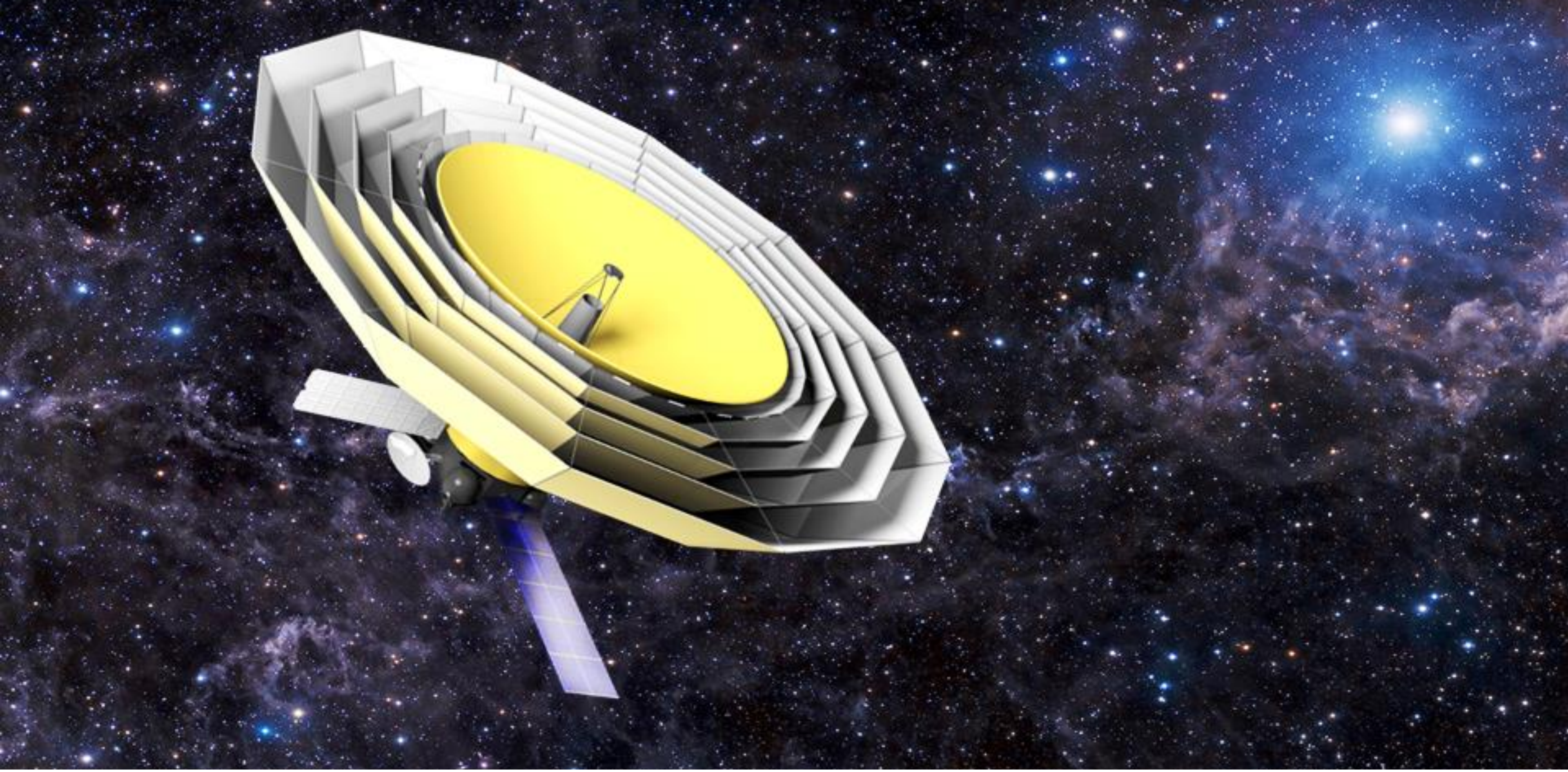

Primary Mirror Panels of the Millimetron Space Observatory

Elena Filina on behalf of the Millimetron team

ASC LPI

RESHETNEV COMPANY

Millimetron Workshop, 9-11 September 2019, Paris

Requirements for the panels

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- Operational temperature up to 4.5 K
- Surface accuracy (RMS) at the operational conditions:

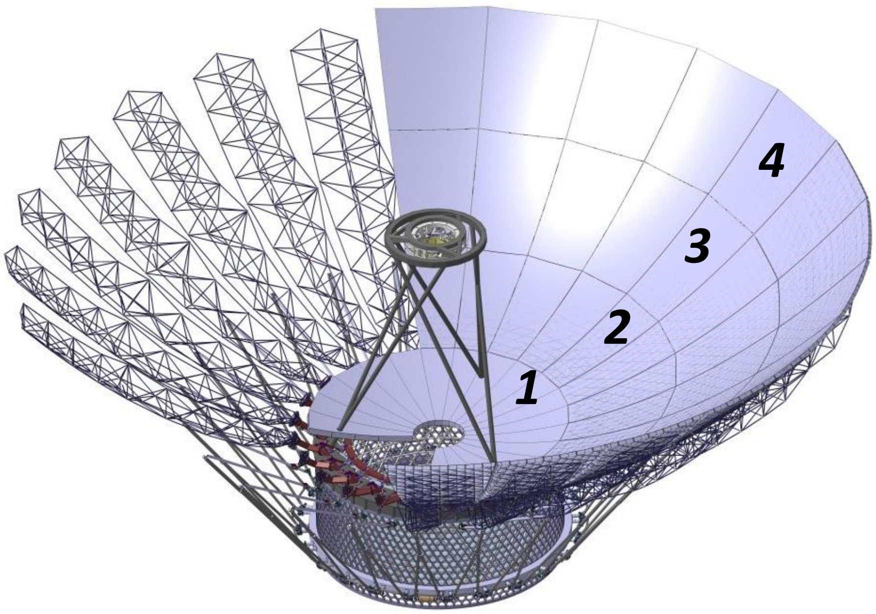
  panel 1 $\leq$ 3 μm

  panel 2 $\leq$ 5 μm

  panel 3 $\leq$ 7 μm

  panel 4 $\leq$ 8 μm
- Roughness: $Ra \leq 0.3$ μm
- Reflection coefficient: $R \geq 0.98$
- Areal density $\leq$ 8.5 kg/m^2

Primary mirror	Areal density, kg/m^2
Hershel (SiC)	21.8
Planck (CFRP)	12.5
JWST (Be)	17.7
Millimetron (CFRP)	**$\leq$ 8.5**



24 panels of the non-transformable central part *(1)*
72 panels of the deployable petals *(2-4)*

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Problem statement

Requirements	Challenges	Development steps
Areal density ≤ 8.5 kg/m^2	Optimal panels design	▪ Create and verify FEM ▪ Perform geometry optimization ▪ Analyze the panel's sensitivity to various external factors
Surface accuracy at operational conditions	Thermal distortions / conductivity	▪ Improve thermal conduction ▪ Measure thermal distortions at 4K
	Highly accurate manufacturing technique	▪ Validate the replica technique accuracy and repeatability
Reflection coefficient $R \geq 0.98$	Quality of the reflective layer	▪ Analyze the effect of microcracking on the surface reflectivity

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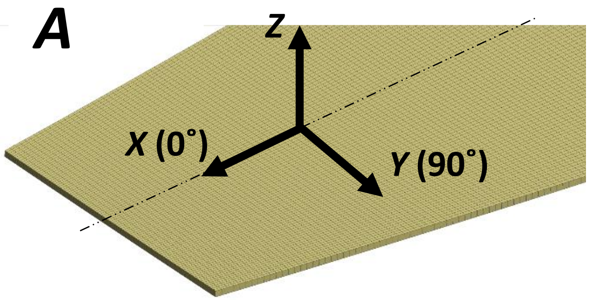
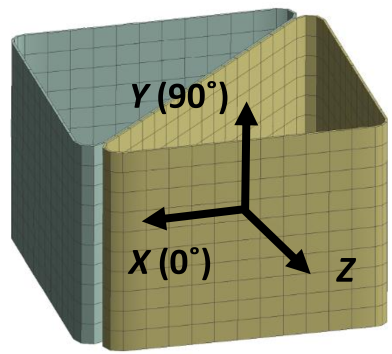
Finite element model of the panel

Allows to consider:

