# TESTING AND EVALUATION OF TRANSPARENT DRAG SAIL MEMBRANE MATERIALS FOR DARK SKIES

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# Why Transparent Sail Membranes?

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- ADEO drag sail family (HPS GmbH): passive end-of-life de-orbiting of LEO satellites
- Growing satellite population: de-orbiting is mandatory, but large reflective sails add to sky brightness
- “Dark and Quiet Skies”: protect ground-based astronomy from artificial sky brightening
- Previously used aluminized polyimide: reflectance > 90% – almost a perfect mirror
- **Transparent candidates: total hemispherical reflectance only ~20% (ProFilm MPI) / ~22% (FEP)**
- AFO – ADEO Family Development and Qualification (ESA Contract 4000138835/22/NL/GLC/va)
  - Prime: HPS GmbH, Munich – material testing: DLR Institute of Space Systems, Bremen

First transparent sail segment breadboard (ITO-coated FEP)

# Reference Missions & LEO Environment

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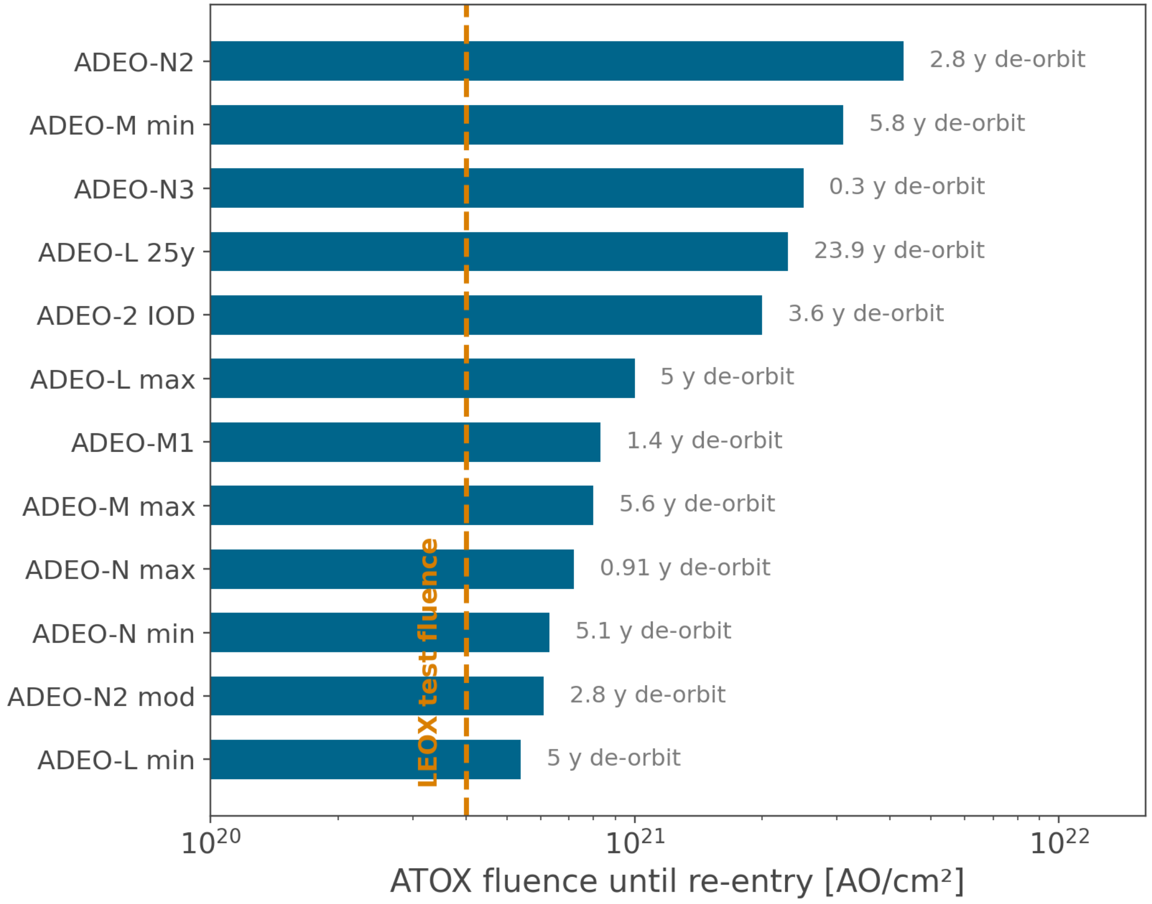
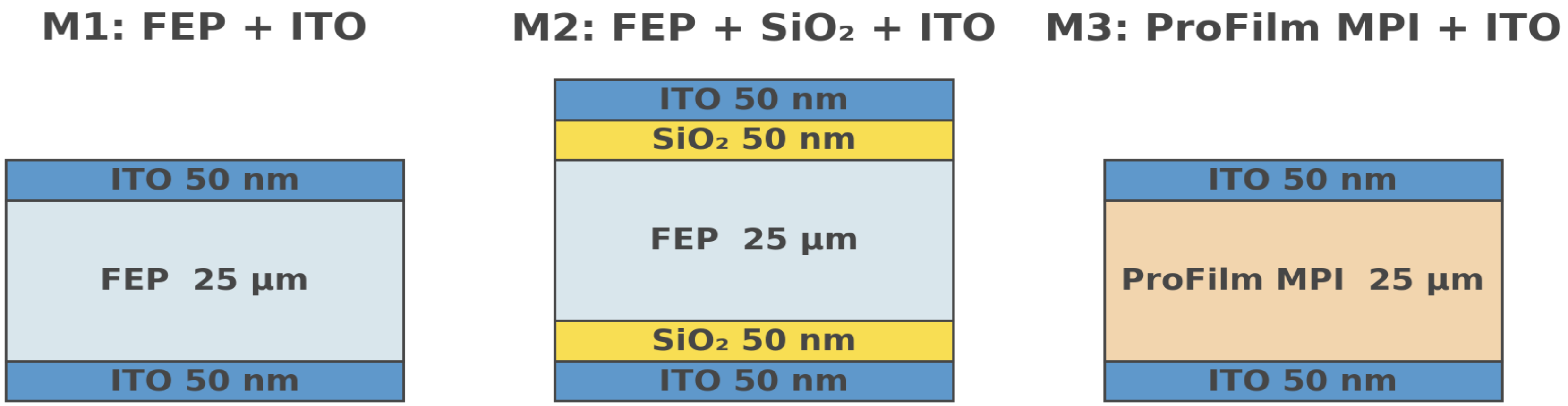



