FZU
Institute of Physics of the
Czech Academy of Sciences

Palacký University
Olomouc

Optical Systems for astro particle experiments: Research and Development at JLO

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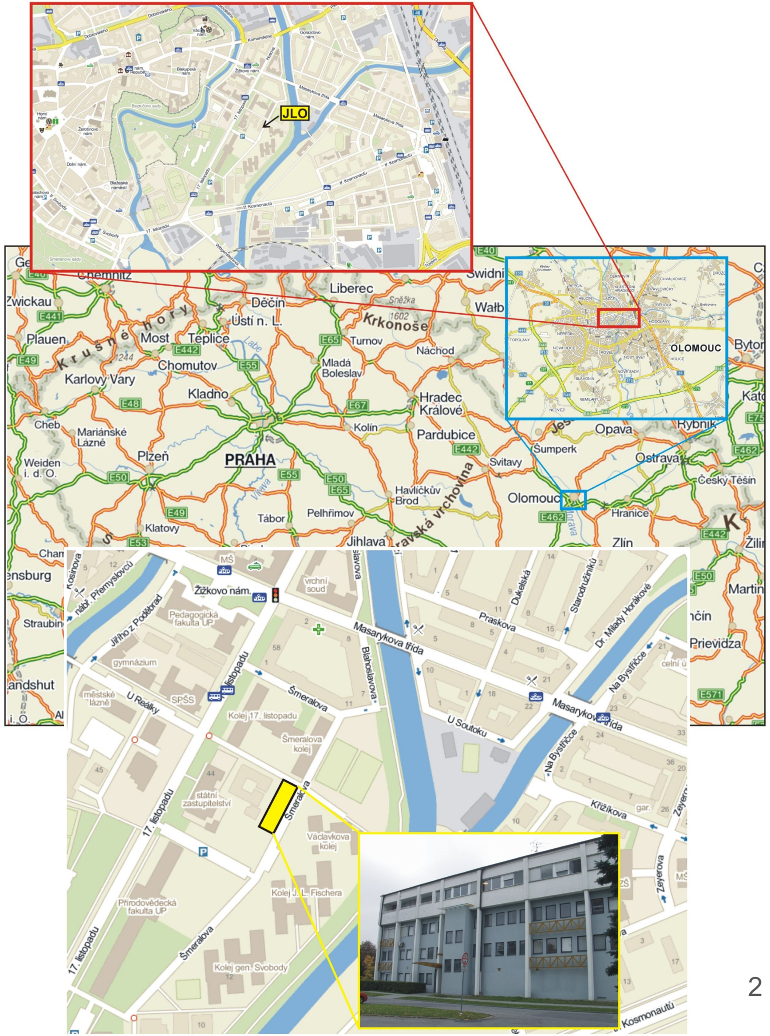
Joint Laboratory of Optics (JLO)

A shared workplace of Palacký University in Olomouc and Institute of Physics of the Czech Academy of Sciences.

The basis of the activities of the Joint Laboratory of Optics (JLO) is performing scientific research in the areas of

- quantum and nonlinear optics,
- laser and optical technologies,
- technologies and nanotechnologies of optical layers and surfaces,
- experimental particle and astroparticle physics,
- wave and statistical optics.

Number of employees: ~70



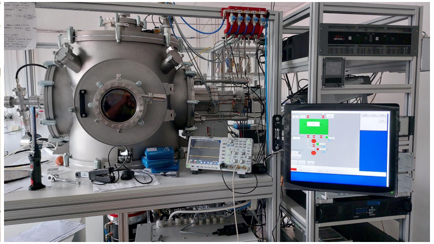
Activities of the JLO department

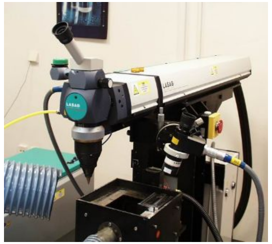
Main activities

- Applied optics – speckle, holography, metrology
- Experimental particle physics – optics for astrophysics and particle physics
- Quantum and nonlinear optics

Support activities

- Laser processing of metal and non-metal materials, mechanical properties using nanoindentation
- Construction of mechanical parts in the mechanical workshop
- Design and construction of optical elements including general surfaces (CNC machine)
- Deposition of optical thin layers by means of PVD technique – evaporation, sputtering
- Design and construction of digital and analog (low current) electronic modules



Formation of Optical Surfaces

Aspheric surfaces (subaperture technology)

- Subaperture grinding & polishing for optics up to 1m
- Low UV scattering, spherical & aspherical shapes
- Process optimization via advanced metrology
- Equipment - CNC machines, interferometer (ZYGO), scatterometer (CASI), profilometer (Taylor-Hobson), spectrophotometer, CCD camera

