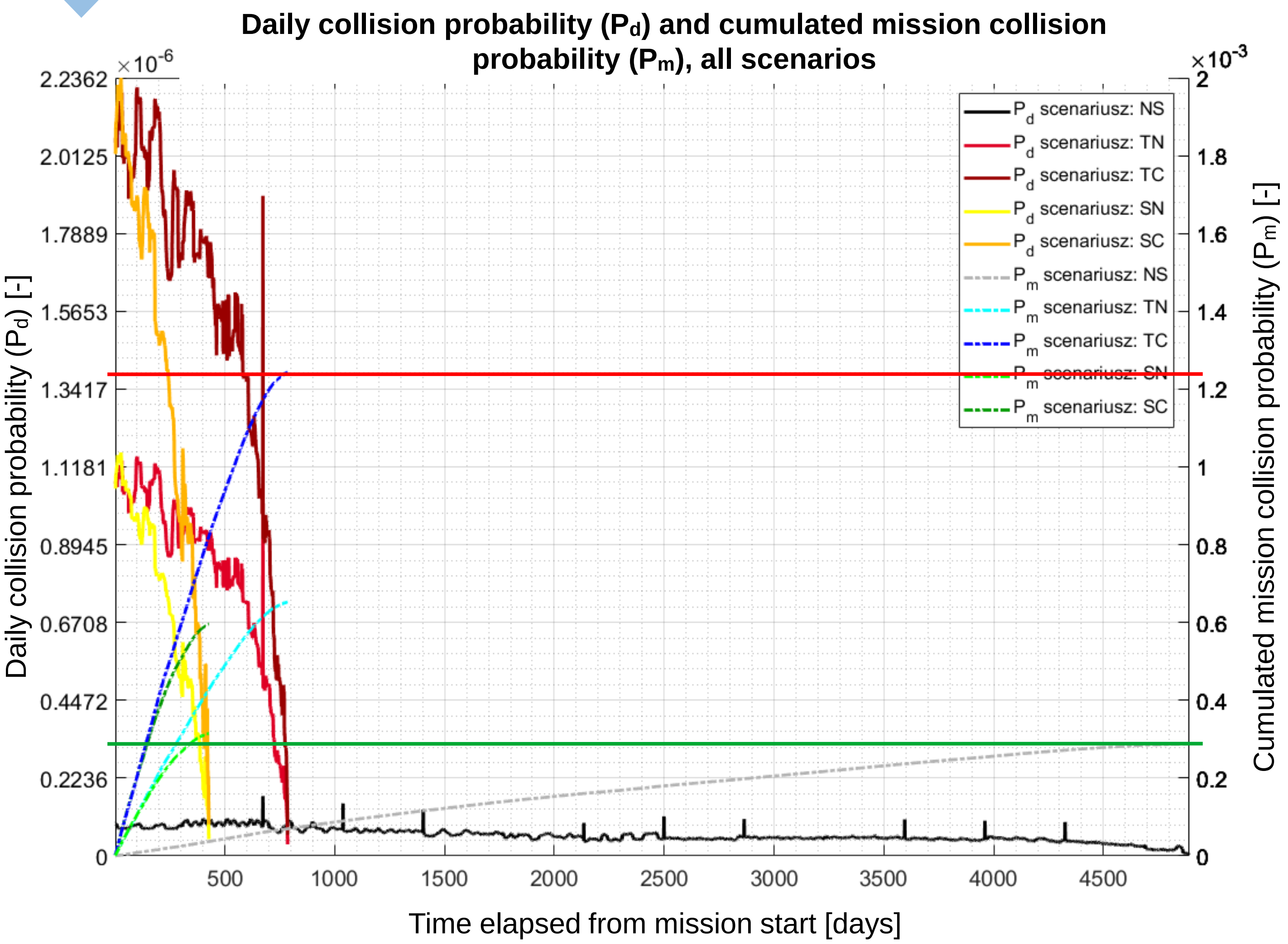

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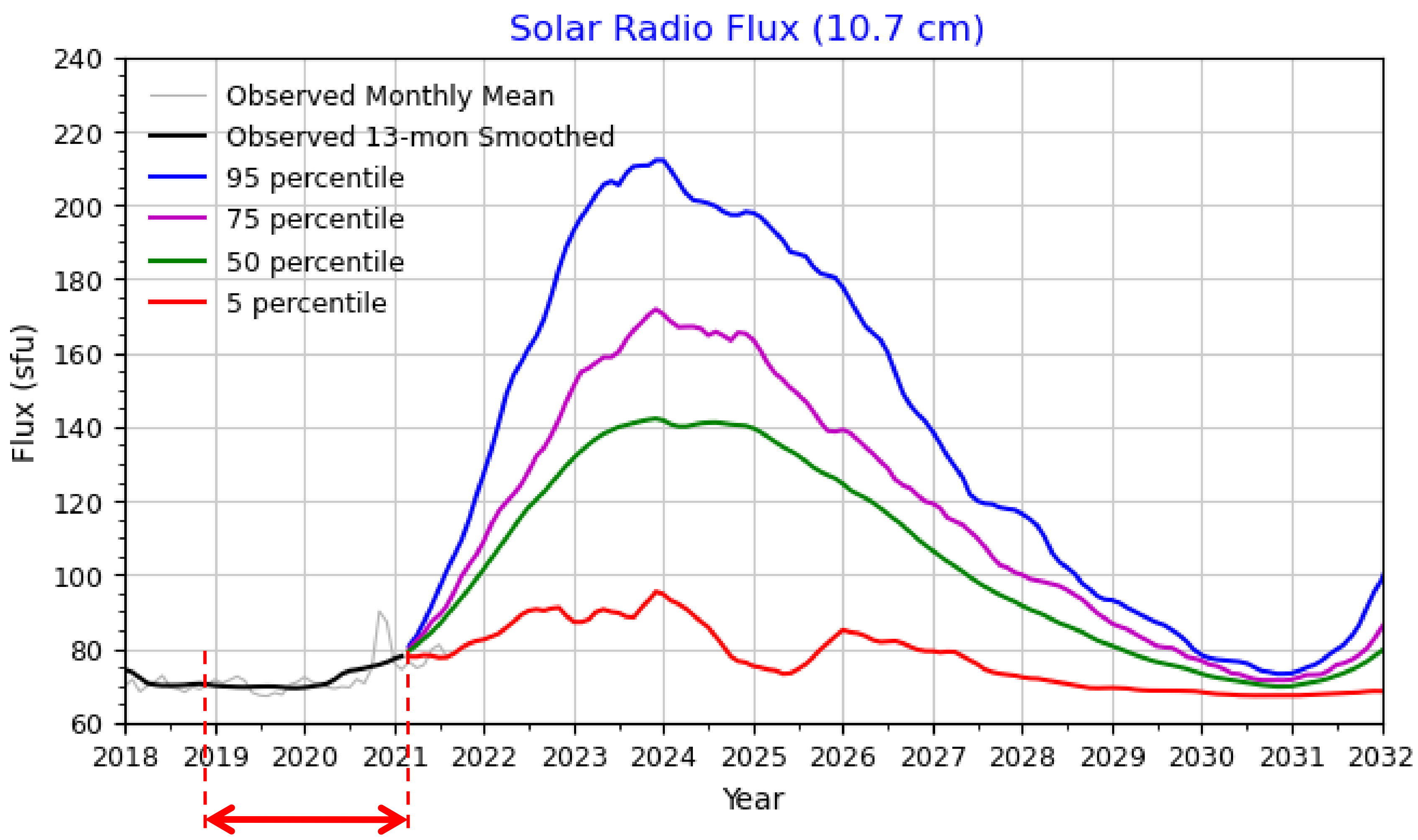
For actual solar activity data from mission time, sail increased collision probability of the mission.

Collision probability analysis – Solar activity influence



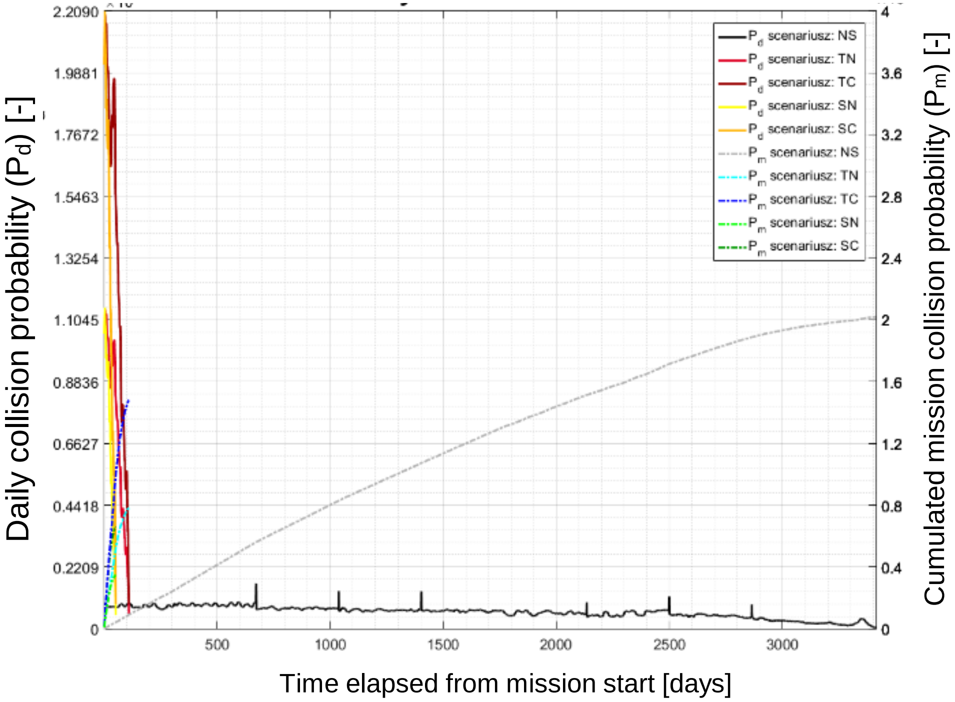
PW-Sat2 mission duration

- Solar cycle 11 years
- Balancing of solar maximum and solar minimu effect over 13.4 years (no sail)
- No balancing for 2.15 years on orbit (TLE, actual orbit)
- PW-Sata2 launch during the prolonged solar minimum
- Elimination of solar activity cycles influence
  - **New scenario – constant solar activity over mission lifetime F10.7 = 140 sfu; Ap = 15 (ECSS)**