ATOX fluence of the 12 reference de-orbit scenarios. Data: AFO-HPS-DD-0002 (redrawn)

- Survey of 4200 implemented LEO missions: clusters at 50–55° inclined orbits, polar orbits and SSO
- 12 reference de-orbit scenarios for ADEO-N/-M/-L, incl. solar min/max and a 25-year case
- **ATOX fluence until re-entry: ~$5\times10^{20}$ .. $4\times10^{21}$ AO/cm²**
- ~15 orbits per day → ~30,000 thermal cycles for a 5-year de-orbit
- Sail temperature estimate (transparent material): about −89 °C (cold case) to −12 °C (hot case)
- **Derived test loads: humidity, thermal cycling, UV/VUV, atomic oxygen**

# Material Candidates & Coating Design



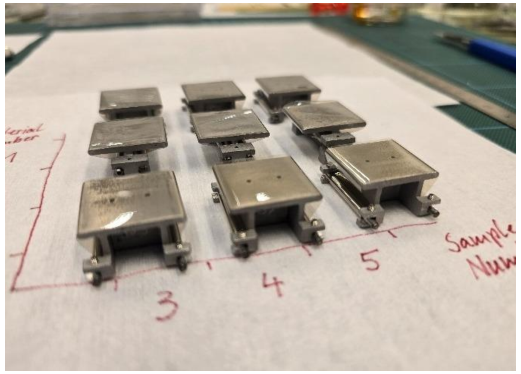

- ITO coating: prevents electrostatic charging during stowing and handling; 50 nm sized to survive AO erosion until re-entry (worst-case scenarios)
- **ProFilm MPI: European space-grade polyimide films developed in the ESA ProFilm project (4000145511/24/NL/KK/mdu) – future commercialization via a joint venture of HPS and AAC**

# Test Campaign Overview

**Accumulative exposure sequence, one sample extracted after each stage (3 materials x 5 samples + 3 reference)**

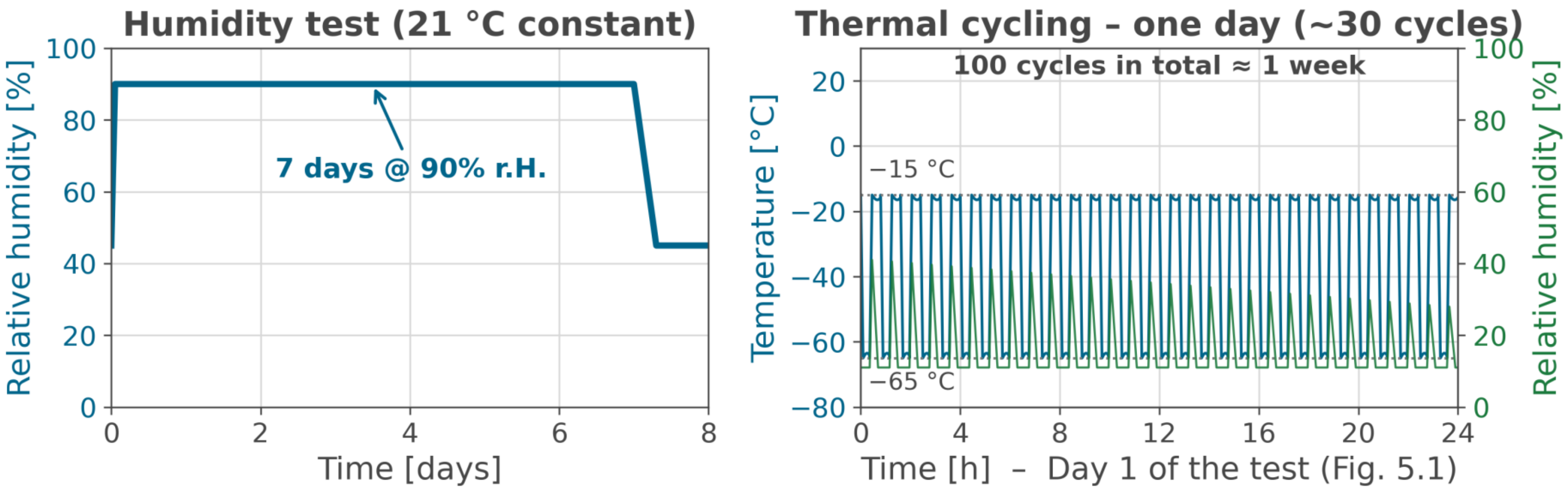
| Humidity | Thermal cycling | UV / VUV | ATOX |
|---|---|---|---|
| 7 d, 90% r.H., 21 °C | 100× −65 / −15 °C | 80 h, CIF (DLR) | $4\times10^{20}$ AO/$cm^2$ (ESA) |

Inspection point: visual | optical microscopy | thermo-optical properties
surface resistance | mass | tensile / peel samples

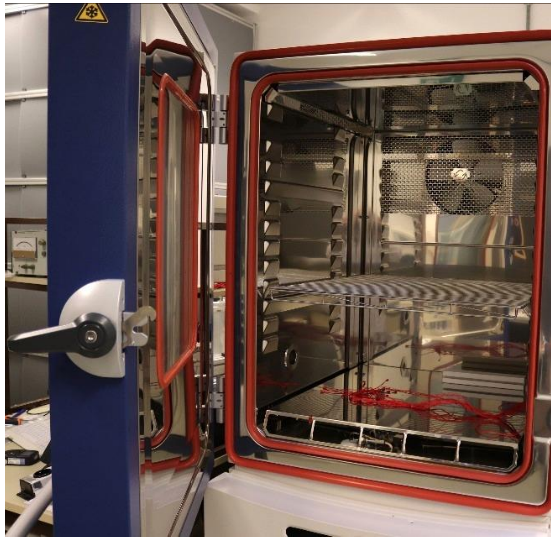

Samples on sample holder blocks

- Sample strips 25 mm × 130 mm, exposed area 21 mm × 21 mm on the CIF sample holder
- Same sample holder used through UV and ATOX tests – no remounting of the exposed area

