Glass Performance Days 2025

10 – 12 JUNE 2025 | NOKIA ARENA - TAMPERE, FINLAND

GLASS PERFORMANCE DAYS 2025

# High Perfomance Windows for Applications in Space. Open problems and challanges

Balancing transparency with strength and radiation protection


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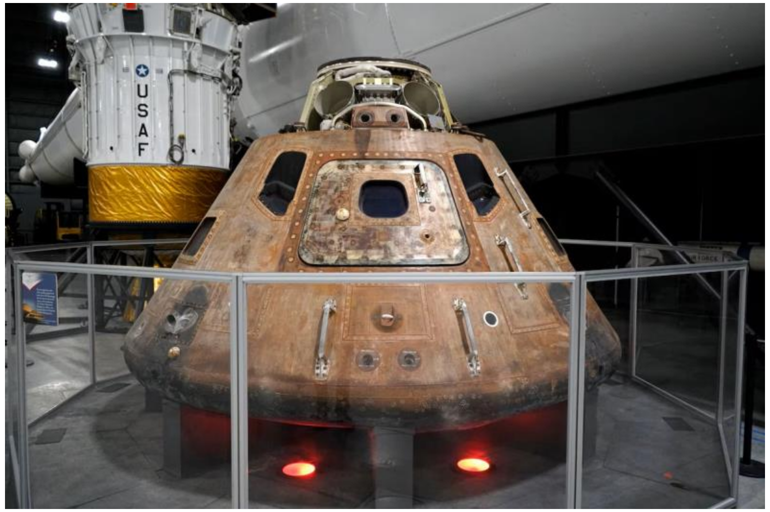
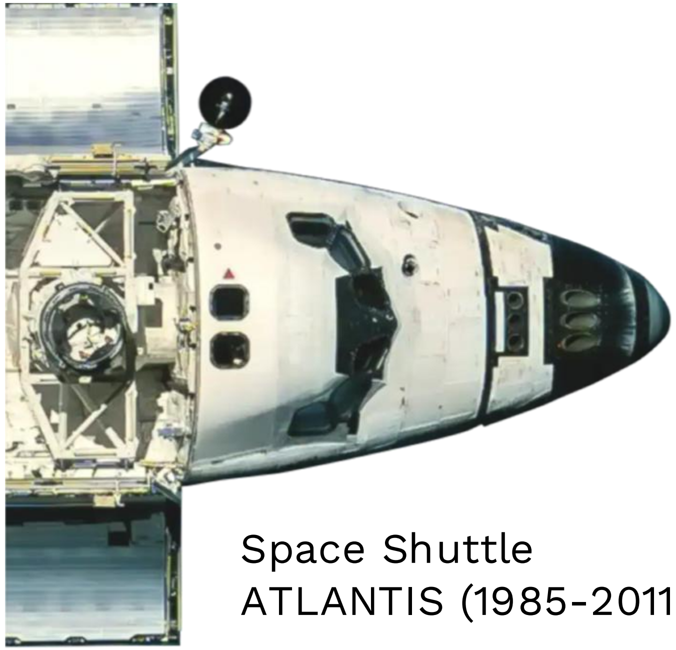
# SPACECRAFT WINDOWS

Project MERCURY (1958-1963)


GEMINI Capsule (1961-1966)




APOLLO 11 Command module (1969)



Space Shuttle
ATLANTIS (1985-2011)


DRAGON capsule(2022-)

ORION spacecraft (2022-)

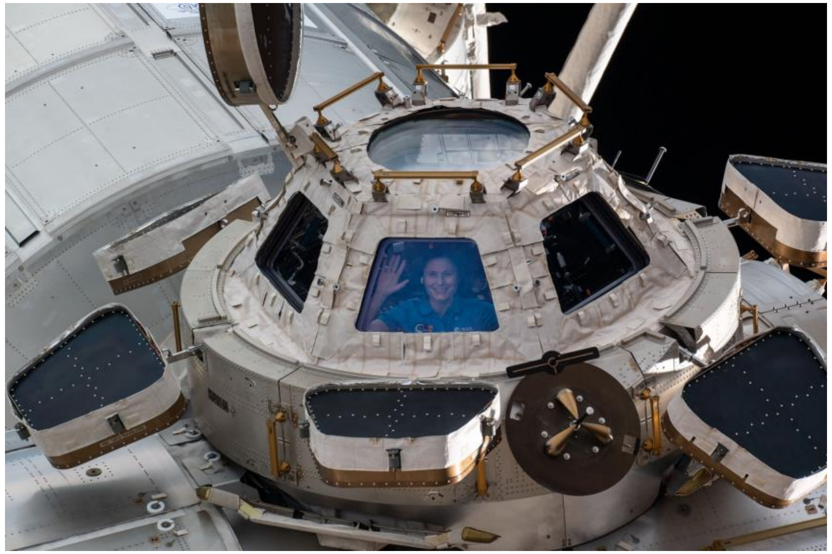
# Projects

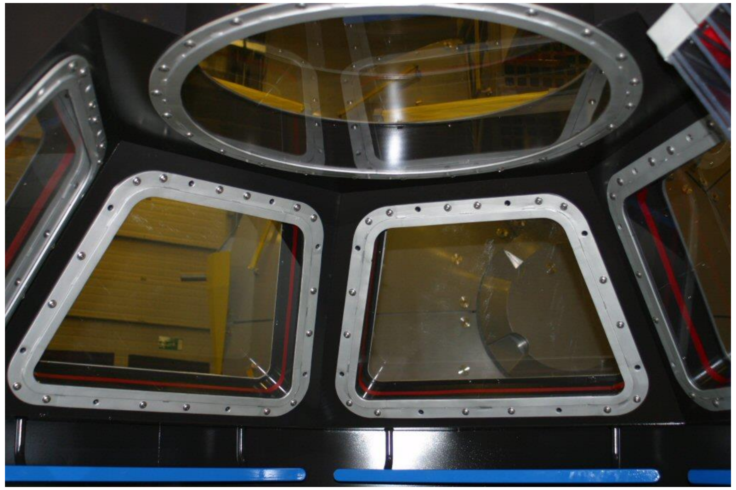
Space Dragon dome observatory
(diameter 46 in; height 18 in)

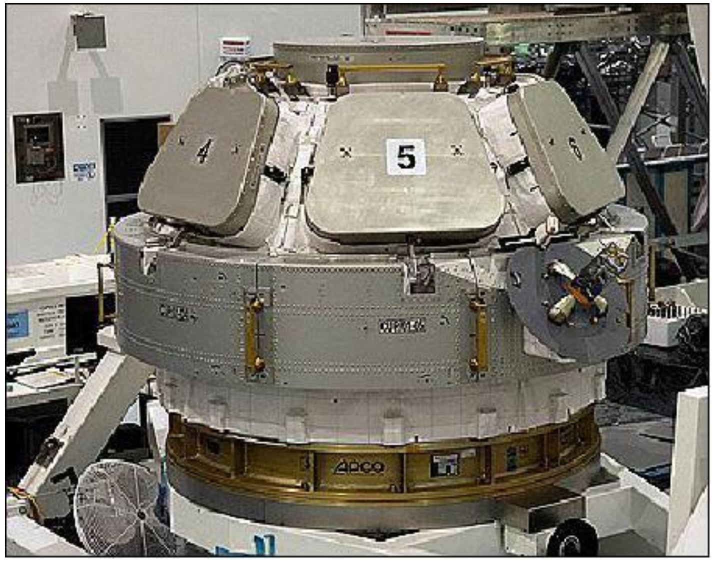
AXIOM Space observatory
(planned 2030)