1 sfu = $10^{-22} Wm^{-2}Hz^{-1}$

Constant solar activity - results

Daily collision probability (P_d) and cumulated mission collision probability (P_m), all scenarios



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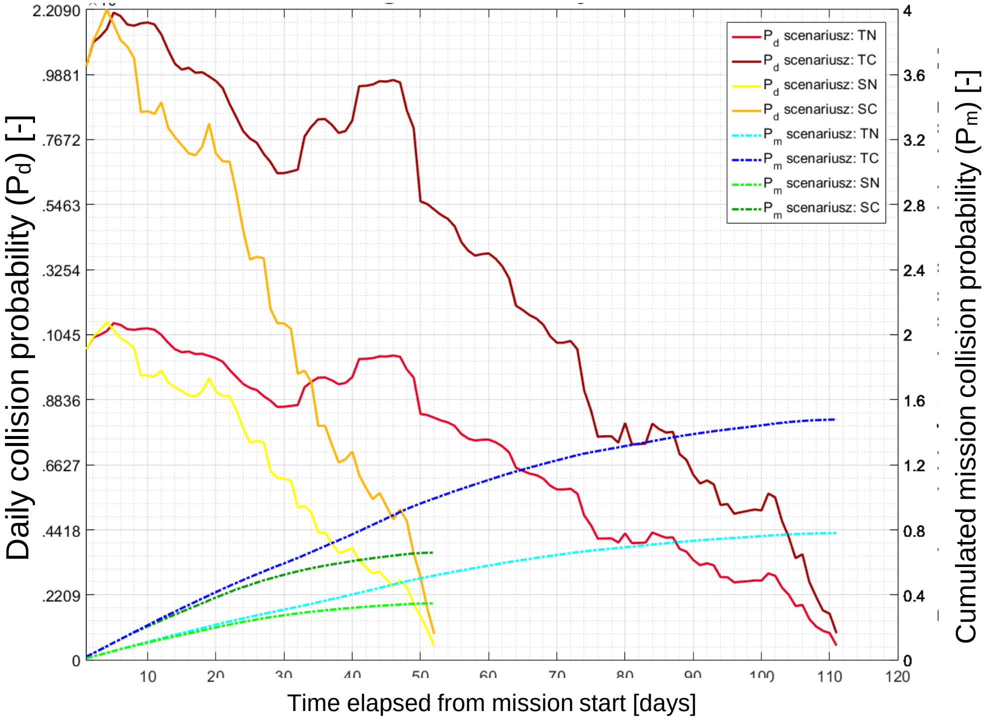

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Total P_m	**2.017E-04**	**7.807E-05**	**1.479E-04**	**3.484E-05**	**6.601E-05**

„No sail" (NS) scenario has the highest cumulative collision probability – **sail improves collision probability** of the mission

*for calculated sail Surface with TLE data

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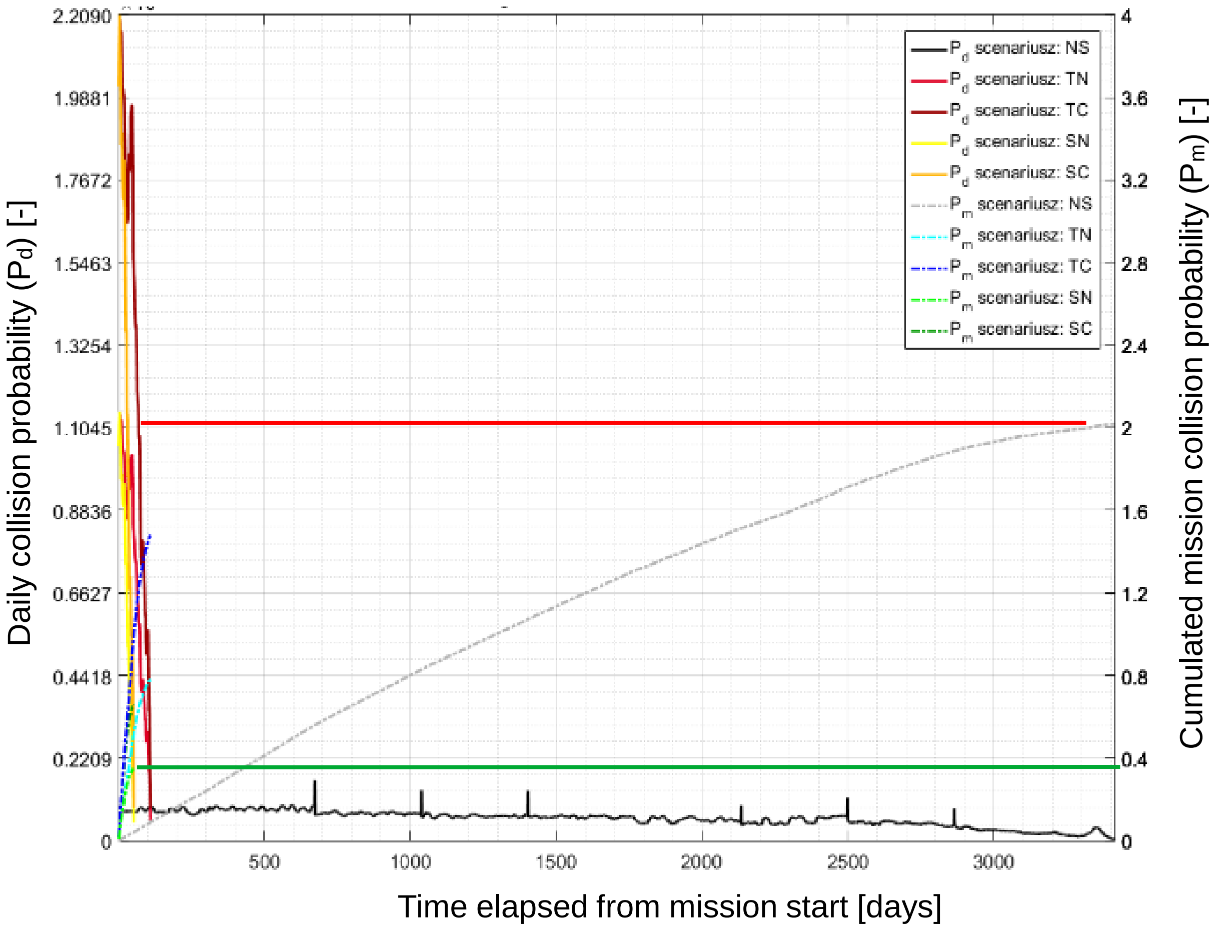