# Humidity & Thermal Cycling Tests




Set points for humidity and thermal cycling



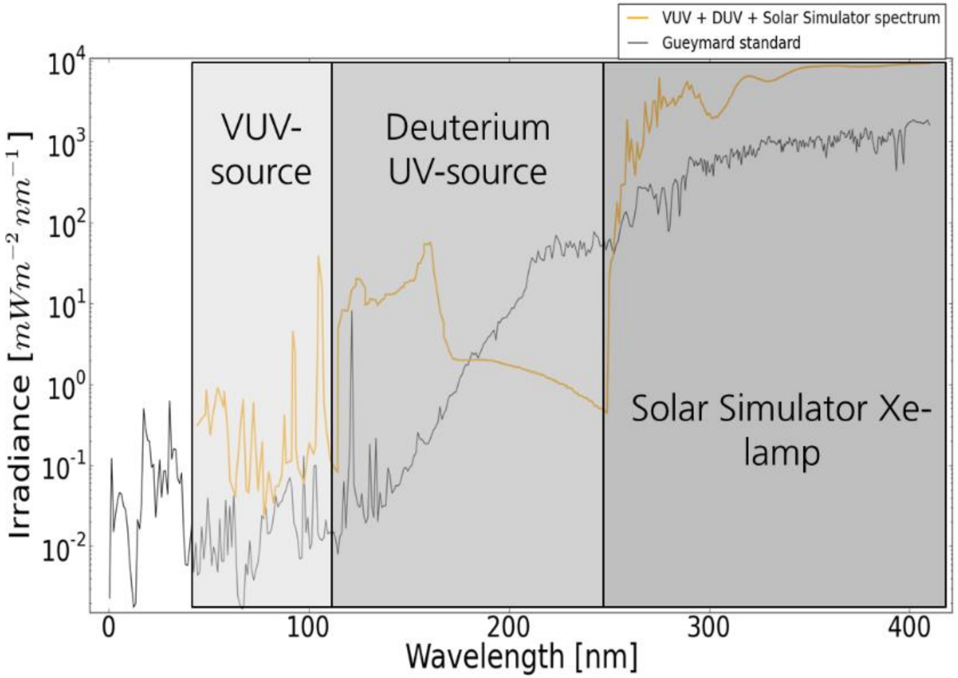
Climate chamber (Weiss WK3)

- All three material candidates tested together; additional (unplanned) thermal vacuum cycles during the UV test campaign
- **Visual inspection after both tests: no visible changes of the materials**

# UV Testing – Complex Irradiation Facility (CIF)

- Ultra-high vacuum facility at DLR Bremen with electromagnetic and particle radiation sources.
- Argon VUV source (40–410 nm), deuterium lamp (112–410 nm), Xe solar simulator (250–2150 nm)
- Acceleration factors: 26.3 (40–120 nm), 16 (116–200 nm), 2 (200–400 nm)
- **80 h irradiation over 11 test days ≈ half a year in orbit for the high-energy VUV range**
- $LN_2$-cooled sample station, sample temperature limited to < 50 °C

The Complex Irradiation Facility (CIF)