Philippe Starck
&
Mike Suffredini

# State of the art: THE ISS CUPOLA (2010)

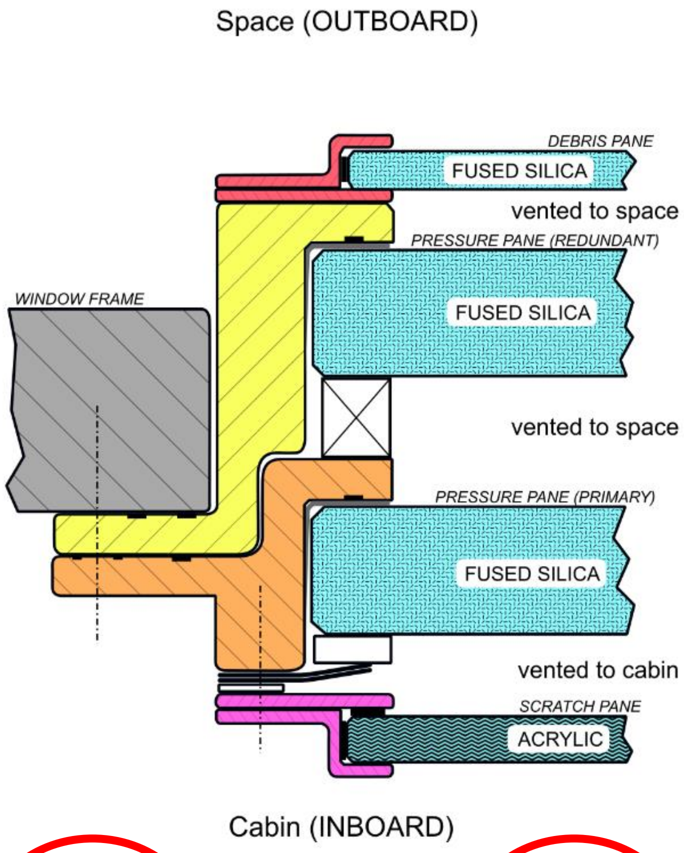


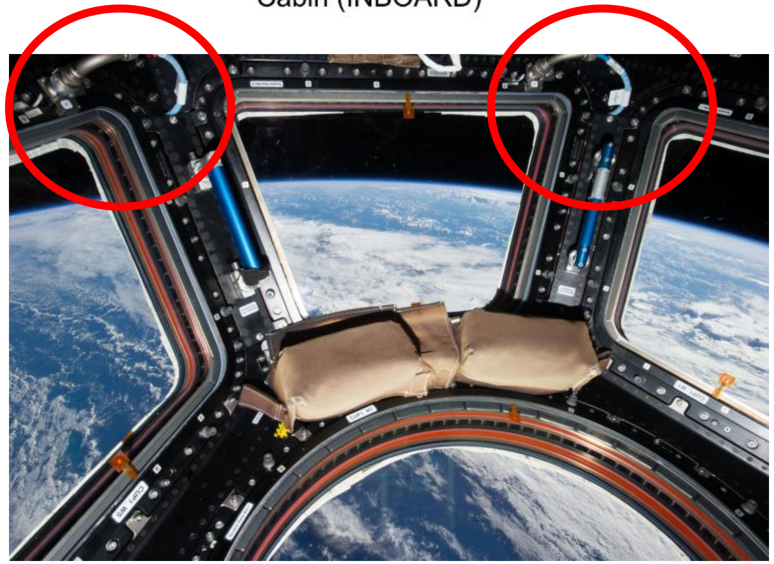





# ISS Cupola windows

- 1800 kg single **forged unit aluminum** structural frame, 2 m in diameter and 1.5 m high
- six **trapezoidal** side windows (from Space Shuttle) + one **circular** top window (80 cm diameter)
- External **shutters** for protection against debris and solar radiation + thermal insulation
- **three subsections**: 1) a debris pane (DP) on the outside to protect from space debris; 2) two pressure panes (PP) 25.4 or 36.8 mm-thick; 3) an inner scratch pane (SP) to protect from accidental damage, providing active heating against condensation
- Gap between pressure panes is ventilated to space. Only **inner pane is pressurized**. Outer pane is a back-up for inner pane
- **fused silica** glass panes (recently, scratch pane in acrylic)
- entire window, or individual scratch and debris panes, can be **replaced**, prior installation of pressure cover in EVA
- Designed for **10-year** on-orbit lifetime (installed in 2010)



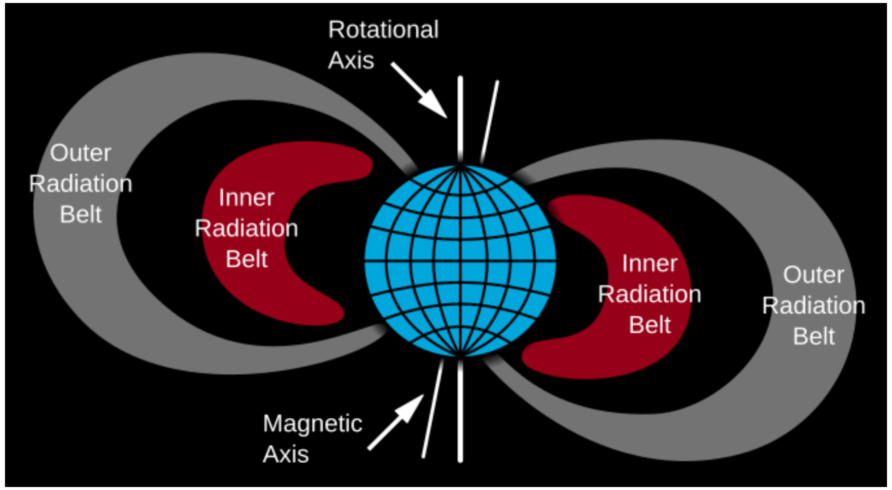
# Hazards

Objects in **Low Earth Orbit (LEO)** and beyond, face significant hazards, primarily from:

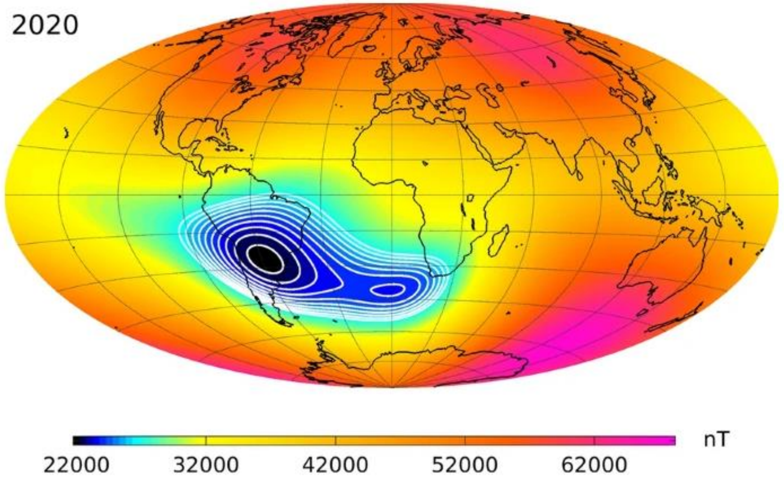
- **Material out-gassing**
- **Debris impact**
- **Electromagnetic radiation from Sun and Earth**
- **Atomic Oxygen interaction with materials**
- **Protons** (solar and trapped in **Van Allen belts**)
- **Electrons** (trapped in radiation belts)
- **Gamma rays** (secondary emissions from interactions)
- **Neutrons** (produced by cosmic rays or shielding interactions)

Transparent materials must balance mechanical toughness and strength with **optical clarity** and **radiation shielding effectiveness**, posing unique challenges

Although we will refer to ISS orbit conditions, more critical scenario would be a Sun-Synchronous Orbit (SSO) at 550 km, within LEO region, partially merged in Van Allen belts, passing through the SAA




Van Allen Belts




South Atlantic Anomaly (SAA)

# Most used materials

**Fused silica** (quartz glass)

Traditional material of choice since the Mercury mission

**Acrylic glass** (PolyMethil MethaCrylate PMMA)

*Orion capsule swaps glass windows for plastic*, by David Szondy May 05, 2015

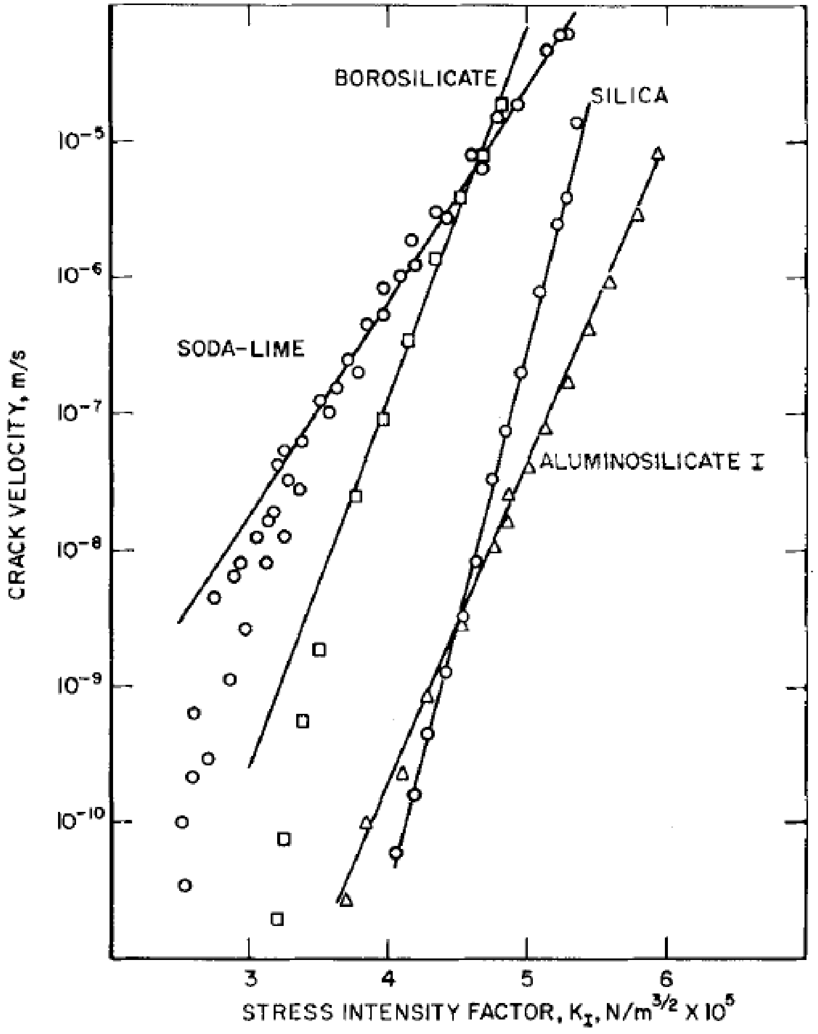
**NASA** highlights acrylic windows' engineering benefits, lighter weight (saving over 200 lb/91 kg on Orion's 2014 test flight), and lower launch costs. They're also more damage-resistant, reducing redundancy needs, and cheaper per volume.