1. Ply orientation

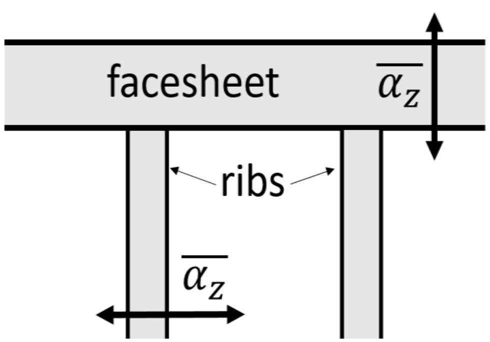


$[0°/ 90°/ +45°/ -45°]ns$



$[0°/ 90°]ns$

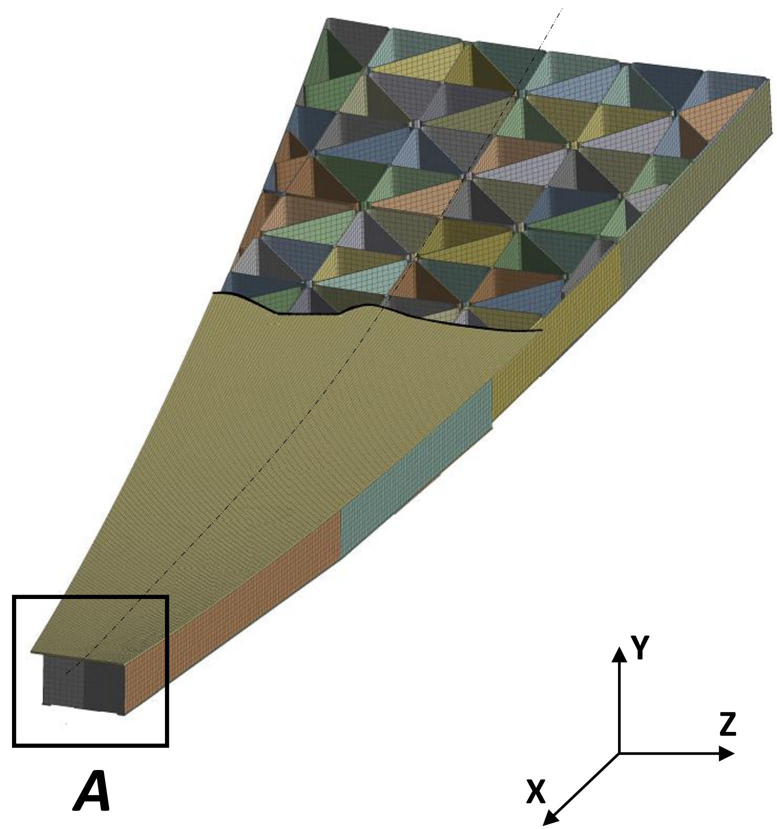
2. CTE through the thickness of facesheets and ribs



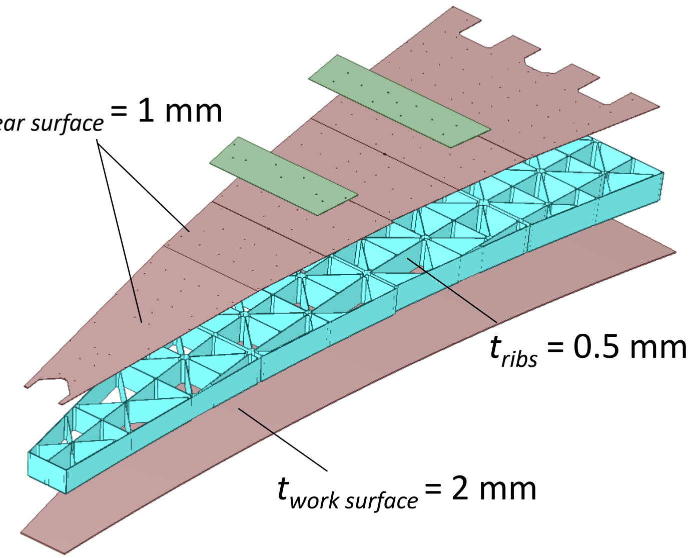
$\overline{\alpha_x} = \overline{\alpha_y} = 0.3 \cdot 10^{-6}$ 1/K

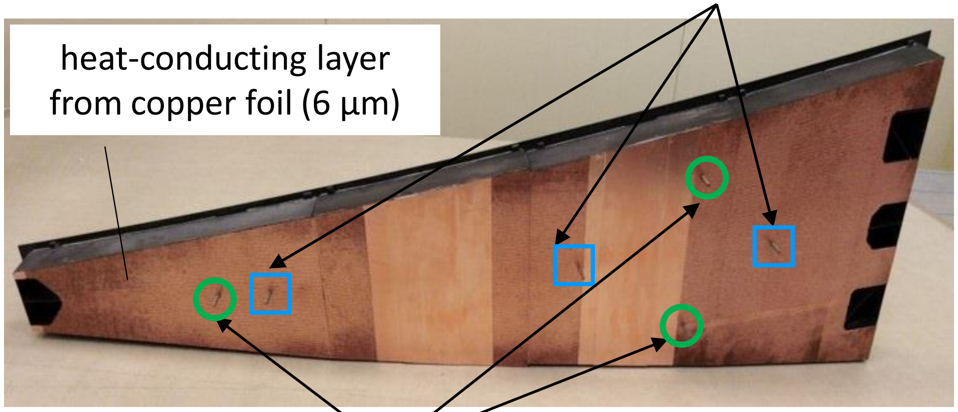
$\overline{\alpha_z} = 25 \cdot 10^{-6}$ 1/K

$\boldsymbol{\overline{\alpha_z} \approx 83\, \overline{\alpha_x}}$



Design of the panels*





The concept of the panels development is based on:

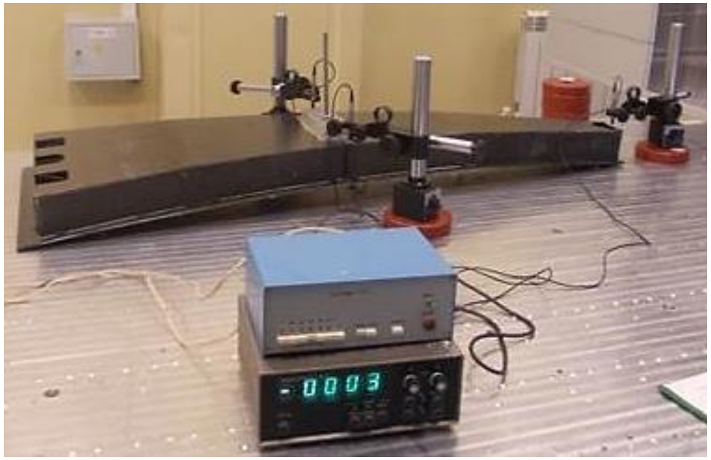
- **Material: CFRP (M55J + cyanate ester resin)**
  Low density;
  Extremely low CTE (for quasi-isotropic layup: $\alpha_{long} \approx 0.3 \cdot 10^{-6}\ \mathrm{K}^{-1}$);
  Low moisture absorption;
  High resistance to micro-cracking;
- **Ply orientation:**
  [0°/ 90°/ +45°/ -45°]*ns* - facesheets
  [0°/ 90°]*ns* - ribs
- **Parts are glued with cryoresistant adhesive**
- **Replica technique that significantly increases manufacturing rate**

✓ **After redesign mass of the panels was reduced by 20%**

*The design and concept are the same for all types of panels. Here the central panel is used as an example.

Verification of the finite element model

Stiffness measurement under point load



Case	Compliance, µm/N	Error, %
Modelling	1.04	3.8
Experiment	1.08	

Eigenfrequencies measurement

Mode	Frequency, Hz		Error, %
	Modelling	Experiment	
1, bending	315.8	301.4	4.6
2, bending	661.1	635.4	3.9
3, twisting	658.4	652.8	0.9