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„No sail" (NS) scenario has the highest cumulative collision probability – **sail improves collision probability** of the mission in each scenario

*for calculated sail Surface with TLE data

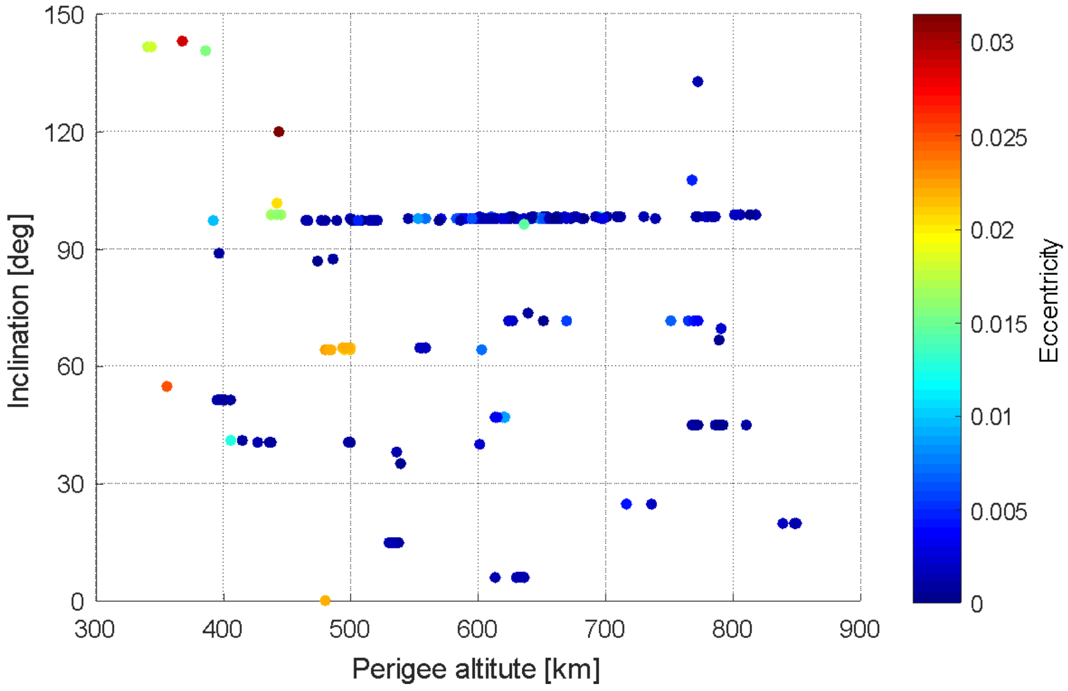
Collision probability analysis - conclusions

- For orbit lifetimes far from integer multiple of solar cycle (11 years). **Solar phase during sail deployment is a critical** factor for final collision probability.
- Sail deployment near **solar maximum** **decreases orbit lifetime and total collision probability**
- Proper sail sizing for 25-year orbit lifetime should minimize the influence of initial solar phase on total collision probability (minimums and maximums would equalize)
- Short orbit lifetime and sail deployment close to **solar minimum** could result in the **increase of the total collision probability** after sail deployment
- Historically, foreseen space debris population increase has been underestimated (e.g. megaconstellations) – **better to deorbit faster** even with the same collision prob
- Collision model used doesn't differentiate between the collision with sail surface and sail structure - collision with sail surface is **not necessarily catastrophical** in effect

PW-Sat2 sail effectiveness space

- Popular small satellite platforms up to 100 kg analysed
- Popular orbits - SSO + other examples (40° and 60°)
- PW-Sat2 exact sail size – 4 m^2 – the same as tested on orbit (no scalability)