# Materials

| | Soda lime glass | Fused silica | Borosilicate glass | Aluminum oxynitride | Chemically strength. glass | Acrylic glass PMMA |
|---|---|---|---|---|---|---|
| Relative density | 2500 kg/m$^3$ | 2170 kg/m$^3$ | 2500 kg/m$^3$ | 3800 kg/m$^3$ | 2500 kg/m$^3$ | 1190 kg/m$^3$ |
| Bending strength | 45 MPa | 60 MPa | 60 MPa | 400 MPa | 150 MPa | 60-100 MPa |
| Young's modulus | 72 GPa | 72 GPa | 60-70 GPa | 335 GPa | 72 GPa | 2.7-3.3 GPa |
| Poisson's ratio | 0.23 | 0.16 | 0.21 | 0.24 | 0.23 | 0.37 |
| Critical SIF KIc | 0.75 MPa m$^{0.5}$ | 0.66 MPa m$^{0.5}$ | 0.80 MPa m$^{0.5}$ | 2.0 MPa m$^{0.5}$ | after decompression | 0.9-1.9 MPa m$^{0.5}$ |
| Max service temperature | 400°C | 1000°C | 360°C | 600°C | 300°C | 80-90°C |
| Thermal conductivity | 0.9 W/m-K | 1.4 W/m-K | 1.2 W/m-K | 12.3 W/m-K | 0.9 W/m-K | 0.19 W/m-K |
| Coeff. Thermal expansion | 9.5 $10^{-6}$ $K^{-1}$ | 0.5 $10^{-6}$ $K^{-1}$ | 3.3-6.0 $10^{-6}$ $K^{-1}$ | 4.7 $10^{-6}$ $K^{-1}$ | 9.5 $10^{-6}$ $K^{-1}$ | 75 $10^{-6}$ $K^{-1}$ |

# Fused silica + Aluminum

- Low strength of silica
- Low fracture toughness of silica
- Low coeff. of thermal expansion -> lower risks of thermal shocks
- Thermal mismatch between silica and aluminum (very different coeff. of thermal expansion -> thick gaskets)
- Difficulty in manufacturing large windows (fusion process)
- Monolithic panes are not robust: first crack provokes failure
- Silica has no static fatigue limit. Reduced durability and delayed fracture




Static fatigue of various glasses
(Wiederhorn & Bolz, J Am Cer Soc., 53, 1970)
Silica: no static fatigue limit

# Mechanical capacity

$$\sigma_{max} \propto \frac{M_b}{d^2}, \qquad w_{max} \propto \frac{M_b}{Ed^3}.$$

$$\frac{\sigma_{max,M}}{\sigma_{d,M}} = \frac{\sigma_{max,FS}}{\sigma_{d,FS}} \quad \Rightarrow \quad d_M = \sqrt{\frac{\sigma_{d,FS}}{\sigma_{d,M}}}\, d_{FS}\,.$$

$$w_{max,M} = w_{max,FS} \quad \Rightarrow \quad d_M = \sqrt[3]{\frac{E_{FS}}{E_M}}\, d_{FS}\,.$$

Inter-material comparison in terms of pane thickness, mass and cost of lunching, for windows with the same structural capacity of the FS pane used in the largest window of the ISS Cupola

| | Soda lime glass | Fused silica | Borosilicate glass(1) | Aluminum oxynitride | Chemically strength. glass | Acrylic glass PMMA(2) |
|---|---|---|---|---|---|---|
| pane thickness | 42.5 mm | 36.8 mm | 39.1 mm | 22.1 mm | 36.8 mm | 153.2 mm |
| mass/area | 106.3 kg/m² | 79.9 kg/m² | 97.8 kg/m² | 83.8 kg/m² | 92.1 kg/m² | 182.3 kg/m² |
| lunching cost/area | \$2.13 M/m² | \$1.60 M/m² | \$1.96 M/m² | \$1.68 M/m² | \$1.84 M/m² | \$3.65 M/m² |

(1) For borosilicate glass, E = 60 GPa has been considered.

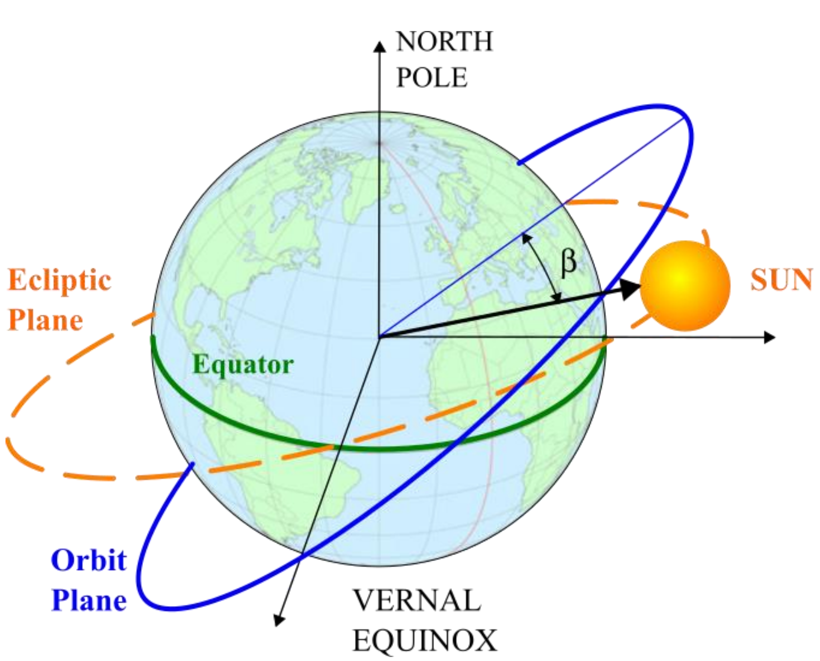
(2) For acrylic glass, on the side of safety, a temperature of about 80 °C has been considered, corresponding to an elastic modulus of about 1 GPa.

# The Low-Earth-Orbit (LEO) conditions

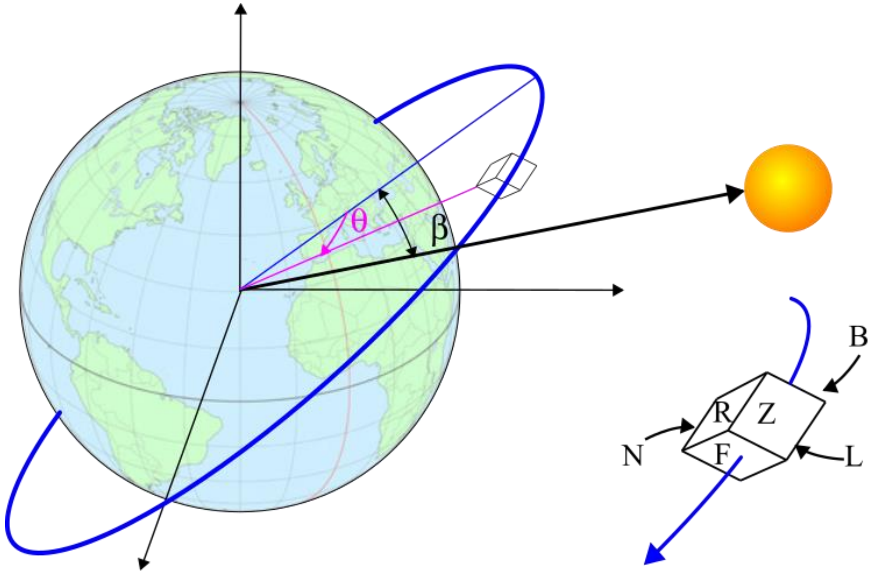
LEO imposes stricter requirements compared to a spaceship traveling over a span of a few days

Main radiation sources; **SUN**, **EARTH's ALBEDO**; Hearth's **PLANETARY RADIATION**

- The ISS completes an orbit (370-460 km height) every ~ 90 minutes, traveling at ~ 28,000 km/h
- Radiation depends upon angle $\beta \in [-75°; 75°]$.