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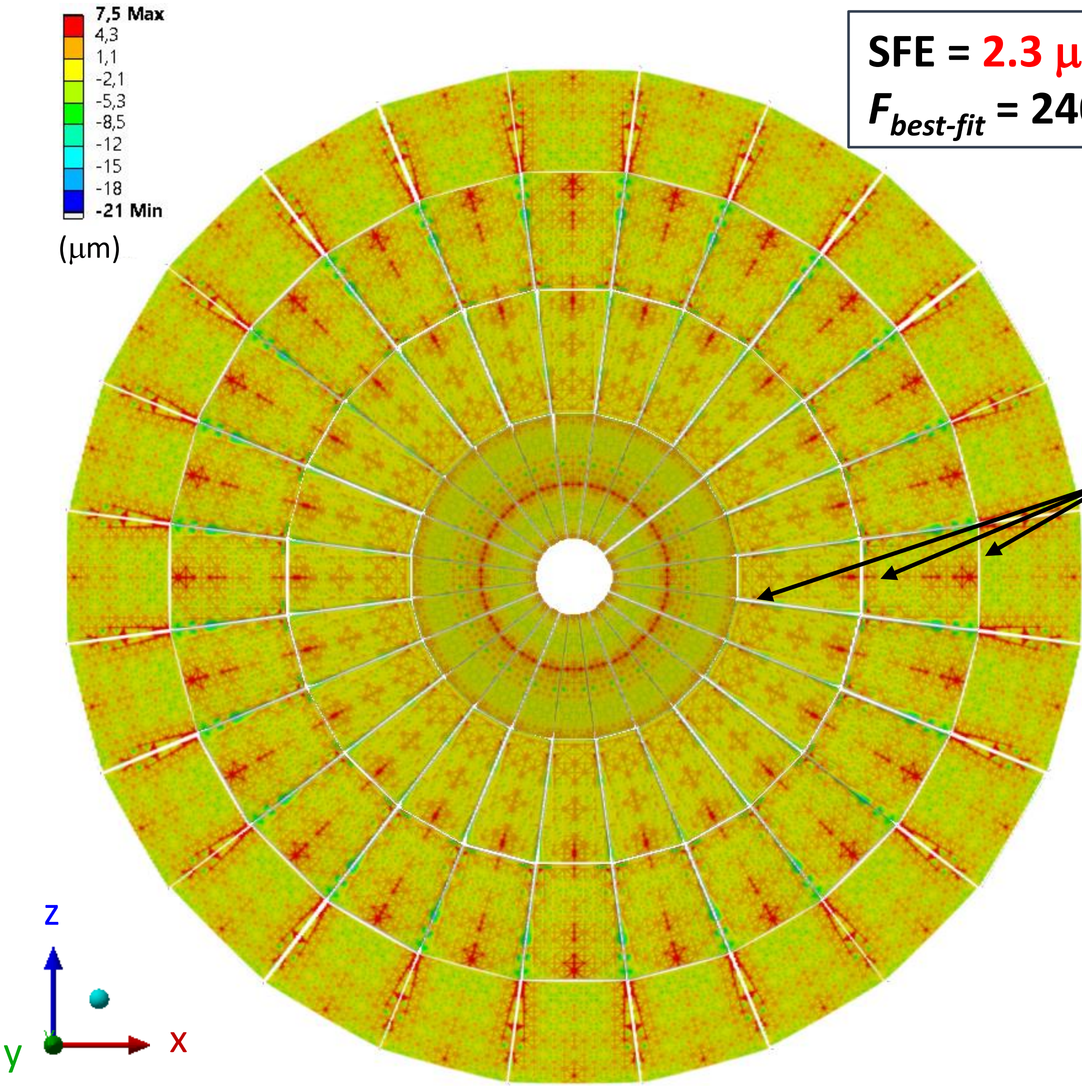
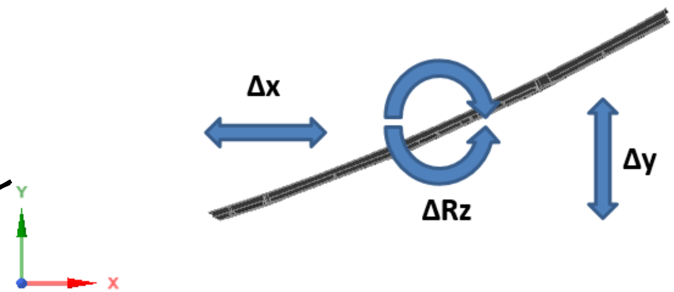
Thermal distortions modelling

SFE = 2.3 μm (RMS)

$F_{best\text{-}fit}$ = 2401.32 mm



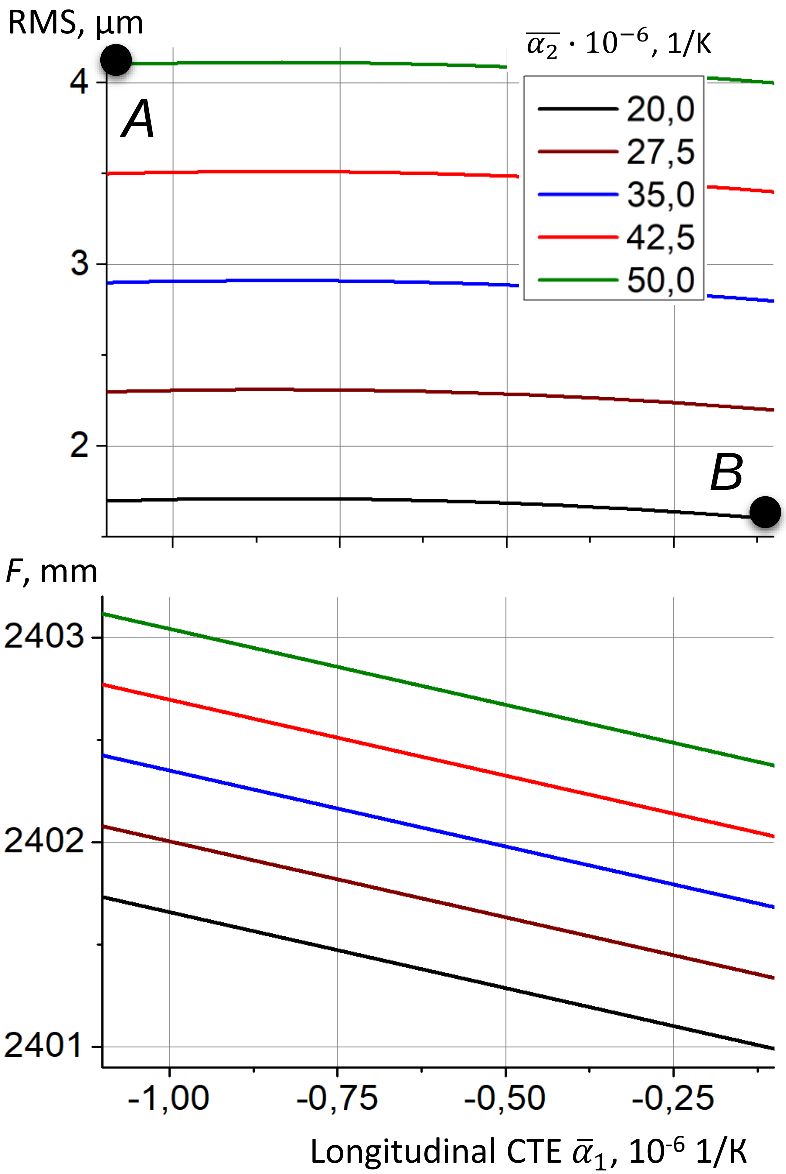


3 Degrees of freedom are used for best-fitting procedure

Similar to the adjustment by 3 actuators

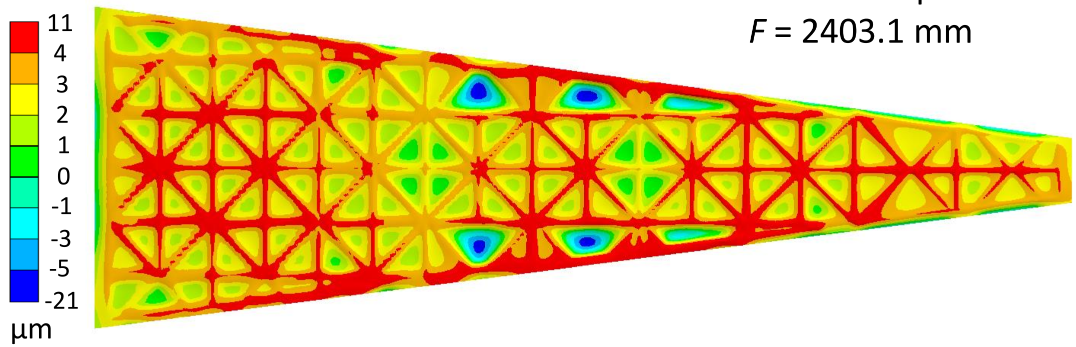
Surface distortions of the panels with respect to the best-fit paraboloid due to cool down from 293 K to 4 K

Panel's sensitivity to the variation in the CTE value of the ply



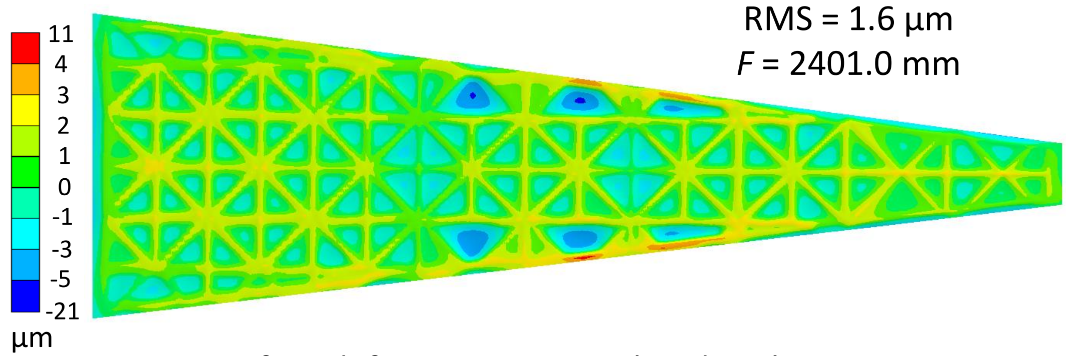
A

$\overline{\alpha_1}$ = -1.10·10^{-6} 1/K
$\overline{\alpha_2}$ = 50·10^{-6} 1/K
RMS = 4.1 µm
F = 2403.1 mm