Spectral irradiance of the CIF sources vs. solar spectrum

# ATOX Testing – ESTEC LEOX Facility

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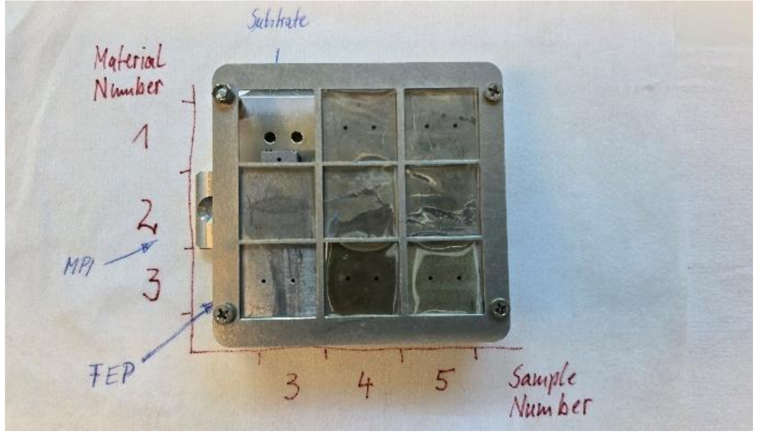
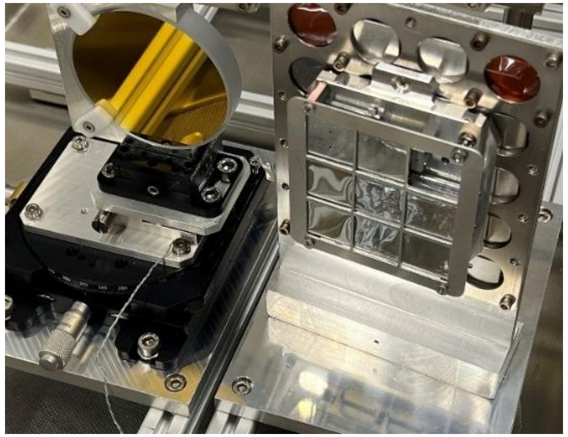
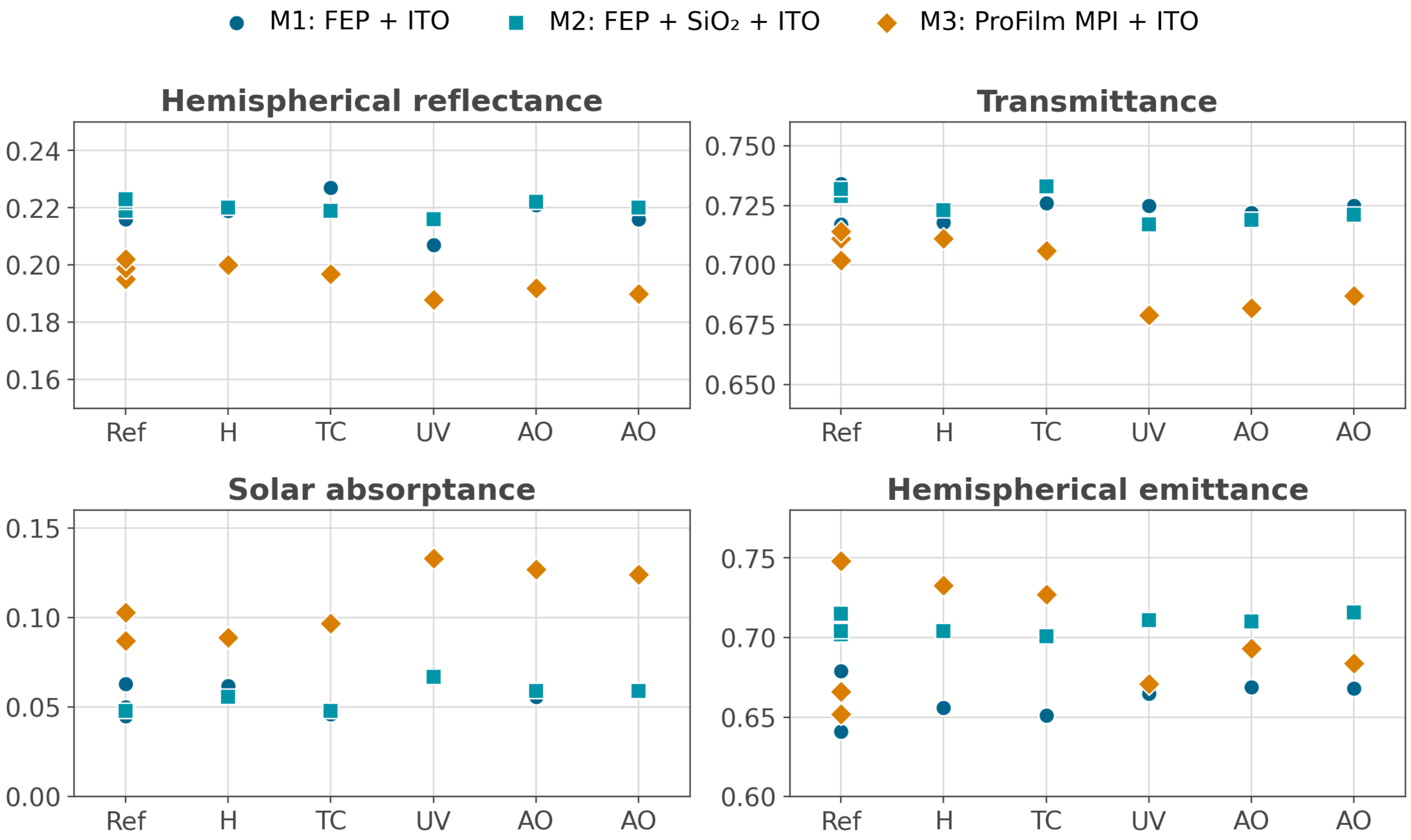
- Executed at ESA/ESTEC in the LEOX facility (test ET0007160)
- AFO sample holder mounted directly onto the LEOX sample station
- **Target fluence: $4\times10^{20}$ AO/cm² – fluence is smaller than the ones of the reference scenarios (test time, budget), it is sufficient to evaluate erosion yields.**
- Mass measurement at DLR before and after exposure (samples conditioned at 22 °C / 55% r.H.)
- Erosion yield derived from mass loss, exposed area, density and position-resolved fluence