Conventional celestial frame, with indication of the angular parameters



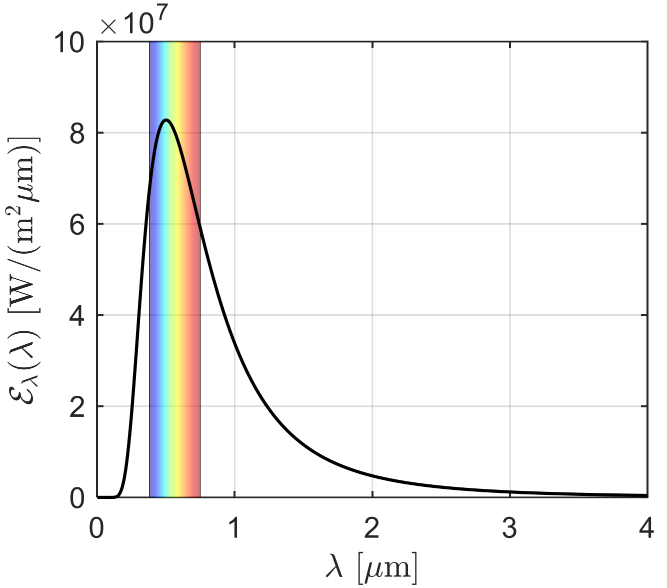

"Orbiting box" and orientation of the window surfaces

- **Z:** Zenith-facing surface;
- **N:** Nadir-facing surface;
- **B:** Backward-facing surface;
- **F:** Forward-facing surface;
- **L:** Left-facing surface (closest to Sun for $\beta > 0$);
- **R :** Right-facing surface, (closest to Sun for $\beta < 0$).

# Electromagnetic radiation

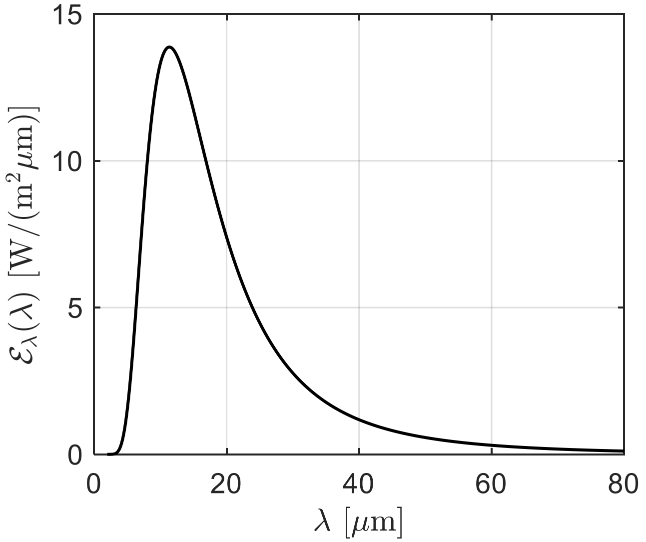
Direct solar radiation
+ Earth’s Albedo

98 % of the emissive power is in the interval λ ϵ (0.25, 2.6) μm



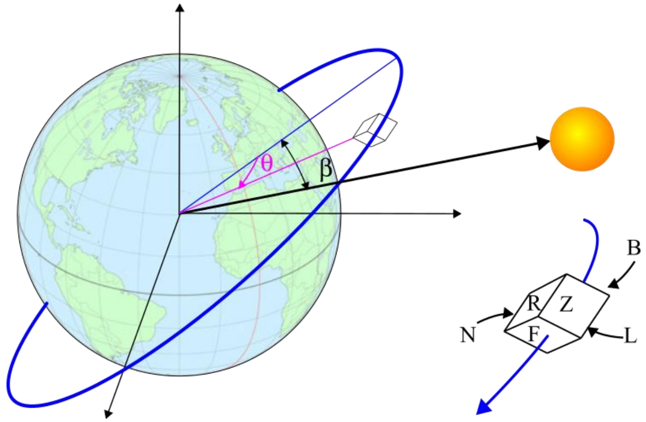

Earth’s planetary radiation

98 % of the emissive power is in the interval λ ϵ (2, 60) μm

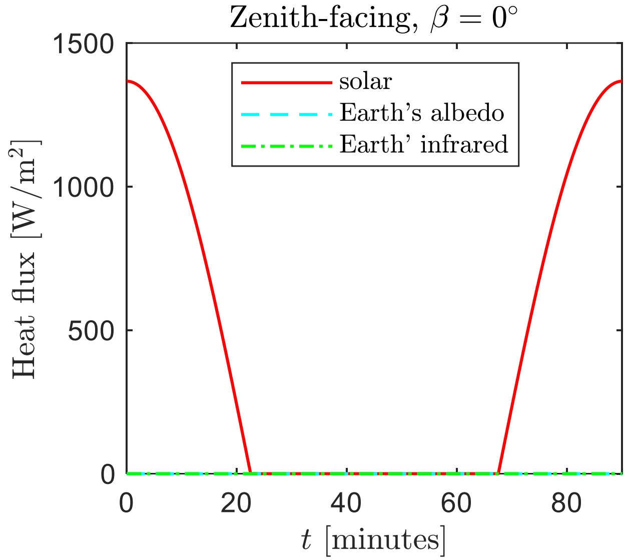


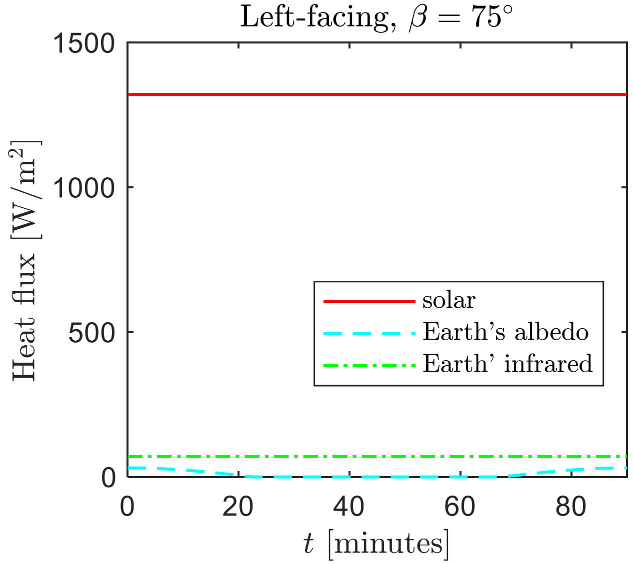

**Worst scenarios:**

- β=0 (orbit plane parallel to Sun rays): greatest variation in solar radiation for Zenith surface **Z**




- β= 75°: almost constant radiation on left-facing surface **L**



# Energy absorption in a plate

## Electromagnetic nature of thermal radiation

Radiation is due to electromagnetic energy waves (Maxwell's equations relate electric field with magnetic field

Since wave propagation in the medium depends on wave-length, one needs to integrate on the wave-length spectrum

**ρ**: reflectivity, **τ**: transmissibility;
**α**: absorptivity,

$$\rho = \frac{\int \mathcal{E}_\lambda(\lambda)\rho_\lambda(\lambda)d\,\lambda}{\int \mathcal{E}_\lambda(\lambda)d\,\lambda}$$

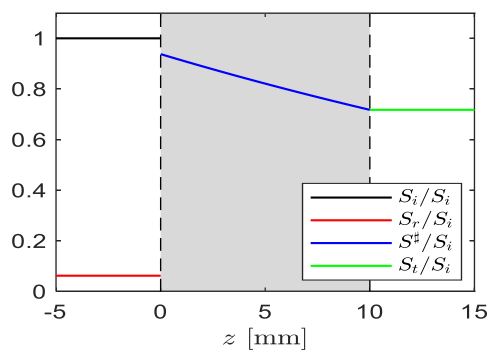
$$\tau = \frac{\int \mathcal{E}_\lambda(\lambda)\tau_\lambda(\lambda)d\,\lambda}{\int \mathcal{E}_\lambda(\lambda)d\,\lambda}$$