B

$\overline{\alpha_1}$ = -0.10·10^{-6} 1/K
$\overline{\alpha_2}$ = 20·10^{-6} 1/K
RMS = 1.6 µm
F = 2401.0 mm



Surface deformation map related to the BFP

Thermal distortions measurement

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Development of a 10-m cooled mirror with high surface accuracy for space telescope

↑

Development of panels with high surface accuracy and thermal dimensional stability

↑

Verification of thermal dimensional stability of panel

Step 1

- ✓ temperature up to 80 K
- ✓ measurement accuracy ≈ 20 μm

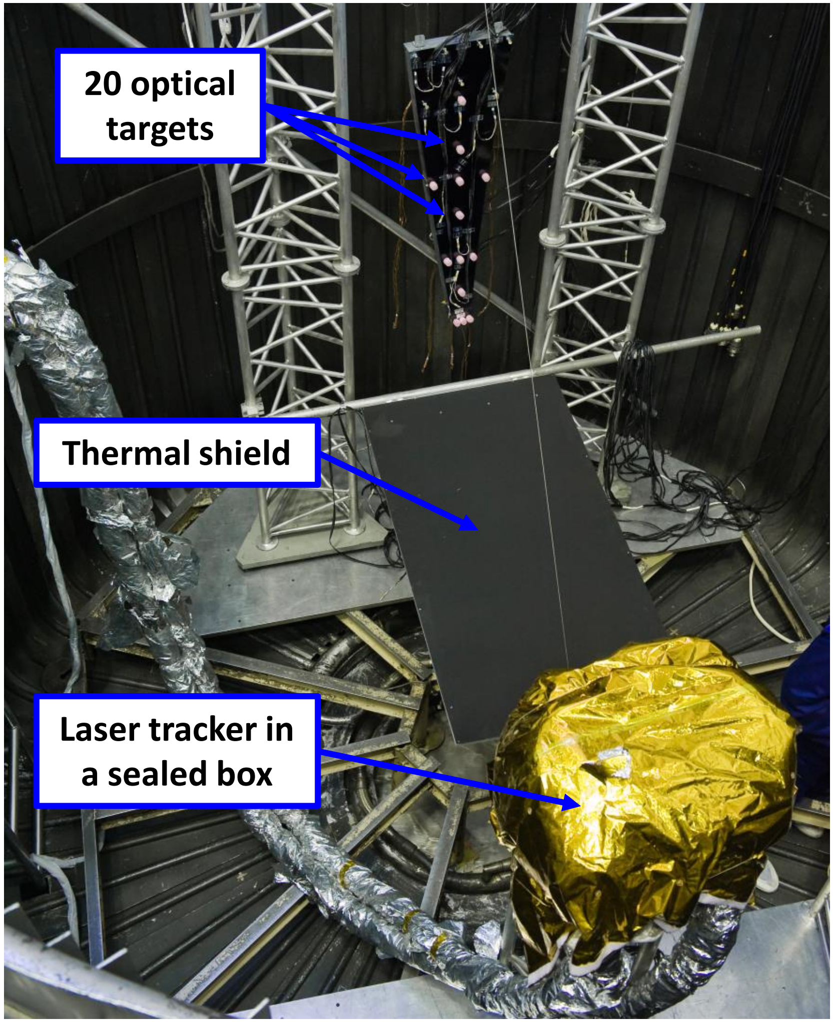
Step 2

- ❑ temperature up to 4,5 K
- ❑ measurement accuracy ≤ 1 μm

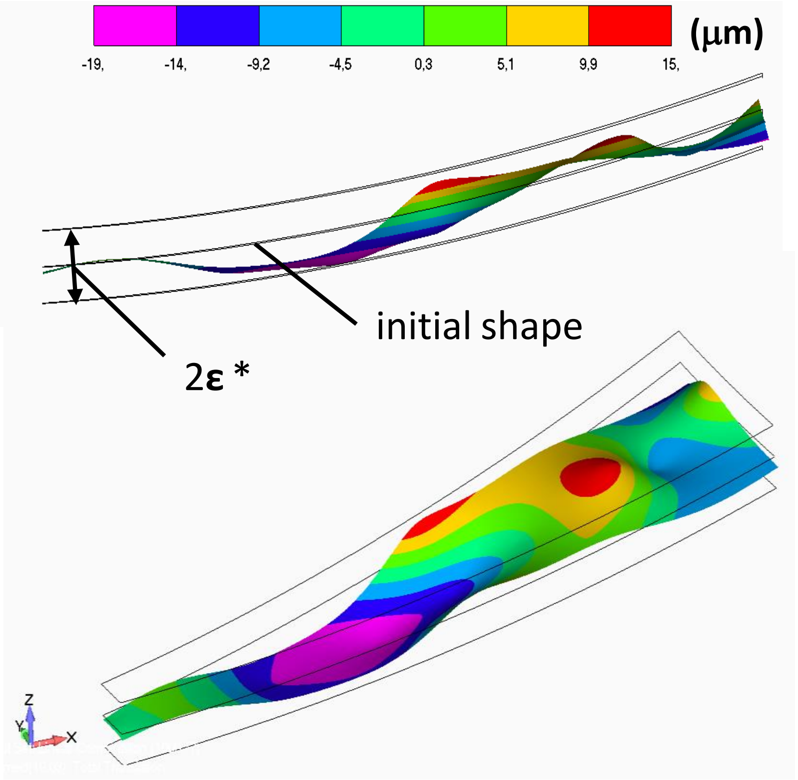
<u>Necessary to implement</u>:

- ❑ a thermal vacuum chamber with required sizes and temperature levels;
- ❑ a measurement system with proper accuracy;
- ❑ a verification program.

Thermal distortions measurement (November, 2016)



Setup for measurement of thermal distortions of the panel in a thermal vacuum chamber



Surface deformation map of the panel at 120 K (not actual scale)

* measurement accuracy ε ≈20 μm

Thermal distortions measurement (August, 2019)

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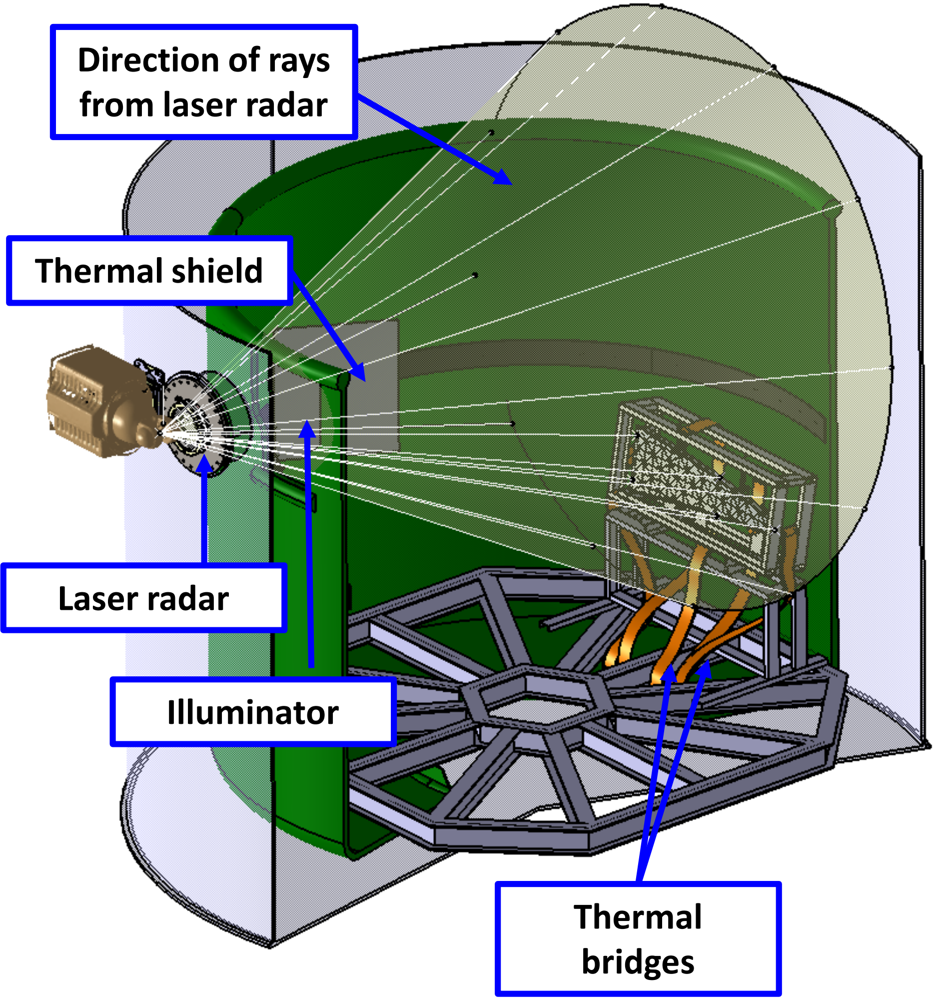