CNC grinding tool IRP800G
https://youtu.be/Zua8AwhtzTE

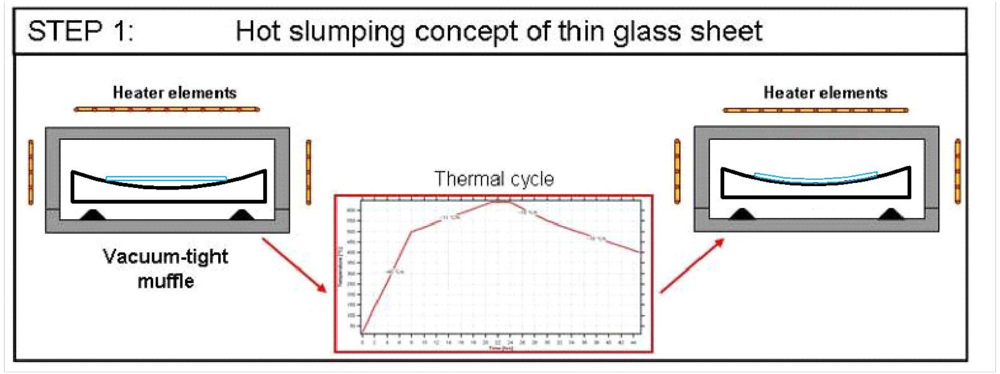
CNC polishing tool IRP800G
https://youtu.be/1C9uG8HYJDw

CNN shape measurement tool
https://www.youtube.com/shorts/jdzM3eVmrkg

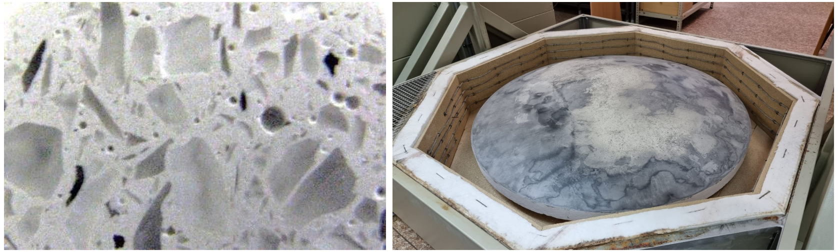
Formation of Optical Surfaces

Optical surfaces by gravitational slumping

- Hot glass slumping for 1m class optics
- Cost–quality optimization for large series (e.g., FAST telescopes)
- Equipment - slumping chamber, interferometer (ZYGO), scatterometer (CASI), profilometer (Taylor-Hobson), spectrophotometer, CCD camera



Hot slumping chamber



Ceramics mould KS98F – 98% SiO_2

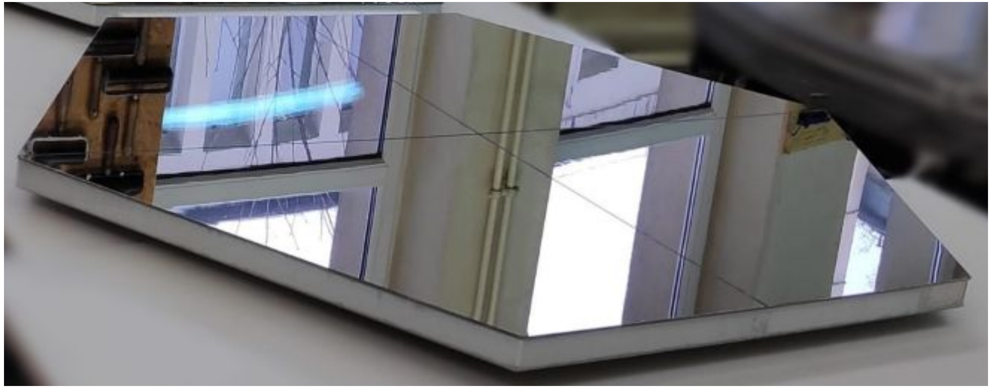
Sandwich back-reflective mirrors

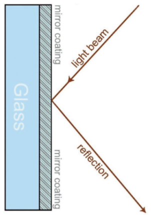
Current development of optical mirrors almost exclusively uses glass substrates and reflective layers on the optical surface of the substrate.

Ideal optical quality x layers susceptible to mechanical wear for harsh outdoor environments.

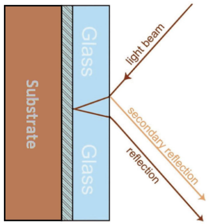
Application of mirrors in telescopes for astroparticle projects, stratosphere, space

- high demands on mechanical resistance (stability of optical parameters).