Samples mounted for the CIF sample holder for ATOX test in the LEOX facility


Sample holder in the LEOX facility

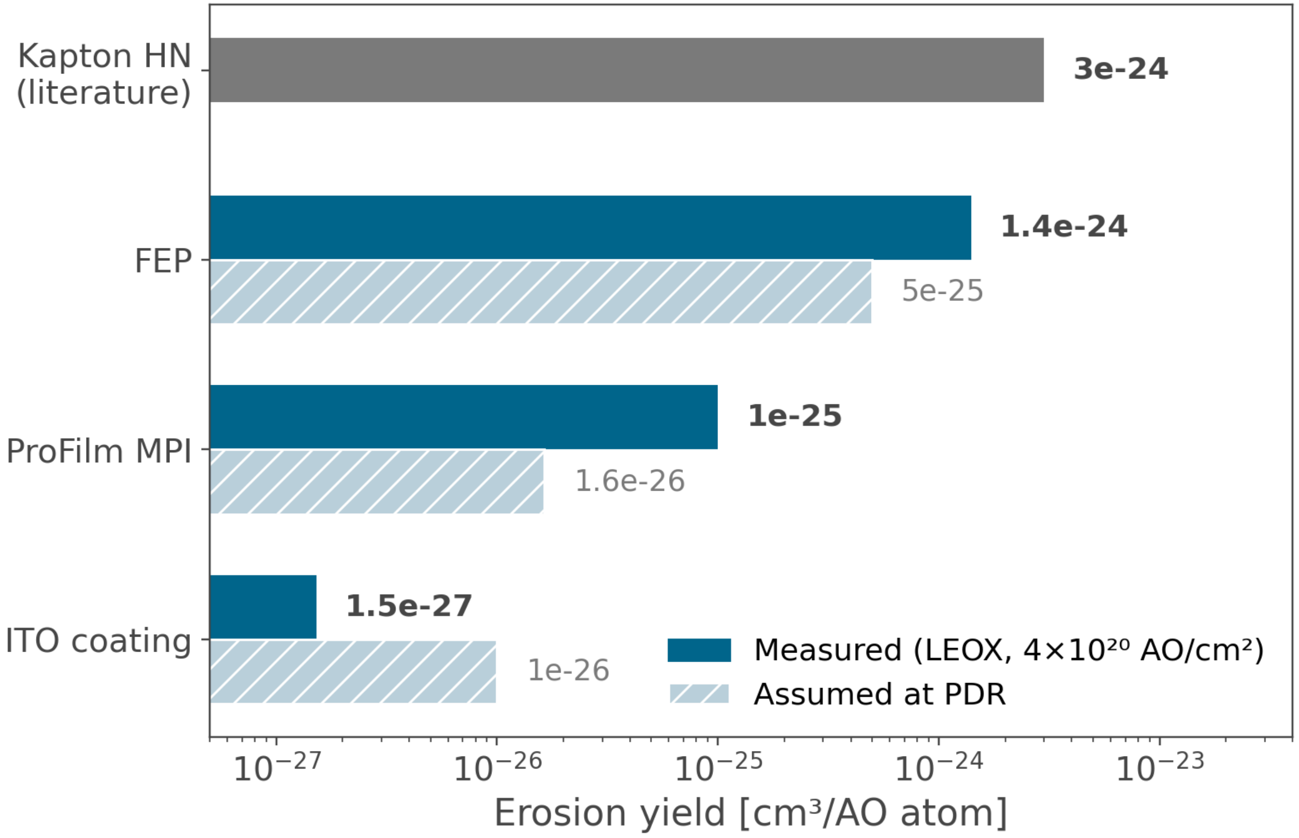
# Results: Thermo-Optical Properties




Ref = pristine | H = humidity | TC = thermal cycling | UV = 80 h UV/VUV | AO = atomic oxygen (cumulative sequence)

- **FEP materials essentially stable over the full campaign**
- ProFilm MPI: slight decrease in transmittance/reflectance, increase in absorptance after UV
- Known polyimide UV darkening – a surface effect, non-linear, slowing down over time
- Changes small compared to measurement error (±0.03…0.06)
- Lower reflectance is even beneficial for dark skies

# Results: ATOX Erosion

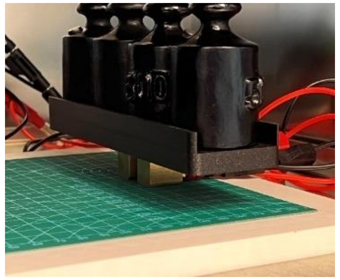



Erosion yields, measured vs. assumed. For ITO it is an average erosion yield across the coated FEP samples.

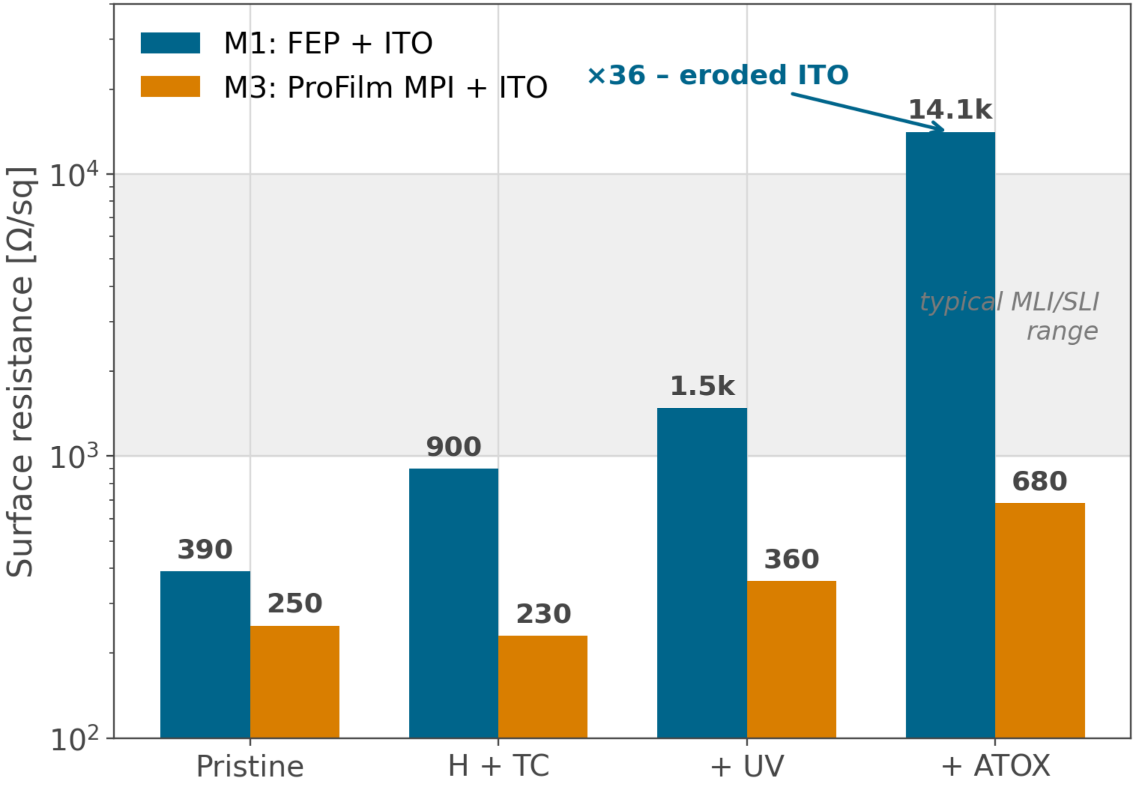
- **FEP erodes ~2× slower than Kapton; ProFilm MPI ~30× slower**
- 25 µm FEP suitable for several mission scenarios without risk of eroded holes
- **Very low ProFilm MPI erosion → much thinner sails possible**
- ITO erosion lower than assumed – 50 nm coating survives almost until re-entry
- Coated MPI showed a small mass increase – likely increased water absorption after UV exposure (hydrophilic surface groups)
- The very low ITO erosion yield is difficult to measure, and other effects can be overlain. We sometimes measured a slightly negative erosion yield (meaning a mass increase). We believe that was due to change in the water absorption capacity of the MPI.