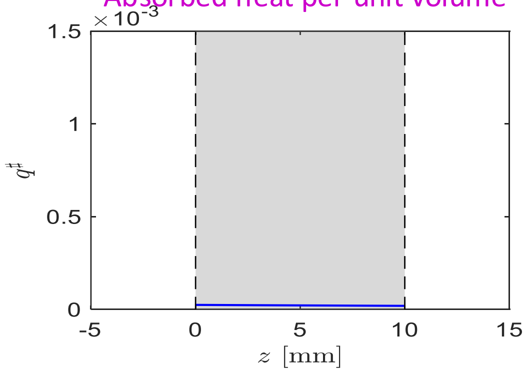
$$\alpha = \frac{\int \mathcal{E}_\lambda(\lambda)\alpha_\lambda(\lambda)d\,\lambda}{\int \mathcal{E}_\lambda(\lambda)d\,\lambda}$$

"Available" power per unit area

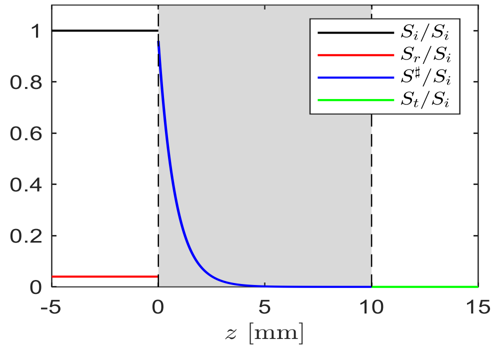
Absorbed heat per unit volume

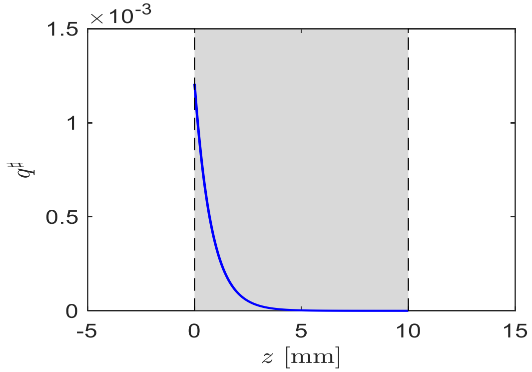
Low-absorbing material



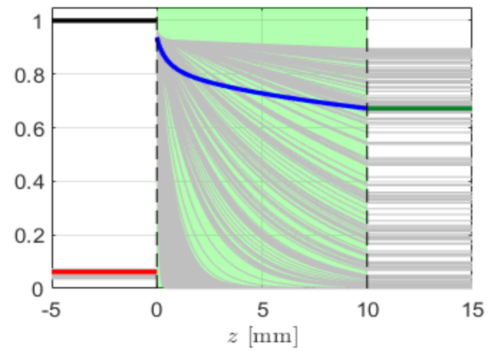

High-absorbing material

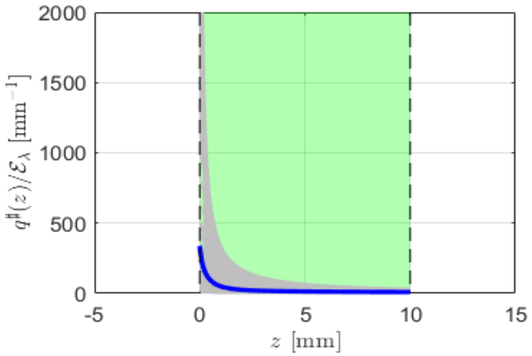



Real material:

Averaged properties with respect to the radiation spectrum



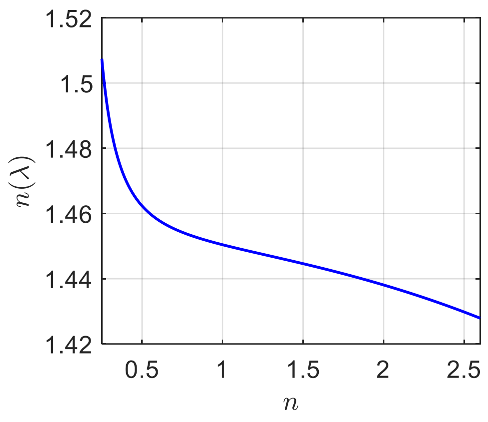
# Solar Spectrum

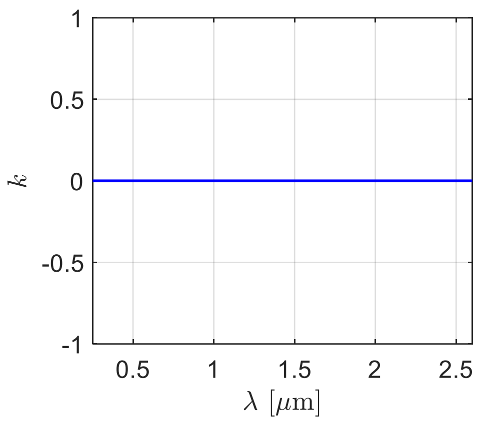
*n-ik* = **wavelength dependent** complex refractive index

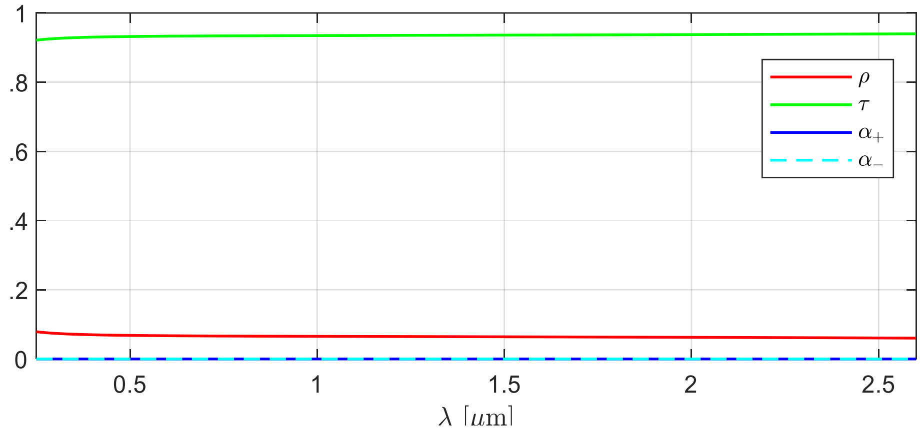
**τ**: transmissibility; **α**: absorptivity, **ρ**: reflectivity

## Fused Silica

Null absorptivity. Transmissivity and reflectivity almost constant and thickness-independent