Parameter	Values						
Platform	**2U**	**3U**	**6U**	**12U**	**24U**	**48U**	**SSTL-100**
Mass [kg]	2,6	3,9	7,8	15	30	60	100
Drag area [m^2]	0,0267	0,0455	0,0667	0,0979	0,1571	0,2509	0,8376
Drag area (with sail) [m^2]	2,0157	2,0188	2,0210	2,0274	2,0466	2,0685	2,4553
Mass to area ratio[kg/m^2]	97,61	85,85	116,8	152,6	192,0	238,3	120,0
Mass to area ratio (with sail) [kg/m^2]	1,29	1,94	3,86	7,39	14,6	29,02	40,96



PW-Sat2 sail effectiveness space

No sail

	2U	3U	6U	12U	24U	48U	SSTL-100
Mass to area ratio [kg/m^2]	1,29	1,94	3,86	7,39	14,60	29,02	40,96
800 km	160,6	148,2	179,9	193,3	199,2	199,7	177,10
750 km	104	93	118,9	149,1	173,8	189,8	121,90
700 km	58,6	49,7	64,2	90,5	108,4	134,8	65,7
650 km	30,2	26,4	35,3	48,2	60,1	73,5	35,7
600 km	**14,7**	**13,4**	**17,7**	**23,2**	30,1	35,6	**17,6**
500 km	**3,7**	**3,6**	**4,1**	**4,7**	**5,6**	**7,1**	**4,1**

PW-Sat2 sail

	2U	3U	6U	12U	24U	48U	SSTL-100
Mass to area ratio [kg/m^2]	97.61	85.85	116.8	152.6	192.0	238.3	120.0
800 km	**3,10**	**3,70**	**6,00**	**12,40**	*26,30*	*49,60*	*70,70*
750 km	**2,70**	**3,00**	**4,10**	**6,60**	**14,90**	*31,10*	*43,30*
700 km	**2,30**	**2,50**	**3,10**	**4,00**	**6,90**	**16,70**	**22,40**
650 km	**1,90**	**2,20**	**2,60**	**3,20**	**4,20**	**7,40**	**12,20**
600 km	1,40	1,70	2,20	2,60	**3,10**	**4,30**	5,30
500 km	0,20	0,30	0,70	1,30	2,00	2,40	2,70

PW-Sat2 sail effectiveness space

PW-Sat2 sail is insufficient to deorbit in < 25 years

No sail

	2U	3U	6U	12U	24U	48U	SSTL-100
Mass to area ratio [kg/m^2]	1,29	1,94	3,86	7,39	14,60	29,02	40,96
800 km	*160,6*	*148,2*	*179,9*	*193,3*	*199,2*	*199,7*	*177,10*
750 km	*104*	*93*	*118,9*	*149,1*	*173,8*	*189,8*	*121,90*
700 km	*58,6*	*49,7*	*64,2*	*90,5*	*108,4*	*134,8*	*65,7*
650 km	*30,2*	*26,4*	*35,3*	*48,2*	*60,1*	*73,5*	*35,7*
600 km	**14,7**	**13,4**	**17,7**	**23,2**	*30,1*	*35,6*	**17,6**
500 km	**3,7**	**3,6**	**4,1**	**4,7**	**5,6**	**7,1**	**4,1**

Don’t require sail to deorbit in < 25 years

PW-Sat2 sail

	2U	3U	6U	12U	24U	48U	SSTL-100
Mass to area ratio [kg/m^2]	97.61	85.85	116.8	152.6	192.0	238.3	120.0
800 km	**3,10**	**3,70**	**6,00**	**12,40**	*26,30*	*49,60*	*70,70*
750 km	**2,70**	**3,00**	**4,10**	**6,60**	**14,90**	*31,10*	*43,30*
700 km	**2,30**	**2,50**	**3,10**	**4,00**	**6,90**	**16,70**	**22,40**
650 km	**1,90**	**2,20**	**2,60**	**3,20**	**4,20**	**7,40**	**12,20**
600 km	1,40	1,70	2,20	2,60	**3,10**	**4,30**	5,30
500 km	0,20	0,30	0,70	1,30	2,00	2,40	2,70

PW-Sat2 sail enables deorbiting in < 25 years

Spacecraft with thrusters – comparison with sail

- Spacecraft heavier than 20 kg are usually equipped with thrusters
  - Delayed deorbit
- Which is better for deorbit - adding more propellant or deorbit sail?
  - For mass minimization
- Platform-orbit pairs close to 25 years lifetime from previous analysis
  - Best fit of sail size to platform/orbit combination
- 2 edge cases of ISP values commonly used for small satellites
  - 320 s
  - 200 s

Propellant mass [kg] required to perform delayed deorbit for chosen platform/orbit pair

	6U	12U	24U	48U	SSTL-100	
I_{SP} [s]	800 km SSO	800 km SSO	750 km SSO	700 km SSO	700 km SSO	
320	0,2	0,41	0,68	1,16	1,42	[kg]
200	0,32	0,65	1,10	1,86	2,10	

Mass of the whole sail subsystem– 0,6 [kg]

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[kg]

Mass of the whole sail subsystem – 0,6 [kg]

Even if a sattelite is equipped with thrusters, it may save mass to add drag sail for End Of Life purposes

Other systems engineering considerations

- Other system engineering aspects:
  - Volume
  - Required power/energy
  - Thermal aspects
  - Space environment – energetic particles
  - Long-term pre-launch storage
  - Attitude control syststem requirments
  - Communication
  - Operational aspects
  - Reliability
  - Cost (finance)

- For other aspects than mass and deorbit effectiveness it is impossible to give general comparisons. These aspects are too mission specific.