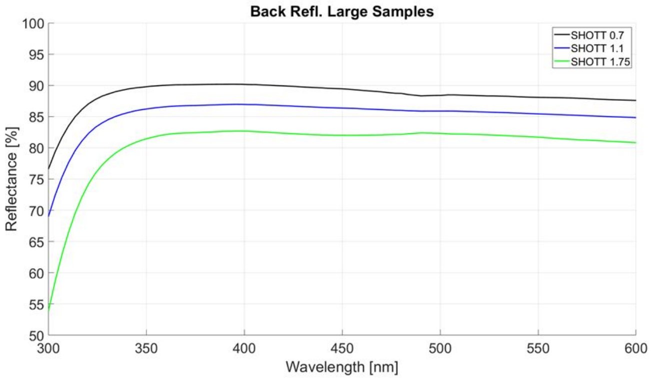




Front-reflective mirror



Back-reflective mirror



Composite mirrors: composite materials + glass matrix

This involves combining additively added metals (3D printing) with other inorganic materials, primarily glass.

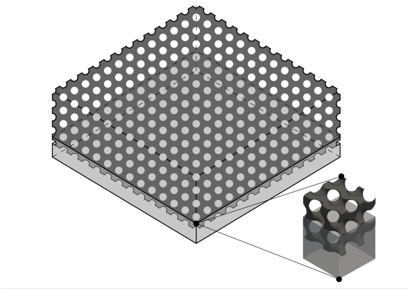
The glass surface can be machined to optical quality.

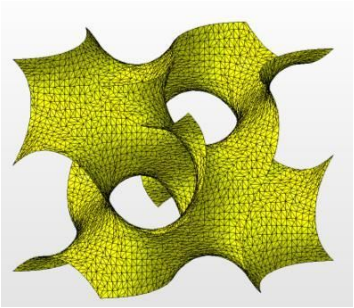
The resulting mechanical properties of stiffness, strength, and toughness are higher than when using the materials separately.

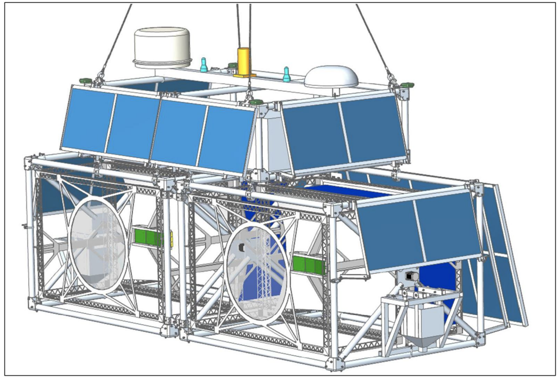
Very light mirrors of any size, where their weight is minimized while maintaining other parameters - gyroid structures.

Applications in space projects and in applications where the mechanical stability and weight of the optical element are important.

Substrate for rear reflective elements.





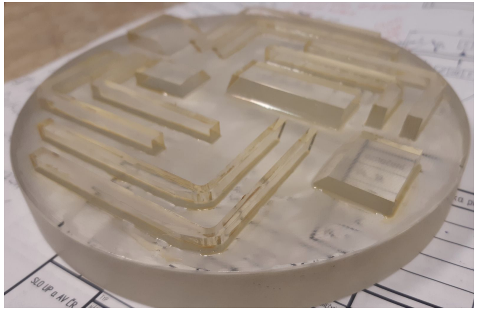


The EUSO-SPB2 payload design including gondola structure shown in a preliminary configuration including telescopes, solar panels, antennas, and ballast hoppers.

Time-of-Flight detector - optical part + electronics

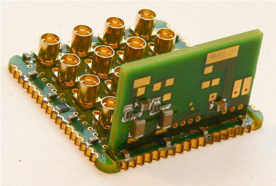
Optical part

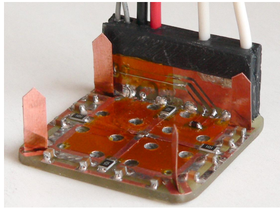
- Fully designed and produced in our optical and mechanical workshop and department of thin layers.
- Each bar in a set has its own unique geometry of an L-shape – difficult to product (grinding, polishing).
- Other optical parts were designed and produced,
  - separation windows with antireflex, radiators for auxiliar detectors.