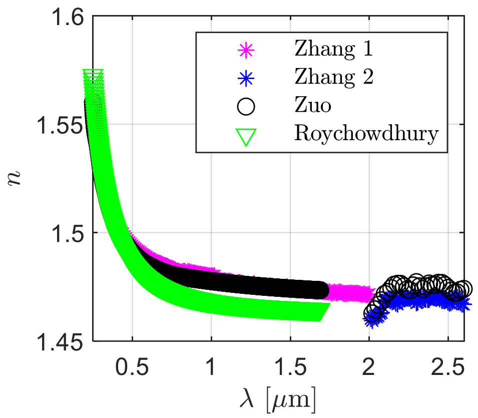


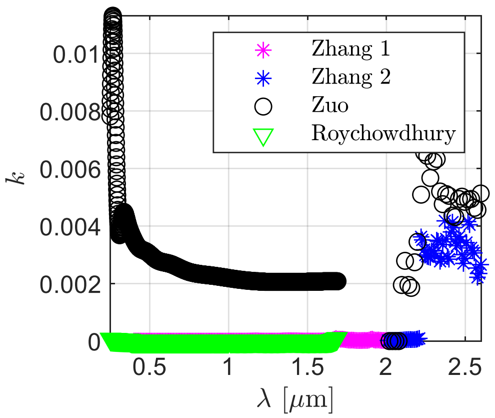



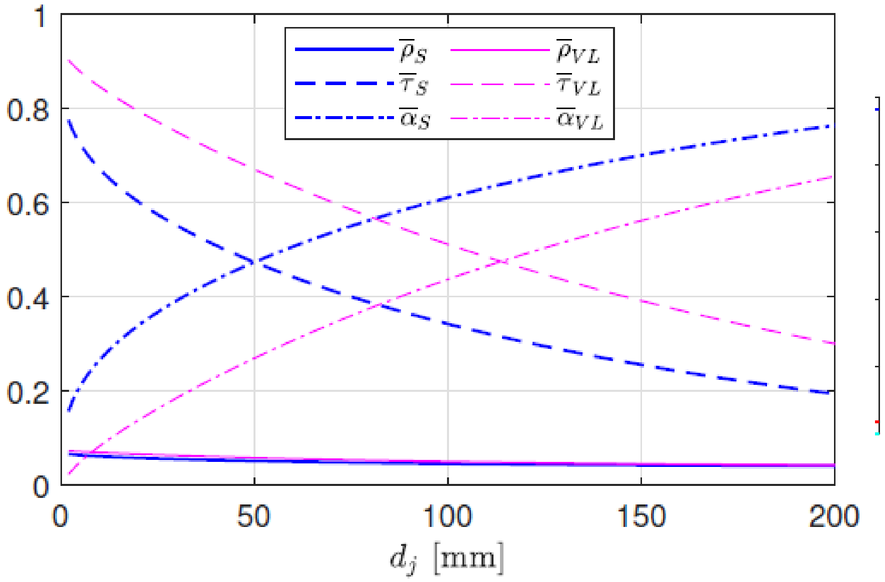

## Acrylic glass

Absorptivity and transmissivity strongly depend on pane thickness




*Literature contradictory/incomplete

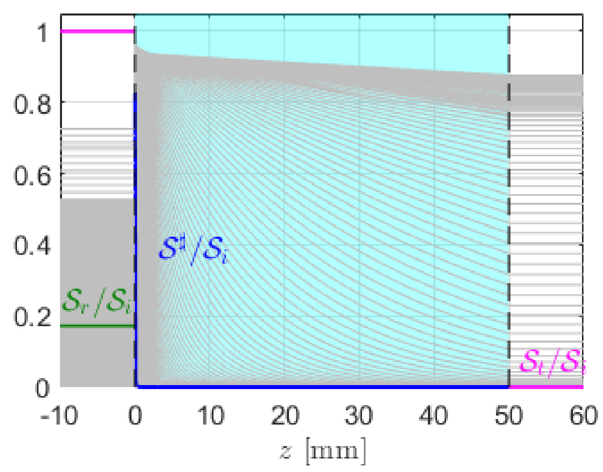


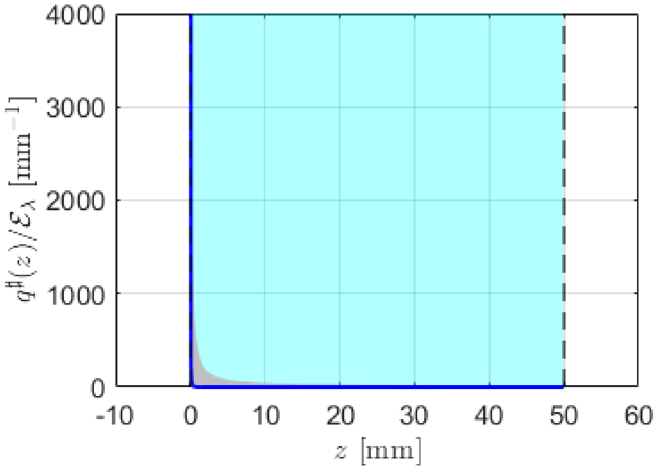
# IR planetary radiation

**τ**: transmissibility; **α**: absorptivity, **ρ**: reflectivity

## Fused silica

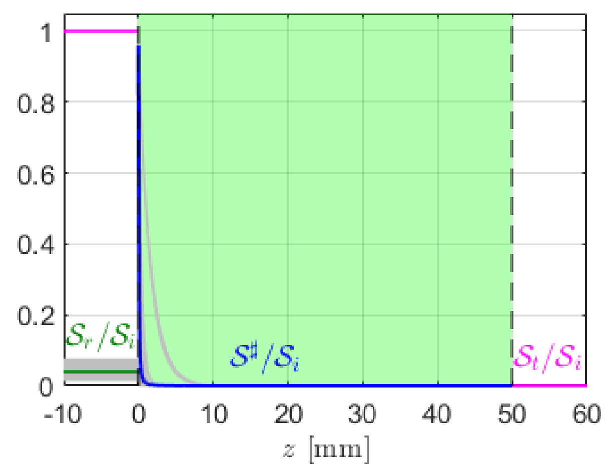
$\rho = 17{,}2\ \%$
$\tau = 0$
$\alpha = 82{,}8\ \%$

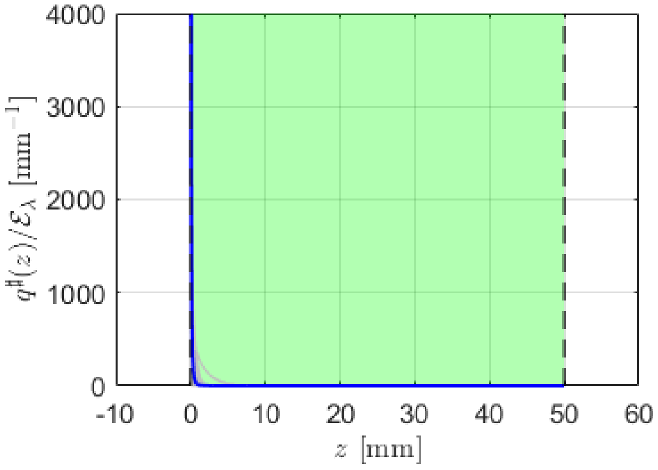



## Acrylic glass

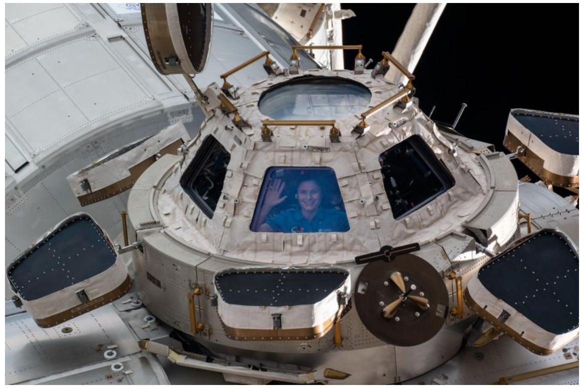
$\rho = 4\ \%$
$\tau = 0$
$\alpha = 96\ \%$



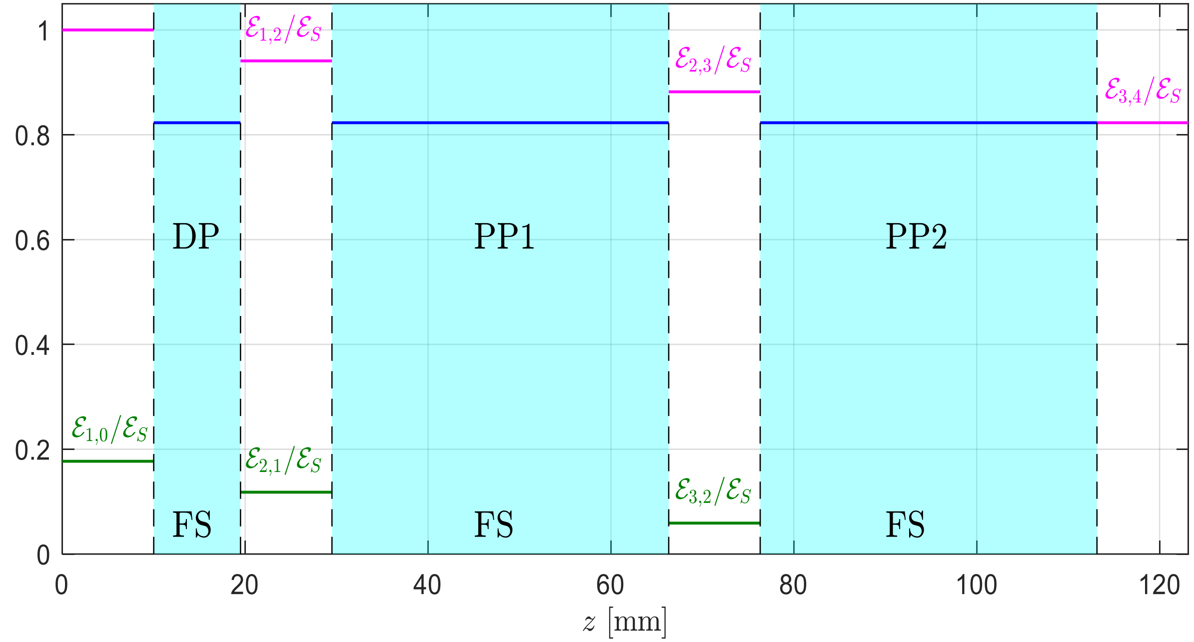

- IR radiation is absorbed in a thin layer
- Null transmissivity

# Window with fused silica (FS) panes



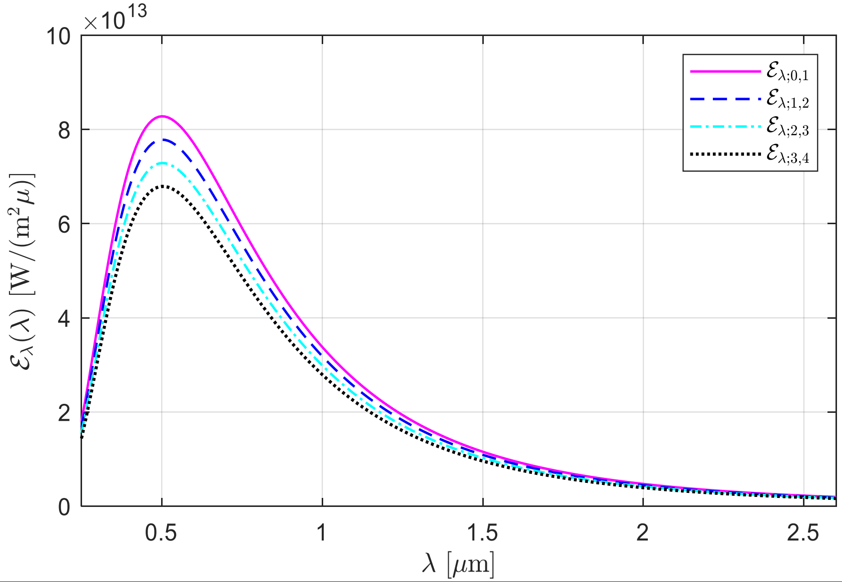
Representative of the Cupola circular window:

debris pane (DP), 9.45 mm
pressure pane (PP1), 36.83 mm
pressure pane (PP2), 36.83 mm




Energy distribution in the different panes

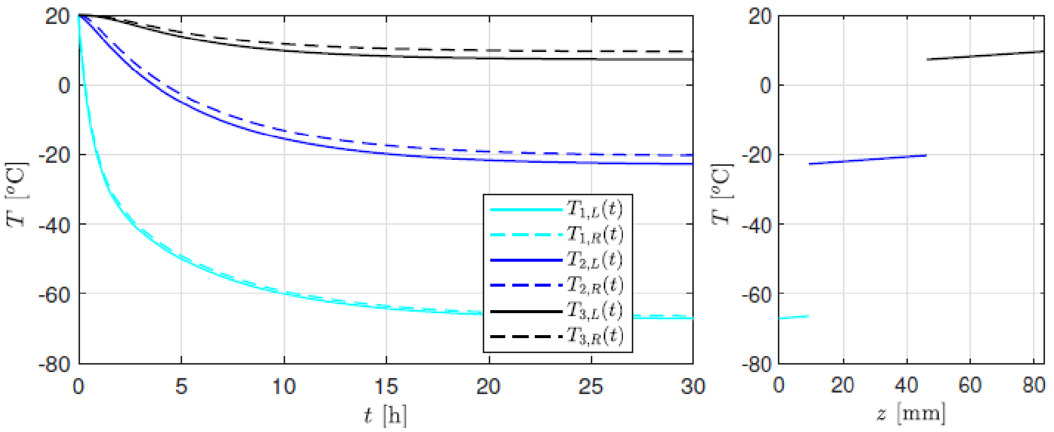
Total reflectivity: $\rho = 17{,}7$ %
Total transmissivity: $\tau = 82{,}3$ %
Absorptivity: 0
Optical transparency: 82,1 %



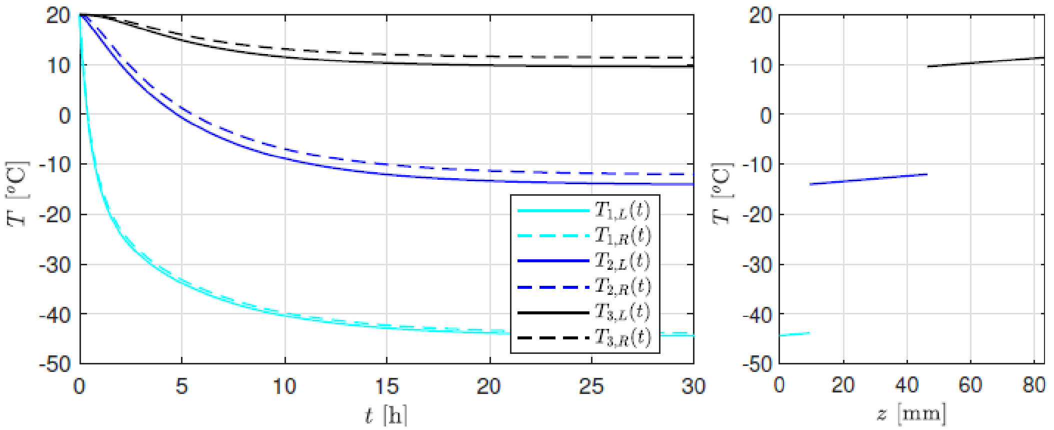

Spectral contribution is differently reflected and transmitted (ρ and τ are wavelength-depedent) → radiation spectra on second and third panes differ from incoming radiation, but the difference is mild

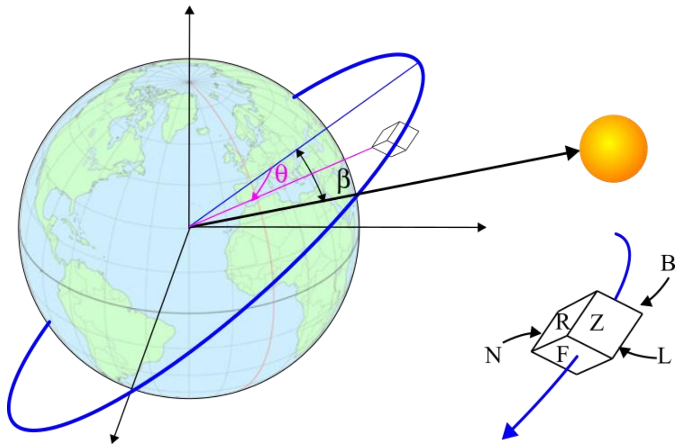
# All panes made of fused silica: temperatures