- Some important, general points of view will be presented to guide system engineers through possible considerations for drag sails when end-of-life strategy is designed.

Other SE considerations - volume

- Depending on the number of factors it may be beneficial (from volume perspective) to fit deorbit sail on a satellite with thrusters
- Sail may be smaller than additional tank (if needed for deorbit propellant)

Theoretical density [kg/m^3] of the propellant required for delayed de-orbit to achieve the PW-Sat2 sail system volume

	6U	12U	24U	48U	SSTL-100
I_{SP} [s]	800 km SSO	800 km SSO	750 km SSO	700 km SSO	700 km SSO
320	652.3	1337.2	2217.9	3783.4	4631.4
200	1043.7	2120.0	3587.7	6066.5	6849.3

Mass of the whole sail subsystem– 600 g,
Volume of sail subsystem – 0.306 l

Example propellant densities:
- Kerosene 810 kg/m^3
- Hydrazine 1021 kg/m^3

Other SE considerations - power/energy

- It is however, advisable for the spacecraft to perform detumbling before deploying the sail which may cost additional energy.
- Depending on mission design, if satellite is to be operational after sail deployment (as PW-Sat2 proved to be possible) sail **will influence satellite power budget** as it will may cast shadow on the solar arrays.
- For PW-Sat2 average power gathered from solar arrays decreased, however **it was still possible to operate the satellite** in more energy-conservative mode

- PW-Sat2 sail deployment system uses approx. **2 W of power for 60 s** (for thermal knife) to deploy the system. Rest of the energy required is already stored in sail springs. **This is the total energy consumption** of the system during the **whole mission**.

Other sys eng considerations – thermal aspects

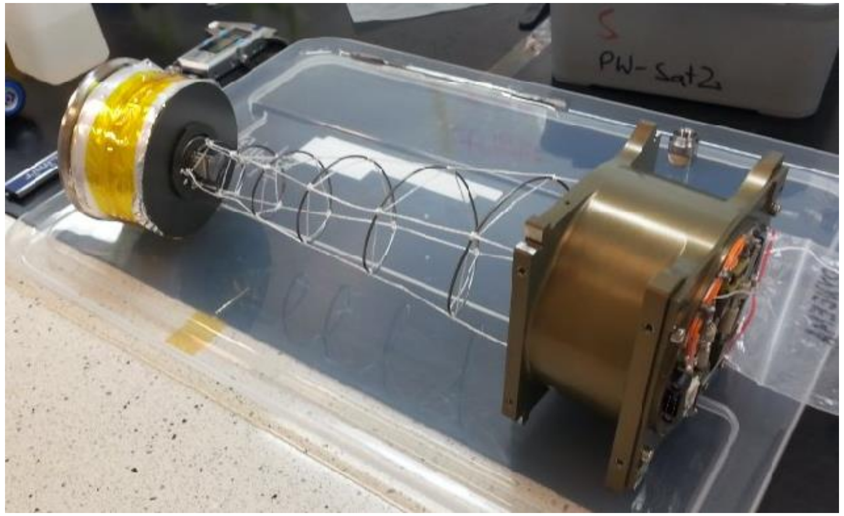
- PW- Sat2 sail deployment system requires 2W of power for maximum of 60 s. There is **no other heat generation** involved in the system operation
- Deorbit sail may act as a **large radiator**, either collecting a lot of heat from the Sun or radiating it away into deep space. In PW-Sat2 case **it was solved** by good thermal insulation between the sail and satellite bus.

- Deployed sail will impact thermal budget of the satellite by **keeping the bus in its shadow**
- Thermal aspects are **necessary to be taken into account** only if the satellite is planned to be operated after sail deployment.
- PW-Sat2 didn't have any thermal problems after sail deploying and it was equipped with only a **rudimentary thermal control** system consisting of battery heaters.

Other SE considerations – space environment

- In case of PW-Sat2 mission there was no sign of sails influence on the satellite's space environment resilience.
- Drag sail is made of an aluminized Mylar foil deployed on 4 flat steel springs (arms). It was not electrically isolated from the container to avoid **potentially collect electric charge**.

- Potential charge accumulation either didn't happen or had no impact on PW-Sat2 mission. However, this aspect should be thoroughly analysed for missions with sensitive electronic instruments if they plan to use these instruments after sail deployment.