Setup for measurement of thermal distortions of the panel in a thermal vacuum chamber

- ✓ Full-scale panel has been coated (Al+SiO_2)
- ✓ 1500 points measured on reflective surface
- ✓ Cool down to 100 K by thermal bridges
- ✓ Thermal interfaces of the panel are verified

Photo of panel setup

Results of thermal distortions are under post-processing

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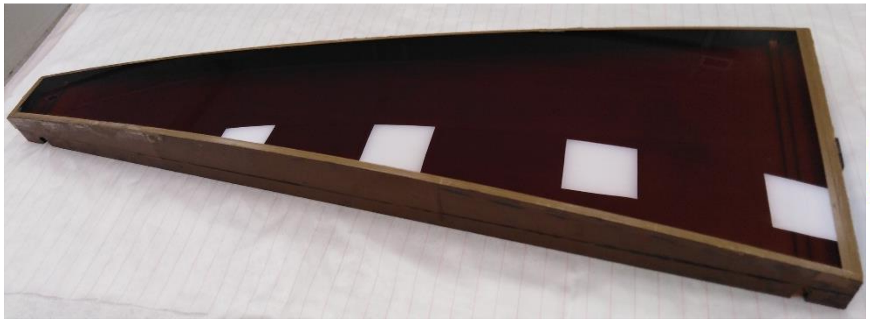
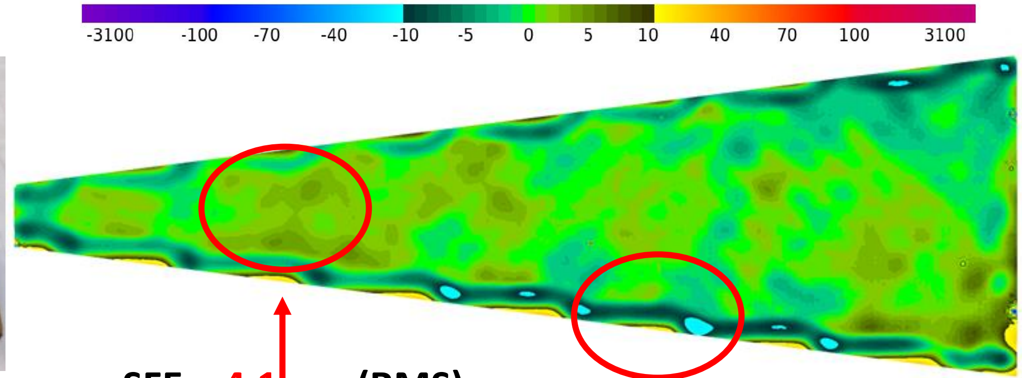
Replica technique



Trial parabolic mold from ULE glass



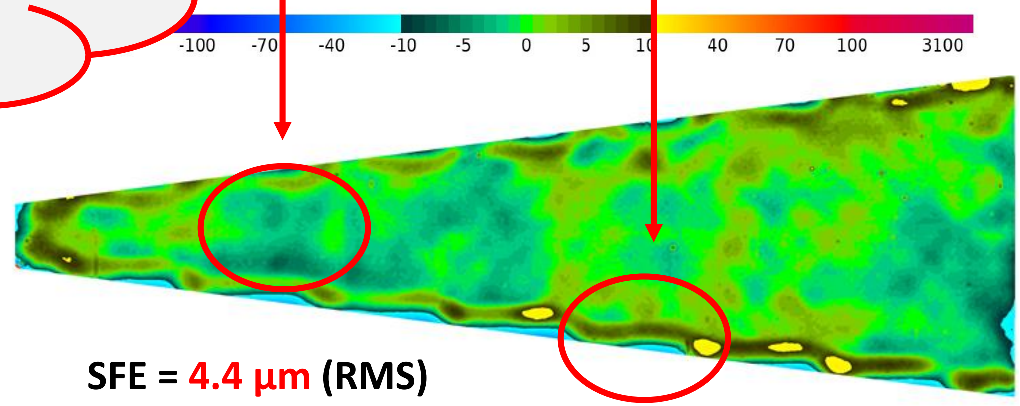
SFE = 4.1 μm (RMS)

$F_{best\text{-}fit}$ = 2407.5 mm

✓ **Replication of mid-spatial-frequency errors (MSF) ≤ 1 μm**

rismo ultra) at room temperature

Panel of the PM central part (1.3 m long)



SFE = 4.4 μm (RMS)

$F_{best\text{-}fit}$ = 2406.1 mm

Roughness: ≤ 0.2 μm

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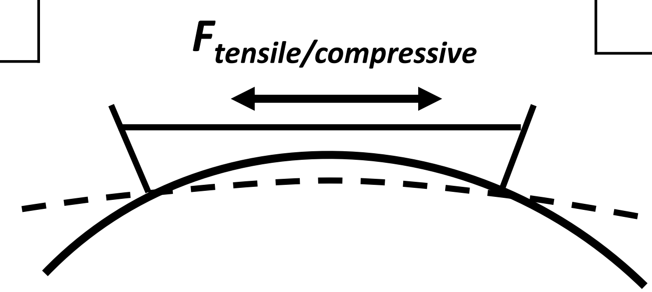
How to get ~100 “excellent” panels?

“Springback” effect

Parameters	Specification	Result
Replica accuracy (MSF)	≤ 1 µm	≈1 µm
$F = F_{mold}$	2407.5 mm	2406.1 mm (±5 mm)
Roughness, *Ra*	≤ 0.3 µm	0.2 µm

Correction of the panel surface curvature

After correction
≈1 + 0.2 µm
2407.5 mm
0.2 µm



Results of the surface curvature correction

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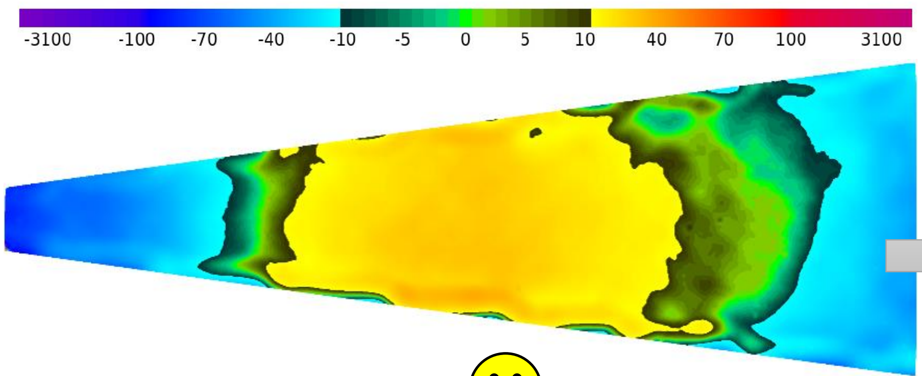
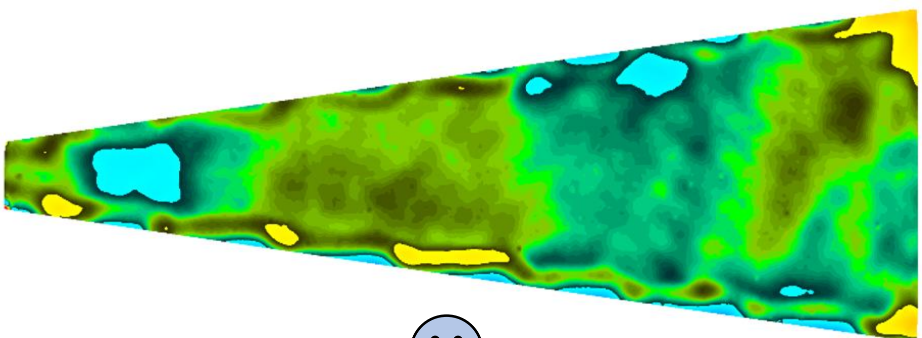
Before



$F = F_{mold}$ = 2406.1 mm

$SFE_{2406.1}$ = 23.8 µm (RMS)



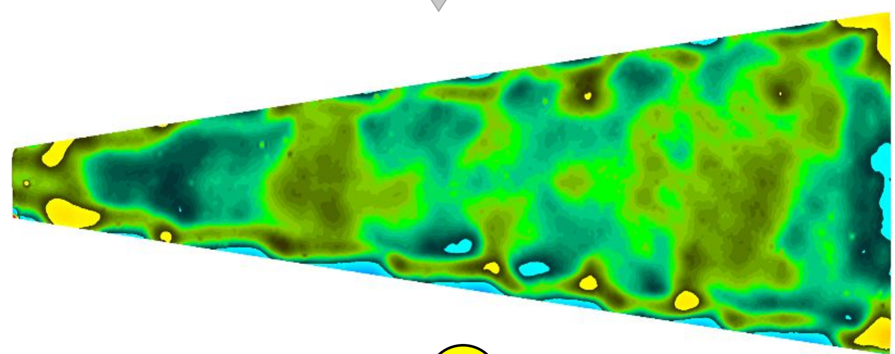
$F_{best\text{-}fit}$ = 2412.8 mm

$SFE_{best\text{-}fit}$ = 5.4 µm (RMS)