# Results: Surface Resistance

- ITO coating: ESD protection during stowing, handling and deployment
- Pristine samples: 231–394 Ω/sq
- FEP: increase after thermal cycling and UV (CTE ~$10^{-4}$/K → micro-cracks in coating), ~14 kΩ/sq after ATOX
- **ProFilm MPI: stable through thermal cycling and UV, only ~2× increase after ATOX**
- Material 2 ($SiO_2$+ITO): inconclusive – coating process issue suspected
- **Conductivity sufficient for the drag sail application over the mission time**

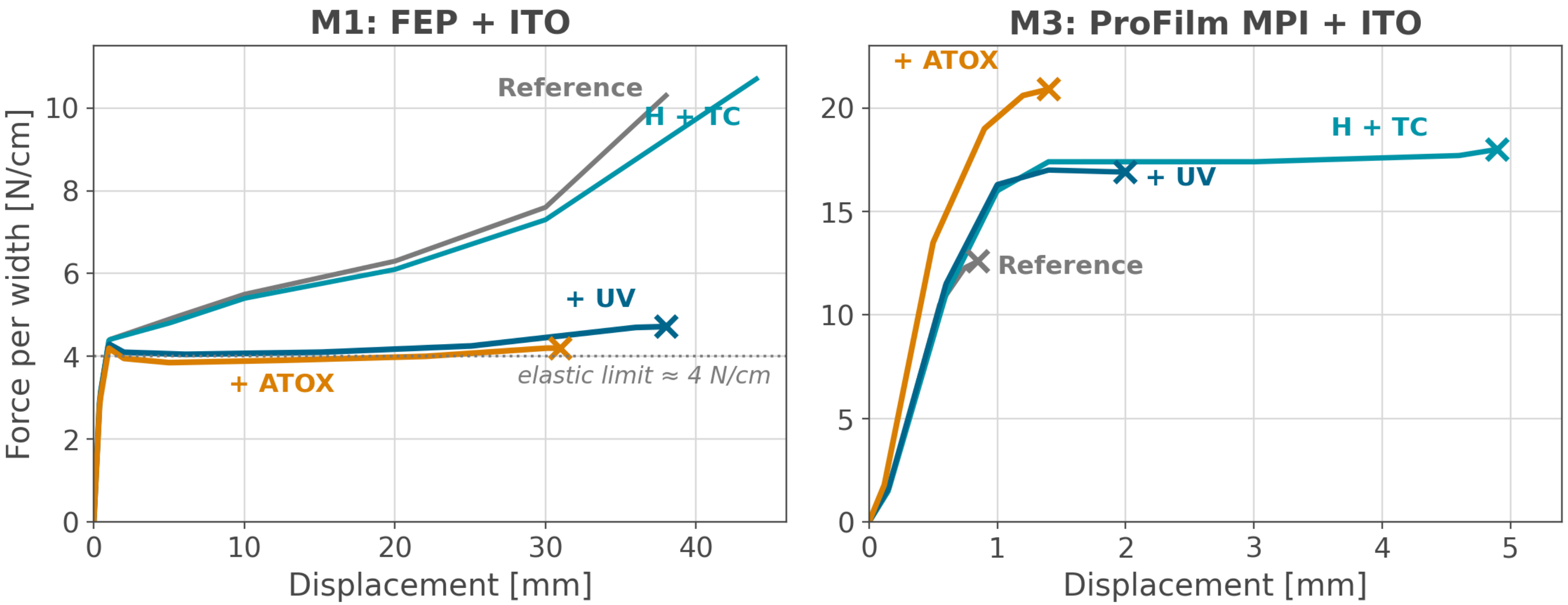


Electrode setup, 2 kg contact weight, measured in vacuum




Sheet resistance after each test stage.

# Results: Mechanical Properties




Tensile strength curves for M1 and M3 after different tests. X=break; samples 12 mm x 10.5mm (original sample was cut in half and only the exposed area was used).

- FEP: elastic limit ≈ 4 N/cm, very robust against crack propagation; UV/ATOX reduce the plastic reserve (embrittlement), elastic regime maintained
- ProFilm MPI: stiffer, tensile strength ≈ 18 N/cm; ATOX exposure even increases modulus and maximum force; thermal cycling extends elongation
- **Allowable design loads of both 25 µm candidates comparable to the previously used 7.62 µm polyimide (Kapton HN: 13.1 N/cm)**