Other sys eng considerations – long term storage

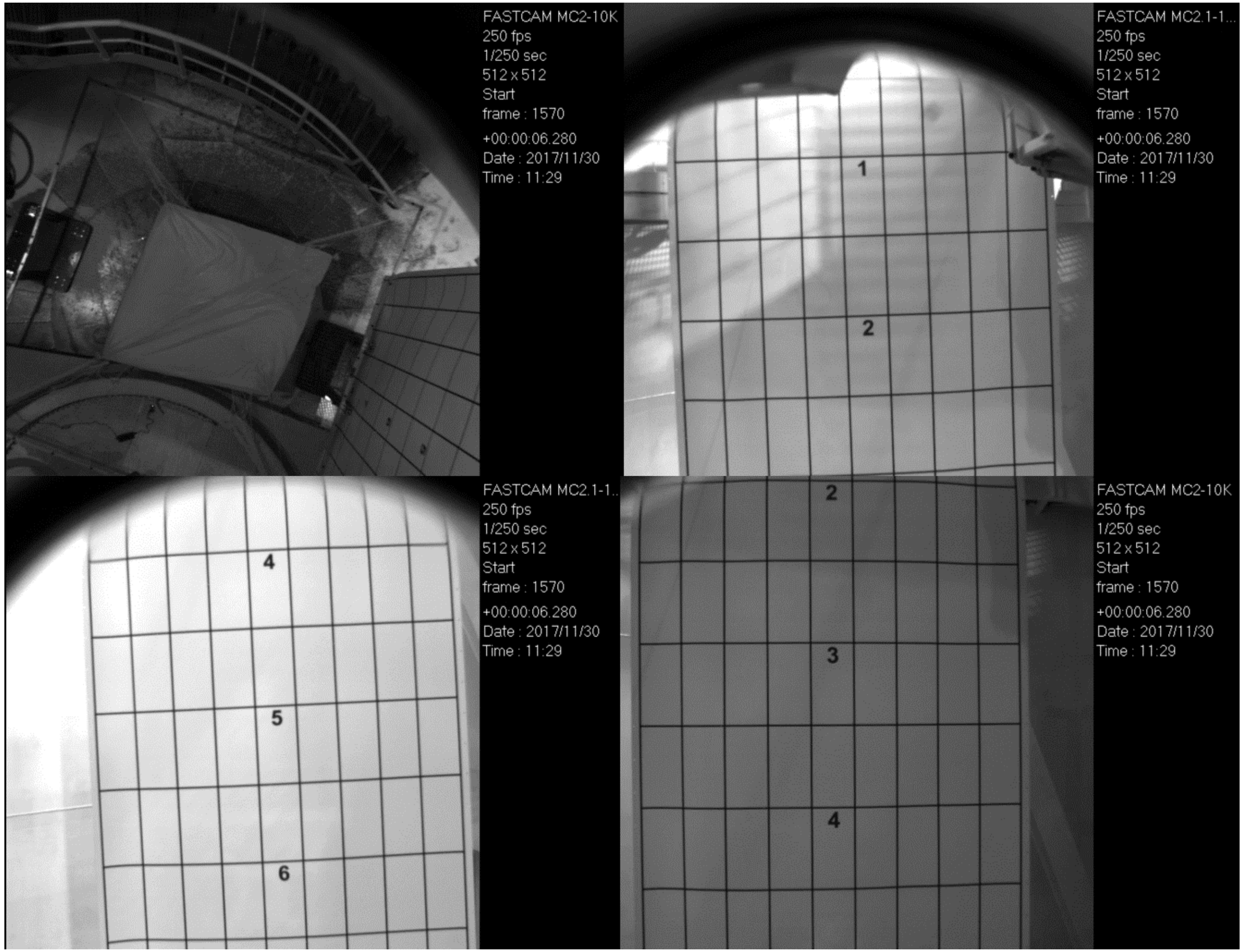
- PW-Sat2 sail did not have any elements storing the electrical energy, pressurized tanks or materials that degrade under sunlight or in presence of Earth's atmosphere .
- Sail deployment **doesn't require electrical motors** which are susceptible for malfunction after long term storage pre-launch or on orbit.
- Although, such effects **were not observed** for PW-Sat2, there were no studies of the impact of long term storage on the sail system.

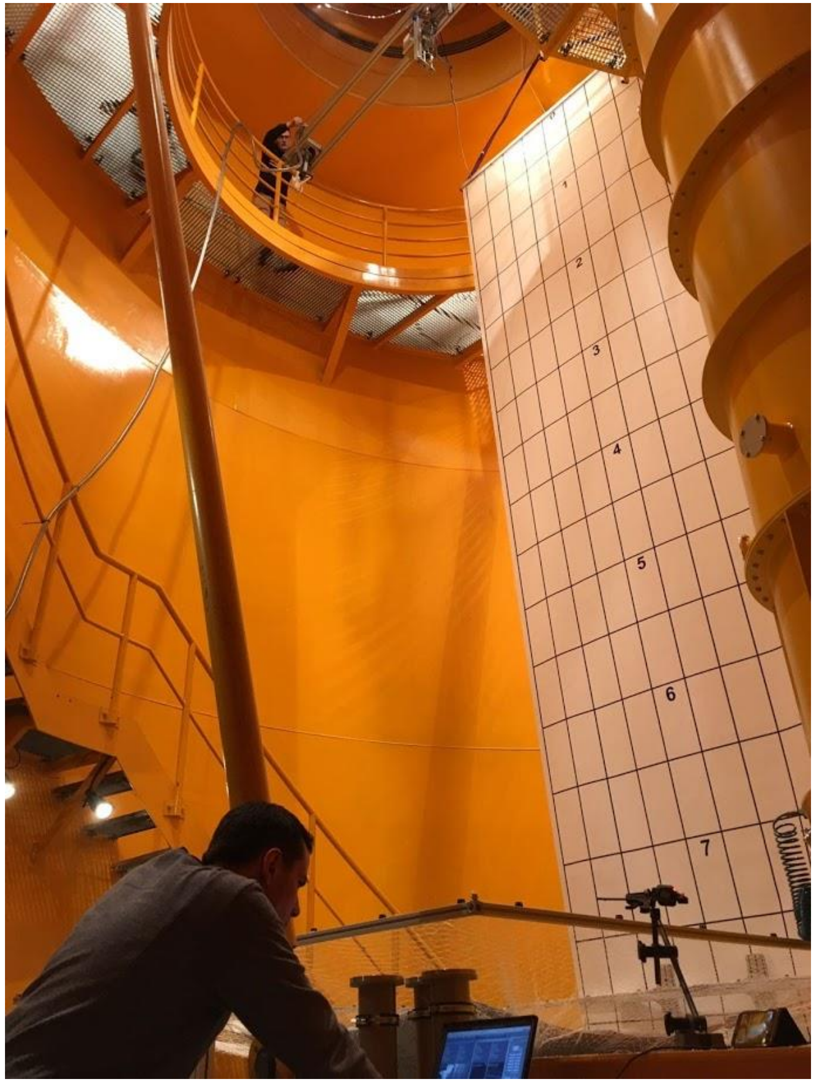
- Possible problems to be analysed:
  - Springs required for sail deployment may undergo relaxation under constant load
  - The lubricant used for sail surface connection with the arms may migrate with time during prolonged storage
  - It is also unknown how the sail surface would behave after long term storage in folded state
  - Dyneema wire creep