After

Goal: F_{mold}= 2406.1 mm

Correction of the panel surface curvature using a suite of mechanical regulators on the rear surface



$F_{best\text{-}fit}$ = 2406.1 mm

$SFE_{best\text{-}fit}$ = 4.7 µm (RMS)

Shape stability of prestressed panel

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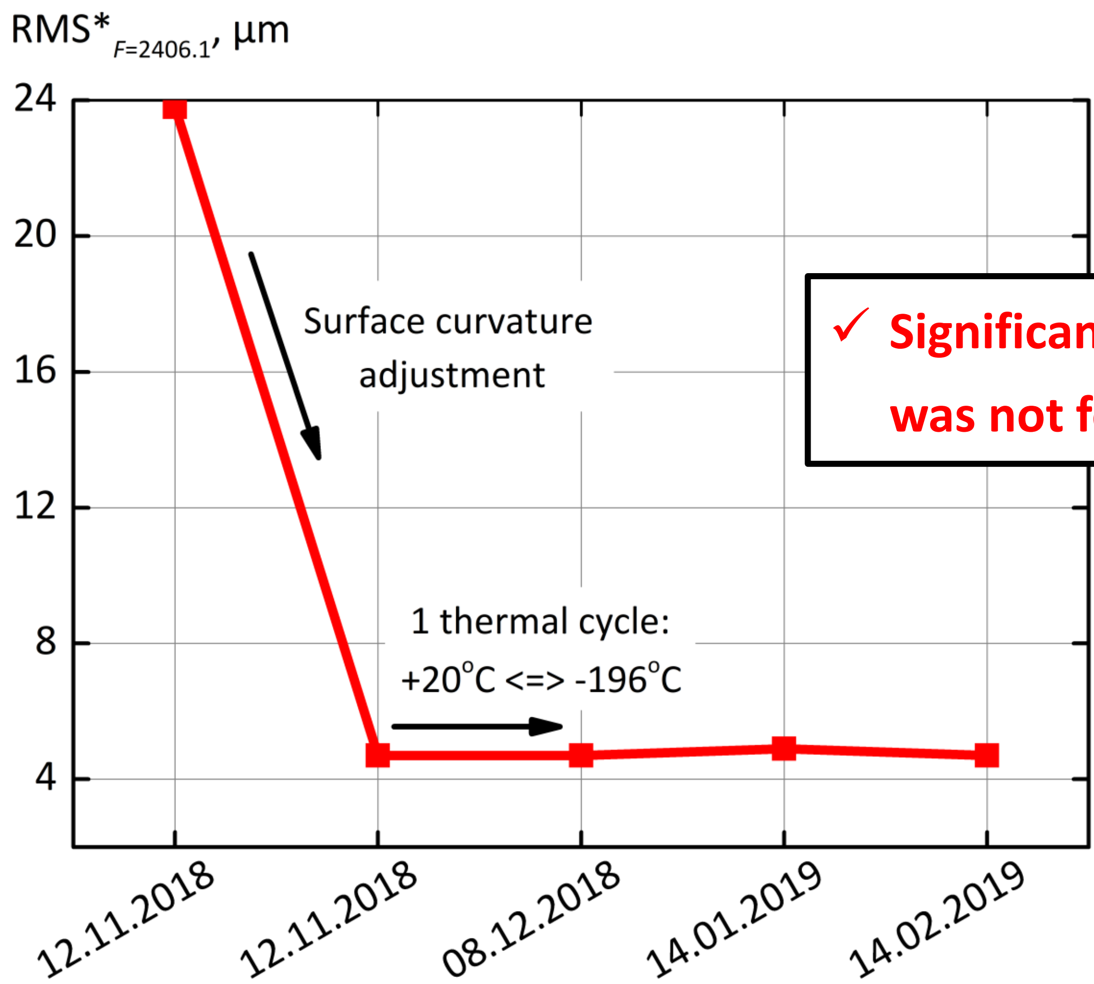
Prestressed panel → Time, creep → Additional SFE factor ???



✓ **Significant creep was not found**

*Based on CMM measurements

Reflective surface of the panels

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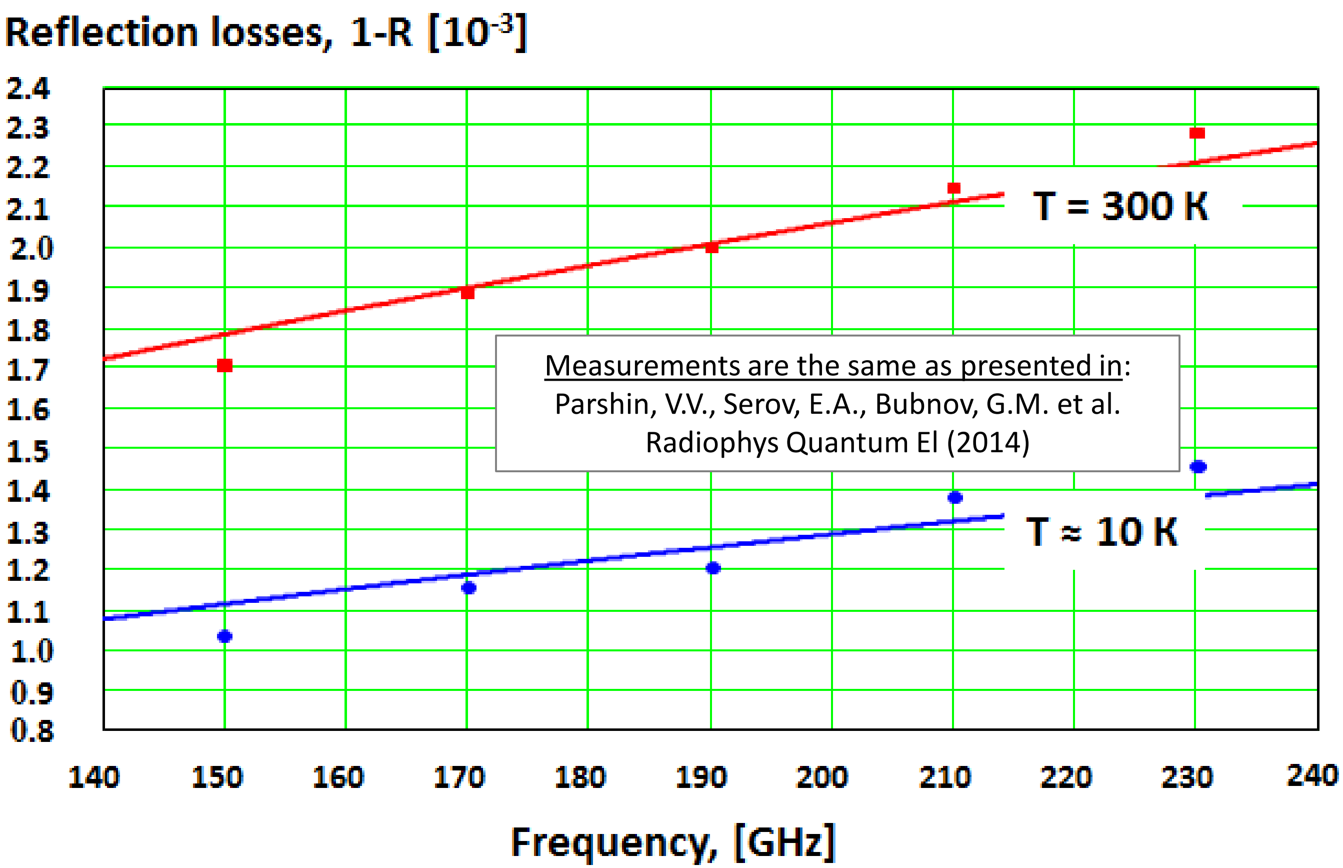
✓ CFRP coated by Al (t = 0.5 μm) + protective SiO_2 layer



$R^* \geq 0.998$

R – reflection coefficient

$R \geq 0.999$

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Microcracking on the reflective surface