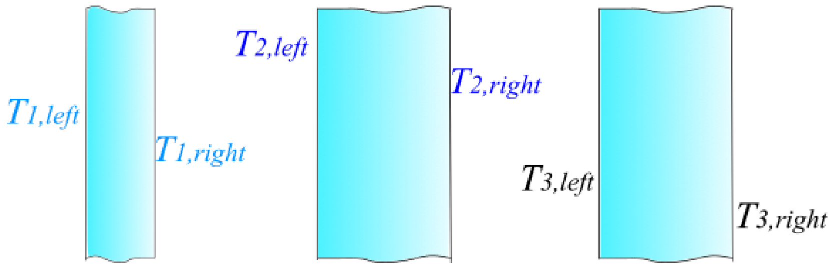
β=0°, Zenith pane **Z**




β=75°, Left-facing pane **L**

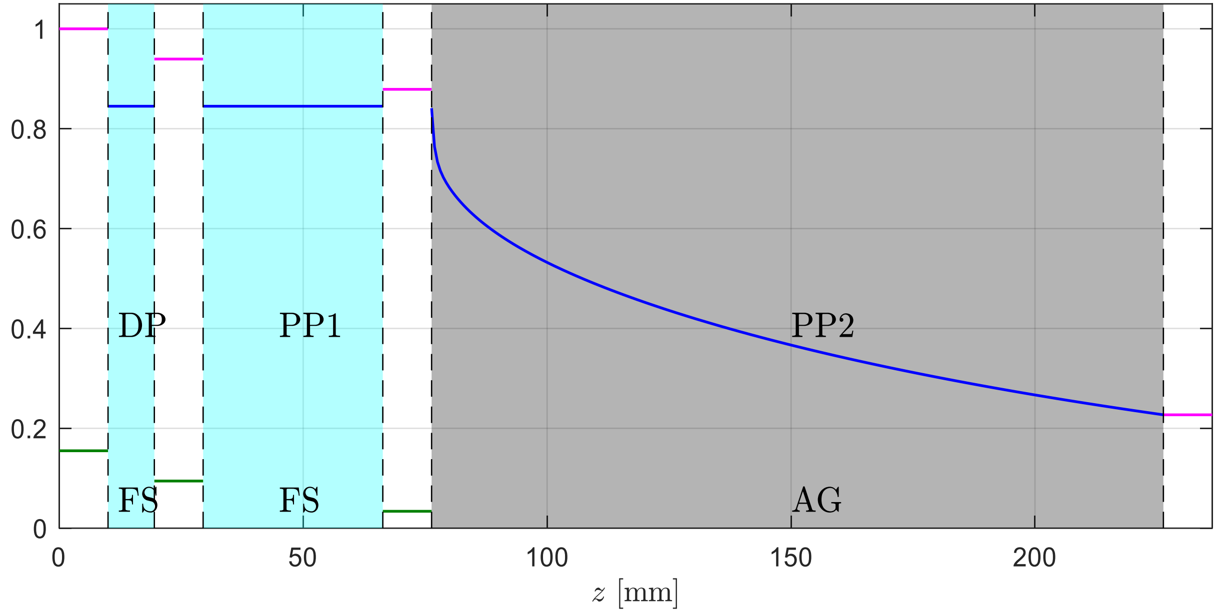


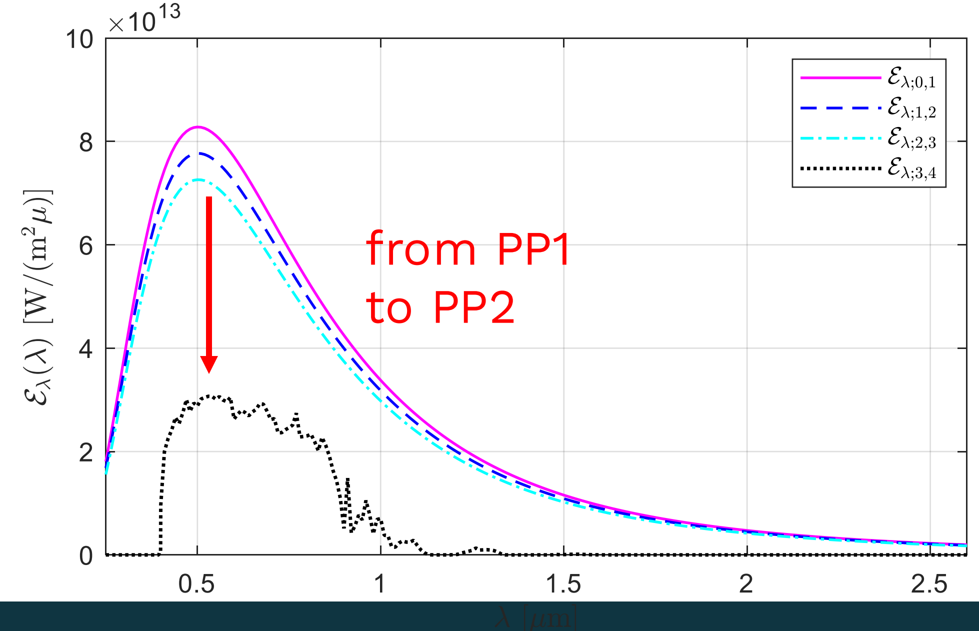

- Time to reach the steady state: about 20 hours
- heat absorption = 0 $\rightarrow$ linear spatial temperature distribution at steady state
- Low temperatures due to heat exchange with the external environment

# Inner pane in acrylic glass (AG)




Energy distribution in the different panes

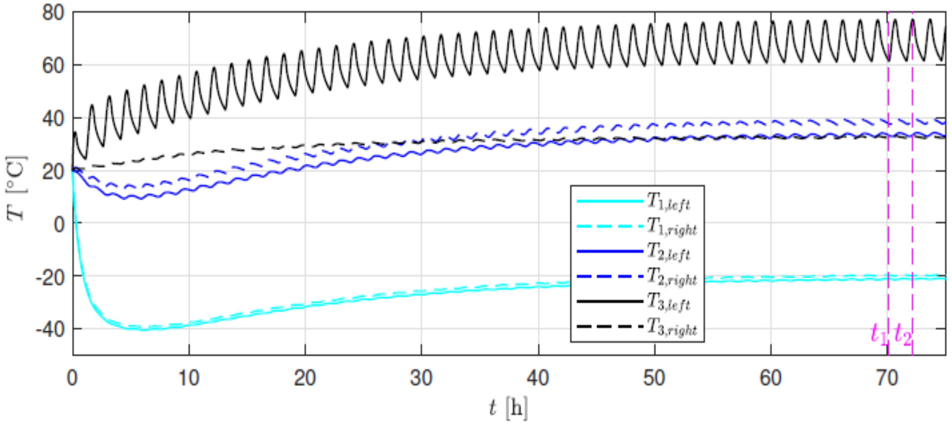
Total reflectivity: $\rho = 15{,}5\ \%$
Total transmissivity: $\tau = 22{,}7\ \%$
Absorptivity of DP: $\alpha_1 = 0$
Absorptivity of PP1: $\alpha_2 = 0$
Absorptivity of PP2: $\alpha_3 = 61{,}8\ \%$
Optical transparency: 34,4 %

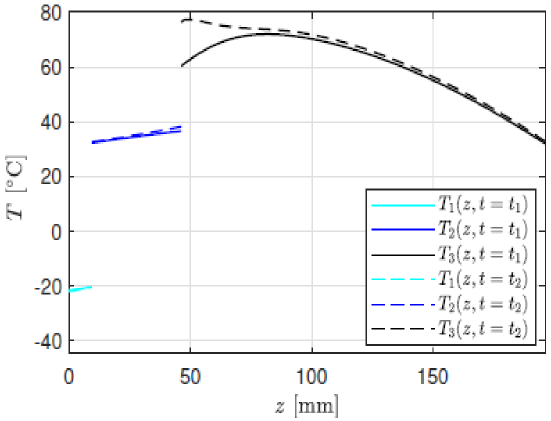



Radiation spectra for the panes is different from that of the incoming radiation.
The main variation is recorded in the AG pane
FS panes do not shield the radiation so that a large amount of energy is absorbed by PP2.

# Inner pane in acrylic glass: temperatures

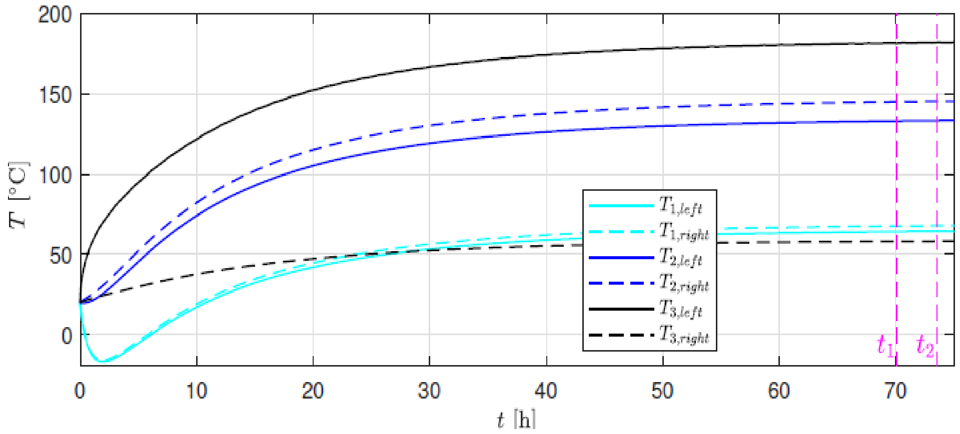
## β=0°, Zenith pane **Z**

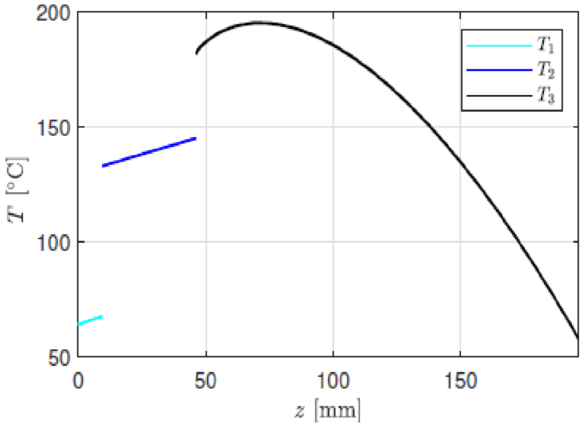



- Cyclic trend in temperature response in the AG pane; "propagates" to the FS PP1, due to the IR heat exchange.
- Higher temperature (of about 80°C) in the AG pane

## β=75°, Left-facing pane **L**




- cyclic trend in temperature hardly recognizable (ΔT=0,47°C)
- temperature at internal surface > 50°C
- AG pane reaches 195°C
- Glass transition temperature in acrylic glass is ~100°C

# Contributions

- **Material Challenges**: Space windows require a careful balance of mechanical strength, thermal resistance, optical clarity, and radiation shielding—making material selection critical.
- **Shift to Acrylic**: While fused silica glass has been the traditional choice, acrylic glass (PMMA) is now preferred due to its cost efficiency.
- **Radiation Protection**: Among the various hazards, we analyzed how multi-pane spacecraft windows absorb and transmit radiation from both solar and Earth sources.
- **Thermal Limits of Acrylic**: Acrylic's energy absorption may cause overheating in thick sections (large windows), raising concerns about structural durability in the extreme space enviroment

If interested in this topic, please send an email to: info@maffeis.it
**"I am interested in space windows"**