# Adhesive Bonding & Reinforcements

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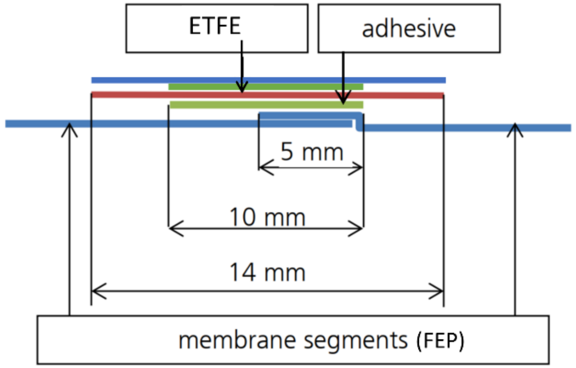
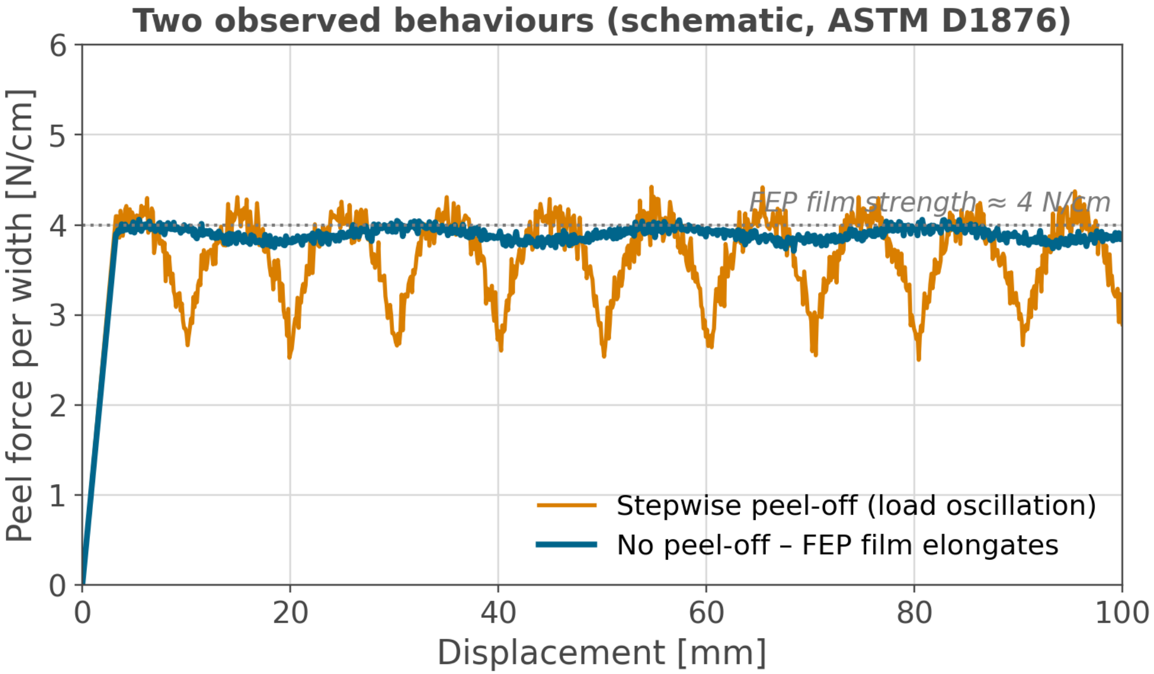



Membrane bonding with transfer adhesive and ETFE layer

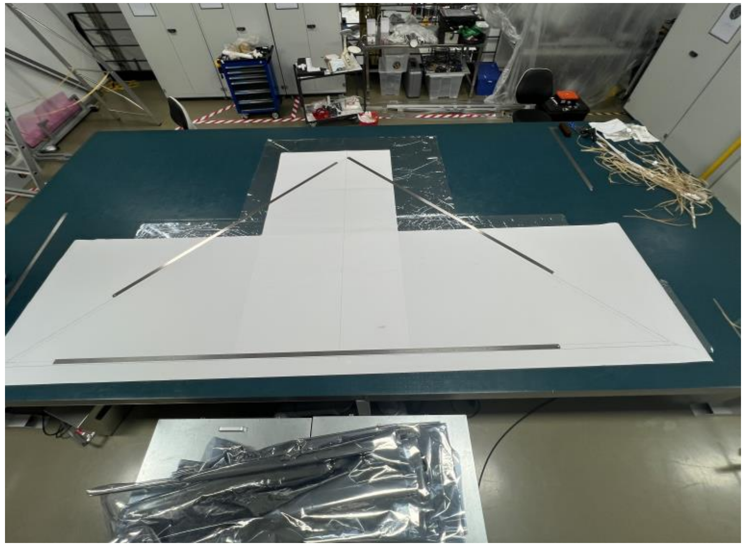
- Acrylic transfer adhesive (3M 966) + ETFE reinforcement + FEP cover layer
- For the FEP, bond strength is in the same range as the film strength (≈3.8–4 N/cm)
- Two behaviours: film elongation without peel-off vs. stepwise peel-off
- **Deployment load case is shear → higher transferable loads**



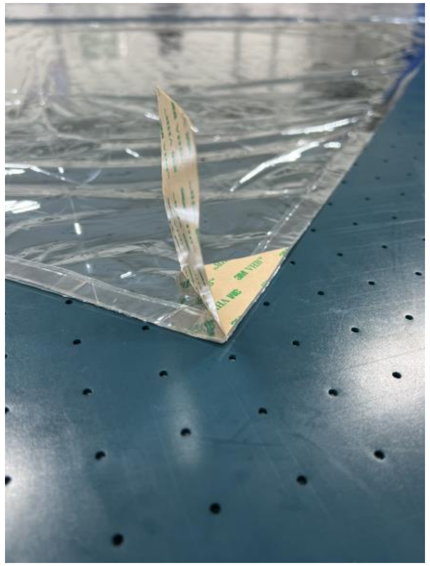

Example from FEP/ETFE peel-of

# Sail Segment Breadboard Manufacturing

- **Full sail segment manufactured from ITO-coated FEP (Material 1)**
- All manufacturing techniques established for ADEO-2 (aluminized Kapton) work unchanged
- Reinforced edges and crack stoppers: ETFE layer + FEP cover
- Three interface types implemented: sail–spool (ADEO-2 style), bonded cord, reinforced strip with washers
- No electrostatic charging of the membrane during handling



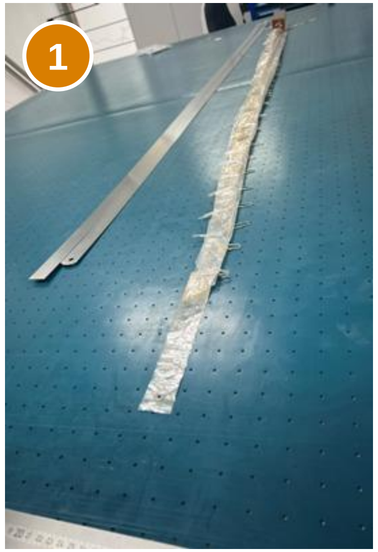
Cutting the segment geometry [AFO-DLR-TR-0001]



Washer interface [AFO-DLR-TR-0001]