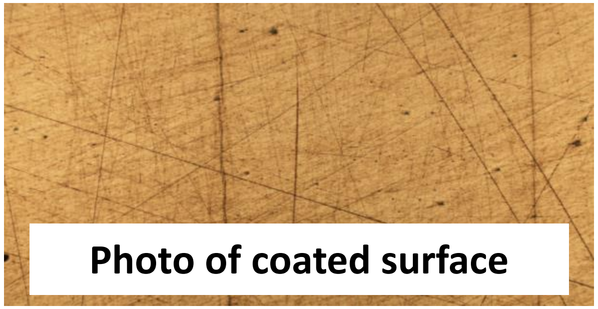
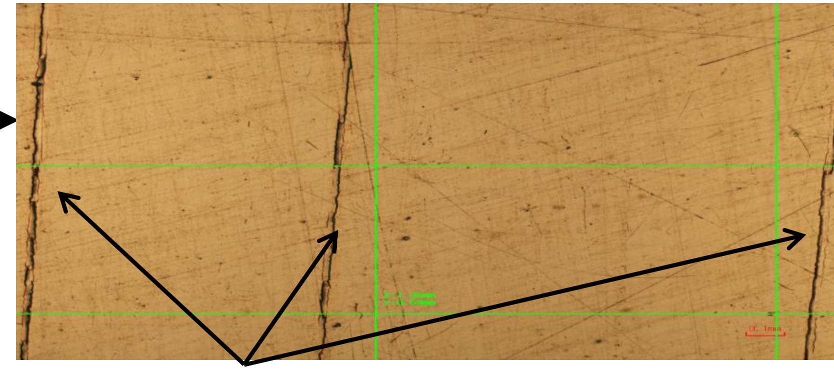
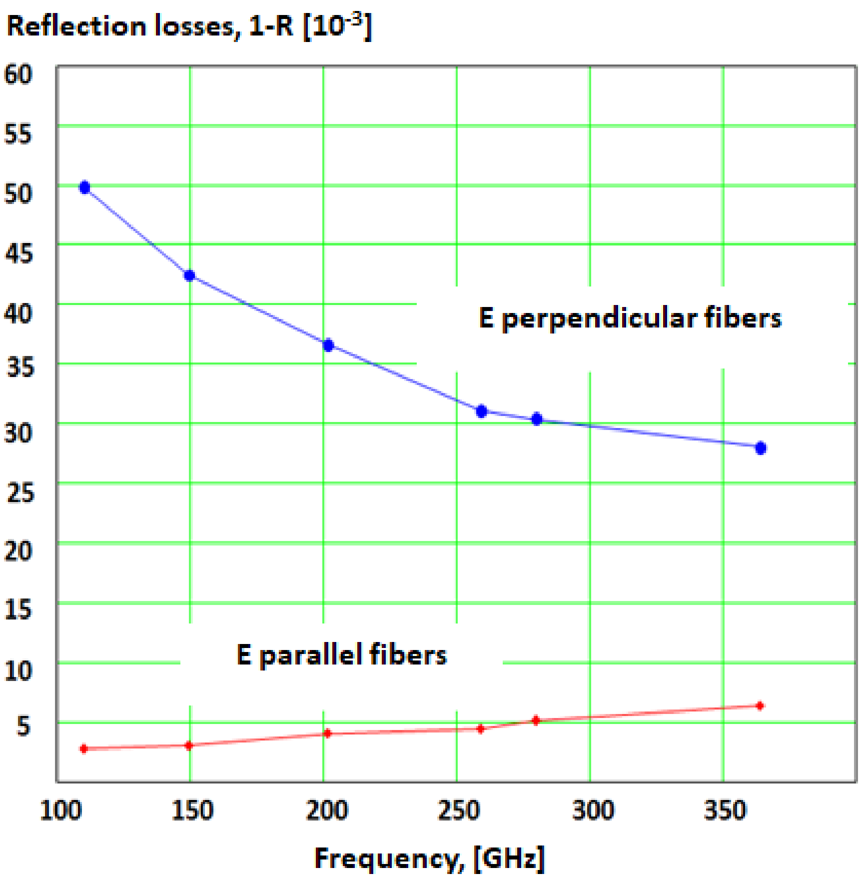


Photo of coated surface

3 cycles
of cooling up to 5 K



Microcracks on the surface



Microcracking is one of the negative CFRP properties (the nature of this phenomenon is quite wide).
It does not interfere with CFRP strength, but leads on the reflective surface to significant degradation of its characteristics in one of the directions.

Solved
(by introducing a specific technological operation)

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Preliminary Error Budget

Panel type / external factor [RMS]	Panel 1 (central)	Panel 2 (internal)	Panel 3 (middle)	Panel 4 (external)
Requirements	3.0	5.0	7.0	8.0
Manufacturing				
Mold	1.0	1.0	1.0	1.0
Replication (MSF error)	1.0	1.0	1.0	1.0
Outgasing and coating	0.1	0.1	0.1	0.1
Residual after focus correction	0.2	0.9	1.1	1.5
Relaxation of internal stresses during storage	0.1	0.3	0.4	0.4
Thermal distortions	2.6	4.0	4.2	4.1
Moisture distortions	0.1	0.2	0.2	0.2
Total	3.0	4.4	4.6	4.6
Reserve	0.0	0.6	2.4	3.4

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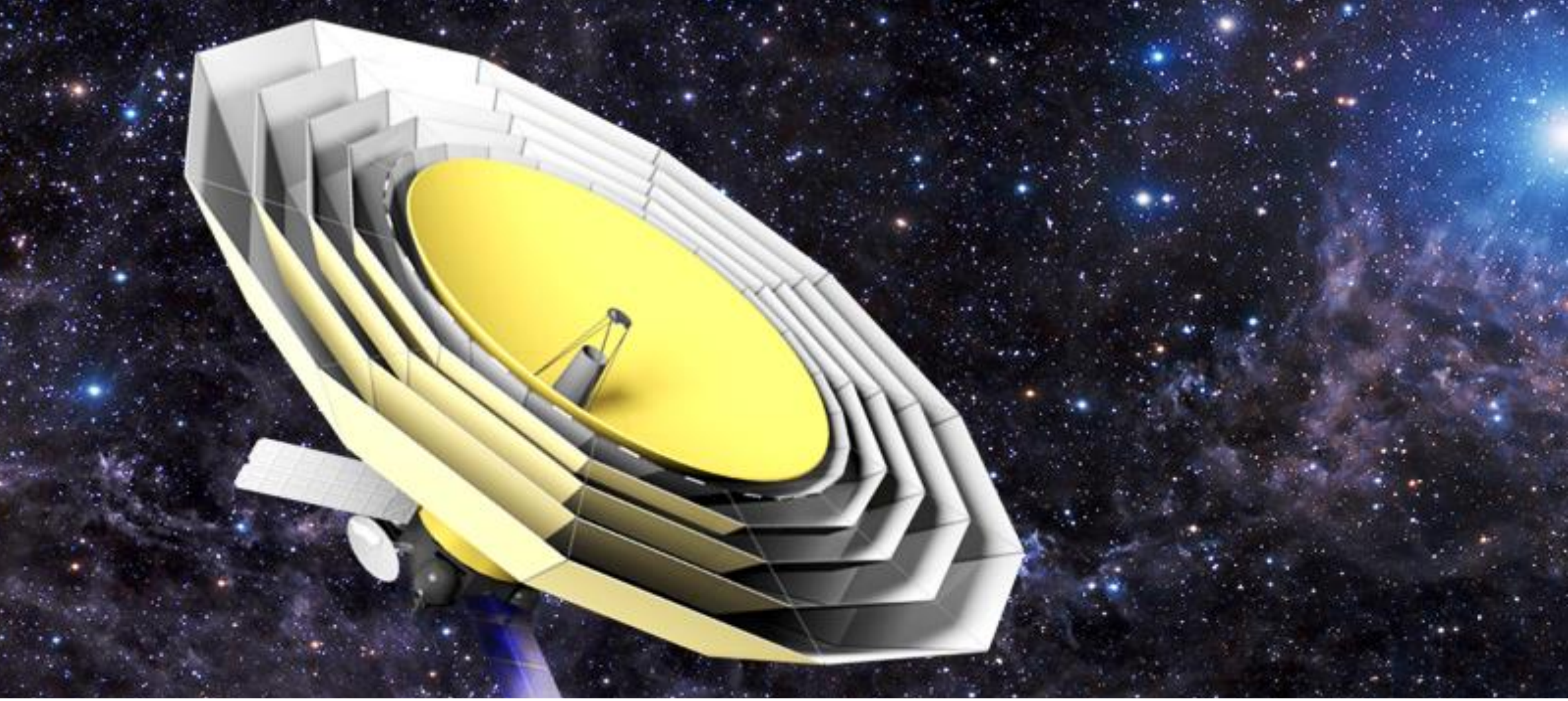
Conclusion

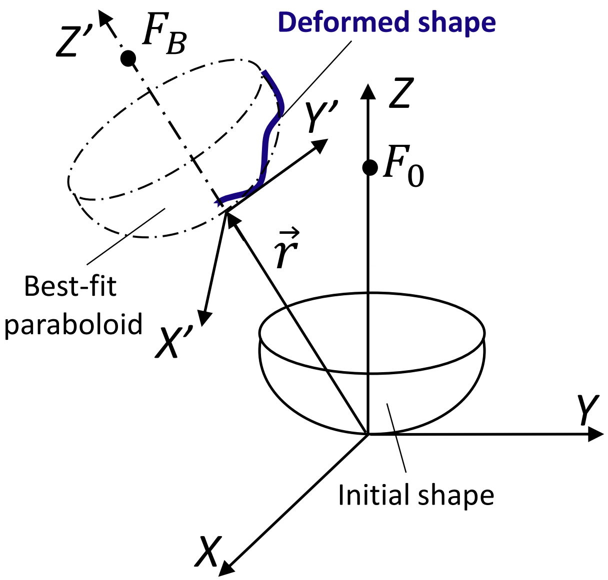
1. Lightweight design of the panels that meets all technical requirements is worked out. The panels possess the record for space solid mirrors areal density (< 8.5 kg/m^2).
2. The manufacturing technique, including technology of the panel curvature correction, allows to achieve surface accuracy about 1 µm / 1m.
3. Technology of the panel curvature correction mitigating spring-back effect is developed.
4. The quality of coating on the panel meets requirements.
5. The problem of microcracking on the reflecting surface is solved.
6. All technological issues, which we faced during panels development, have been solved.
7. Achieved results allow to move forward to the next steps - measurement of thermal distortions at 4K with accuracy ≈1 µm.