Other sys eng considerations – attitude control

- In general flat drag sails (as in PW-Sat2 case) **do not acquire stable attitude naturally**.
- As was shown during a test campaign in a Drop Tower (ger. Fallturm) in Bremen, sail deployment is a dynamic process taking approx. 0.6 s. Because of that satellite might start tumbling and require detumbling again after sail deployment if stable attitude is required post-deployment. To minimize this effect there is a bearing on connection between sail surface and container.
- PW-Sat2 **didn't have any means of detumbling after sail deployment** and it was tumbling slowly enough to maintain stable communication after sail deployment
- Sail deployment may influence the center of mass and satellite moments of inertia which may make the detumbling impossible for a given AOCS system that was not designed accordingly

Other sys eng considerations – drop tower test





Other SE considerations – communications

- Drag sail may influence satellite communication with ground in two ways:
  - **During deployment**, sail (it is attached via conical spring to the satellite bus, this connection is not stiff) **may collide with deployed antennas** potentially damaging them. For that reason, it is advisable to perform the detumbling before sail deployment
  - Sail may cause the **omnidirectional antennas to become slightly directional**.

In case of PW-Sat2 pre-launch analyses showed that 6 μm of sail surface should not impact communication. In reality the satellite maintained the **stable communication with the ground after sail deployment till the end of the mission (2y)**. It was, however, noticable for the operators that there was a slight change in antenna characteristics.

Other SE considerations – operations

- For operators a deorbit sail is a very **simple device**, it doesn't require electrical motors, pyrotechnical devices or any pressurized elements. After the telecommand for deployment the resistors 'cut' the wire holding the sail inside the container and the springs allow the structure to unfold.

- As mentioned previously, it is advisable to **perform detumbling before deploying the sail** and also to take into account **possible changes in power, thermal and communication budgets due to sail deployment.** These aspects may influence the way the sail will be used **from operator's perspective**

Other SE considerations – reliability

- PW-Sat2 sail deployment system doesn't require any of
  - Electric motors
  - Pressurized elements
  - Pyrotechnics
- After thermal knife cuts the dyneema wire the deployment happens thanks to energy stored in springs.

- Sail deployment system was **equipped with a „clock"** which counted time from the last communication with the ground. In case of **loss of communication** (or no communication after launch) sail would deploy automatically **after 30 days**, so a failed mission may still deorbit in line with its requirements. This time could be **functional without OBC** and using the power from solar arrays directly (bypassing batteries in case of their failure).

Other SE considerations – finance

- PW-Sat2 sail deployment system was low cost in production
- The quoted costs do not include R&D, prototyping, wages, test campaign or facilities required to assemble the system and integrate it into the satellite (cleanroom etc.).
- Indicated prices are from 2019

Element	Estimated cost [€](2019)	Description
Mylar foil	200	Mylar foil double aluminized, thickness 6 µm and 25 µm
Flat springs	50	Sail structure arms
Sail pin	100	(cost includes material, manufacturing and coating)
Conical spring	100	
Sail container	1000	Container and cover (cost includes material, manufacturing and coating)
Sail release mechanism	1000	(cost includes material, manufacturing and coating)
Other mechanical parts (e.g., bolts i small springs)	100	
	2550 €	

Conclusions

- **Deorbit sails effectiveness** should be assessed based on the total **collision probability** reduction instead of orbit lifetime reduction
- Sails fitted for short orbit lifetime (up to few years) require careful **collision risk assessment** and optimization of the sail deployment time with respect to solar cycle phase
- Deorbit sail may be an attractive solution even for spacecraft **with on-board propulsion**
- Deorbit sail has number of advantages as a passive deorbit subsystem

Thank you for your attention!

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Maciej Rębisz, PW-Sat2 spalający się w atmosferze Ziemi - wizja artystyczna

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