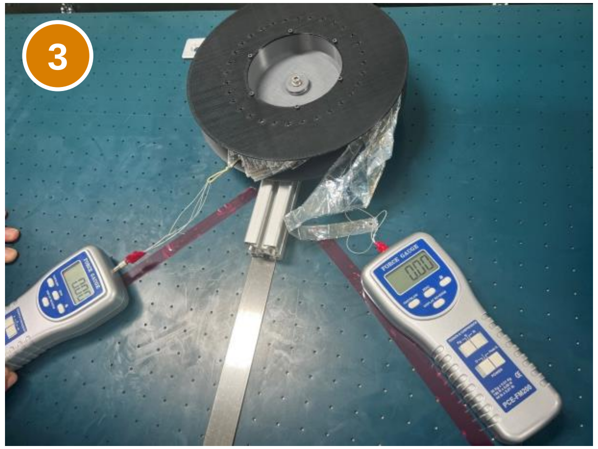
# Stowing & Deployment of the Breadboard

- Stowing per HPS pattern for the ADEO-M spool: 33 mm folding width → 123 folds, stack of ~493 layers for four segments)
- Manual folding successful; segment coiled onto Ø35 cm spool despite slightly exceeding spool width
- **Deployment loads only ≈ 1 N; final tensioning with 5 N caused no damage**

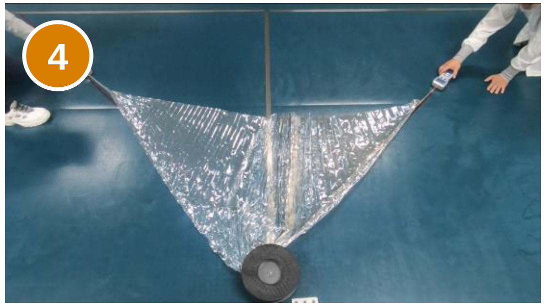



Folded strip (33 mm)


Coiling onto Ø35 cm spool




Deployment forces ≈ 1 N




Deployed segment

# Trade-Off & Conclusions

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| Criterion | Weight | Former polyimide | FEP + ITO | FEP + $SiO_2$ + ITO | ProFilm MPI + ITO |
|---|---|---|---|---|---|
| ATOX resistance | 3 | 1 | 2 | 2 | **4** |
| UV resistance | 3 | 3 | 2 | 2 | **4** |
| Reflectivity | 3 | 1 | 4 | 4 | **4** |
| Tensile strength | 2 | 4 | 1 | 1 | **3** |
| Outgassing | 1 | 2 | 4 | 4 | **3** |
| Manufacturing | 2 | 4 | 3 | 1 | **3** |
| **Total score** | | **39** | **50** | **34** | **60** |

Weighted trade-off (weights 1–3, scores 1–4)

- **FEP + ITO performed as expected → selected as near-term solution for the next ADEO sails**
- Breadboard demonstrated: manufacturing, stowing and deployment comparable to aluminized Kapton
- **ProFilm MPI + ITO: best overall performance – recommended for future sails once available in larger quantities (ESA ProFilm project, HPS/AAC joint venture)**
- FEP + $SiO_2$ + ITO: no added benefit, coating process issues
- **Transparent membranes support “dark and quiet skies” with ~5× lower reflectance**

# ProFilm Simid

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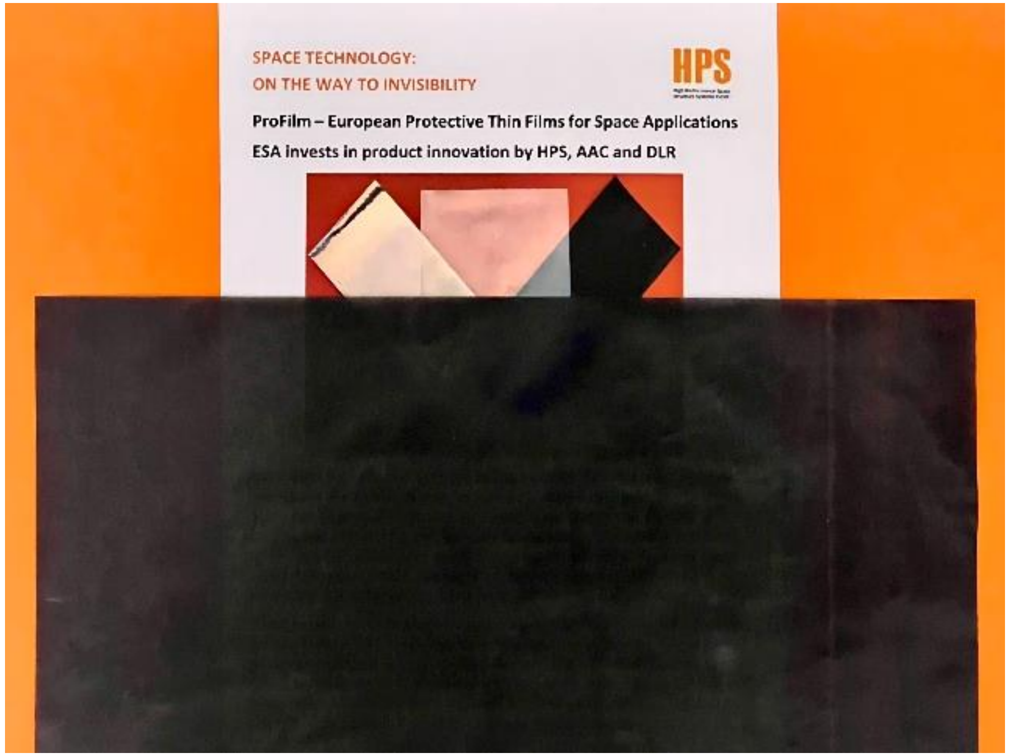
- Dark Skies
  - Reducing the reflectivity of drag sails

ADEO DEORBIT SUBSYSTEM

CleanGreen Space DEORBIT by ADEO, HPS

Transparent Sails

Black Sails

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# Imprint

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- Institute: DLR Institute of Space Systems, Bremen
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