Thank you for your attention

Postprocessing of finite element analyses results

Best-fit paraboloid method:



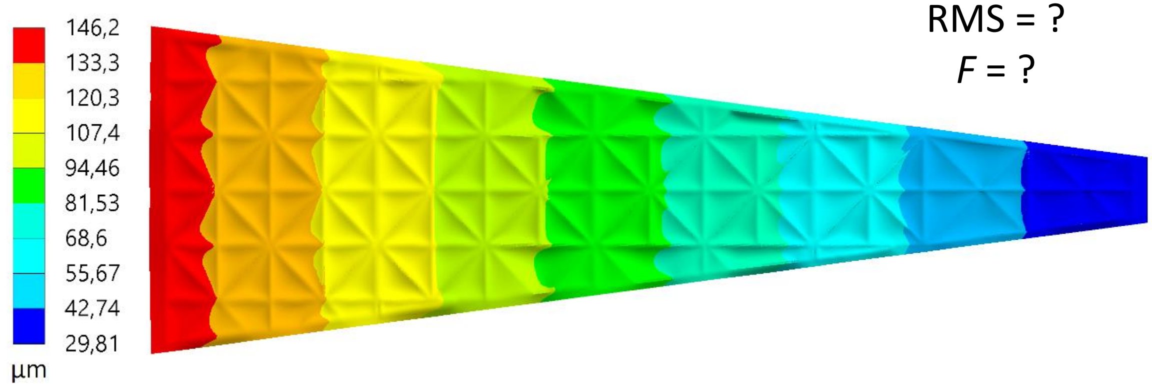
$$RMS \rightarrow min$$

$$\underbrace{F_B\,,\quad \vec{r} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix},\ \theta = \begin{bmatrix} RX \\ RY \\ RZ \end{bmatrix}}_{?}$$

Before postprocessing:

RMS = ?

F = ?

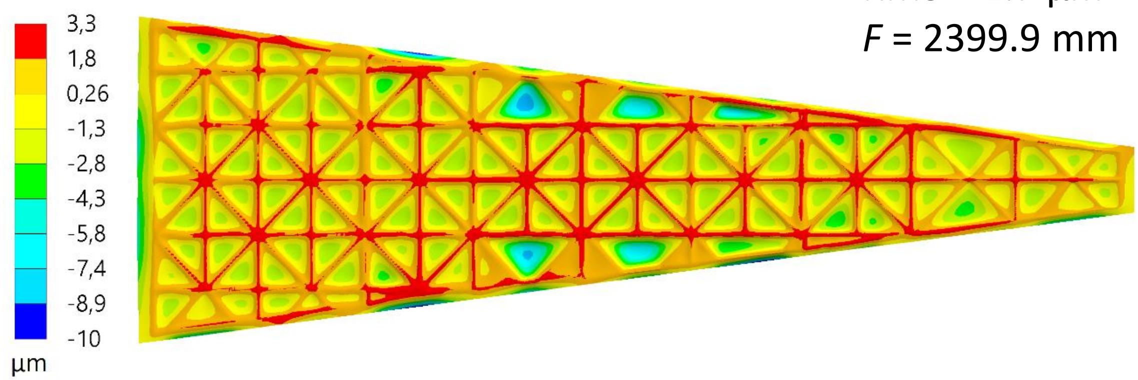


Surface deformation map after cooling down to operational temperature (4.5 K)

After postprocessing:

RMS = 1.7 µm

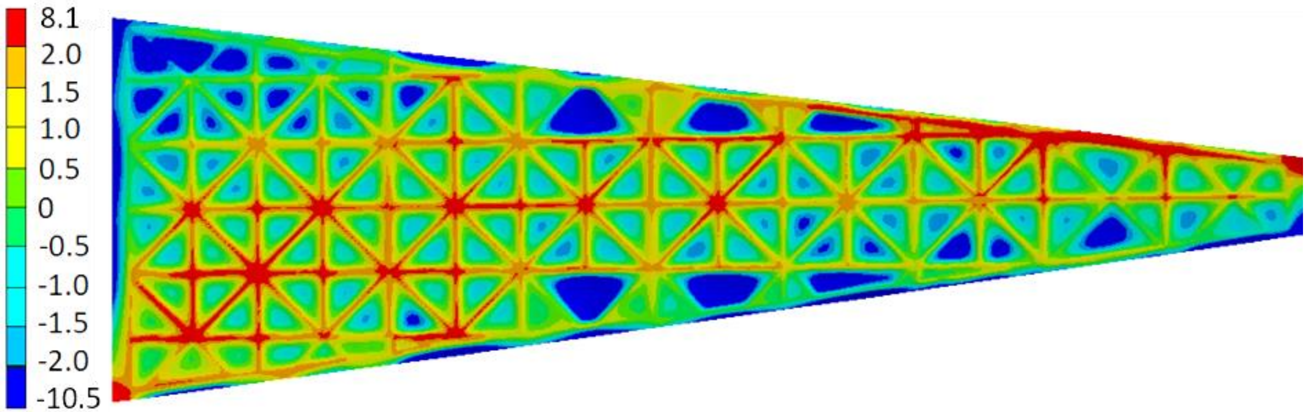
F = 2399.9 mm



Surface deformation map related to the best-fit paraboloid after cooling down to operational temperature (4.5 K)

Panel’s sensitivity to the ply alignment error

If ply alignment error were $\delta\varphi$ = 1°:

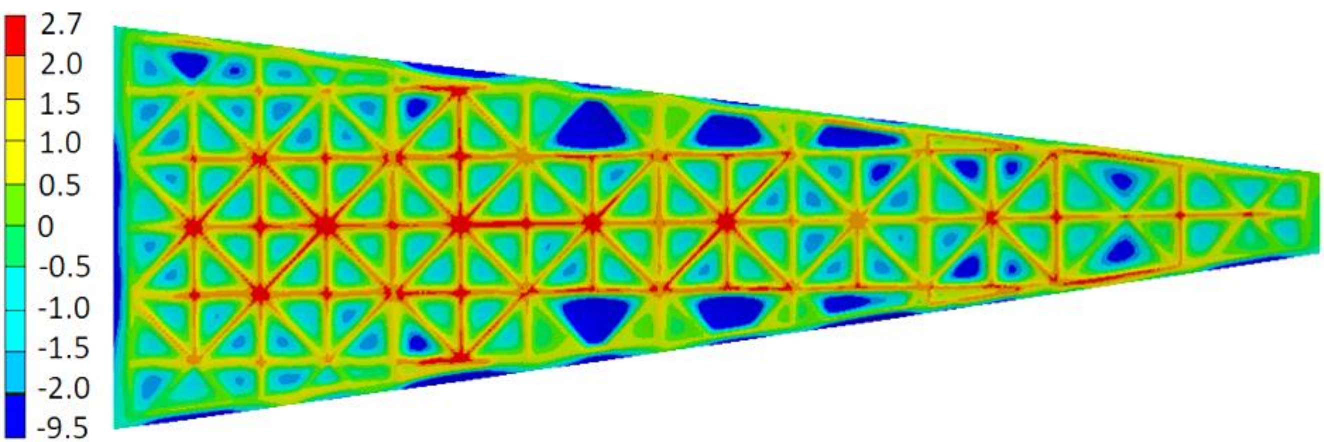


μm

Surface deformation map related to the best-fit paraboloid

RMS = 1.9 μm
F = 2399.1 mm

Actual ply alignment error is $\delta\varphi$ = 0.011° (due to advanced manufacturing technique):



μm

Surface deformation map related to the best-fit paraboloid

RMS = 1.7 μm
F = 2399.1 mm

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Panel performance in dependence on mechanical ply properties

(Податливость)