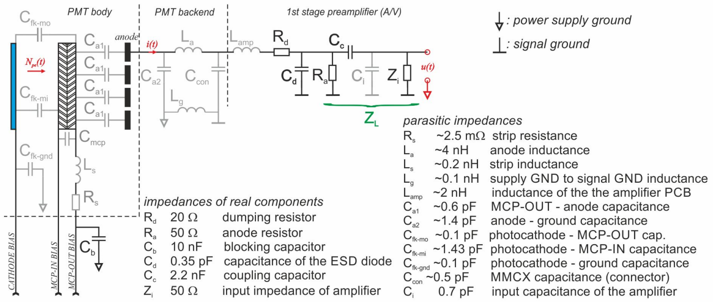


Electronics

- Design and production of amplifiers – NIM modules of eight-channels amplifiers, inline pre-amplifiers.
- PMT backend electronics (in cooperation with Photonis Inc.).







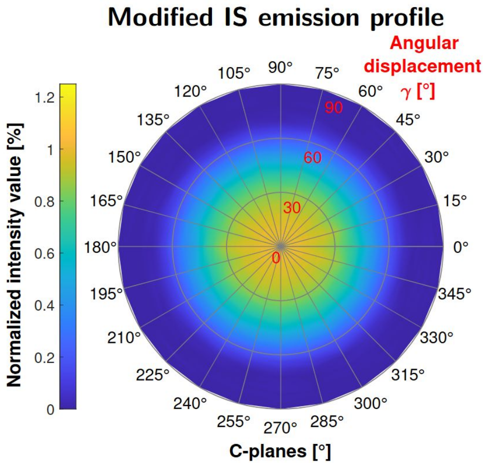
Absolute end-to-end calibration of Auger FD telescopes

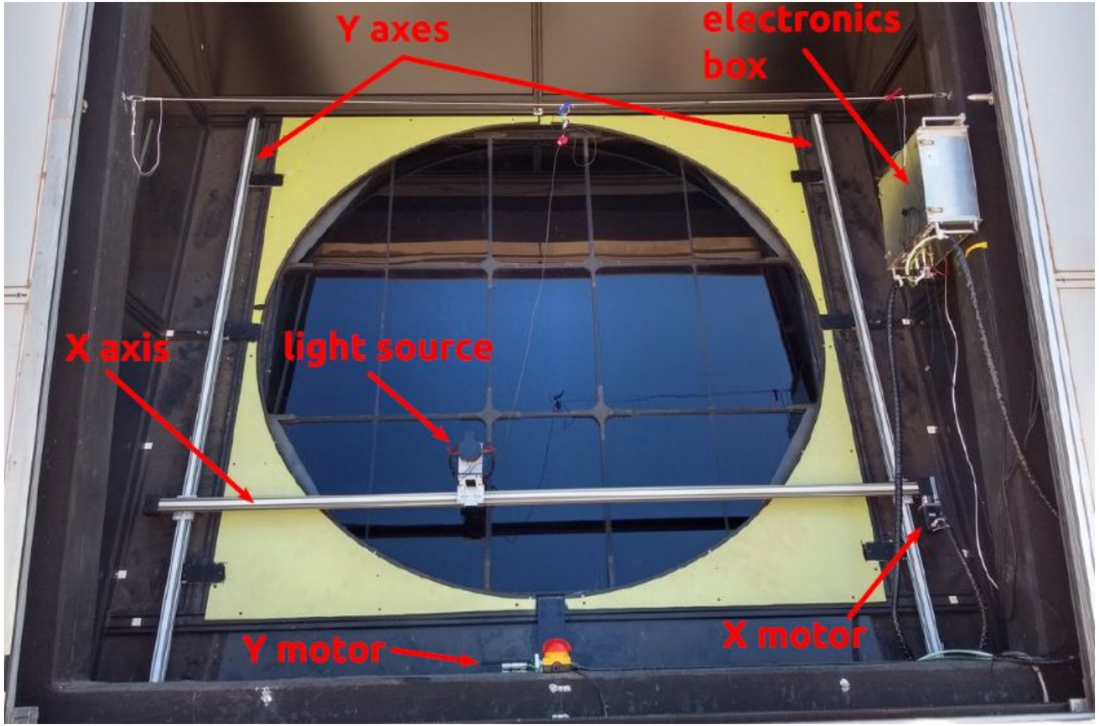
Light source of a small size

Scanning of the aperture

Integrating over all positions

Nearly Lambertian emission profile
of the light source - integrating sphere



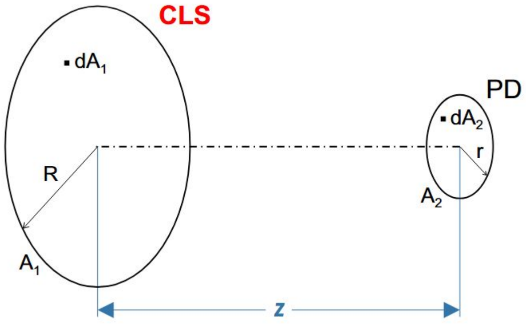


Absolute calibration of Lambertian light sources

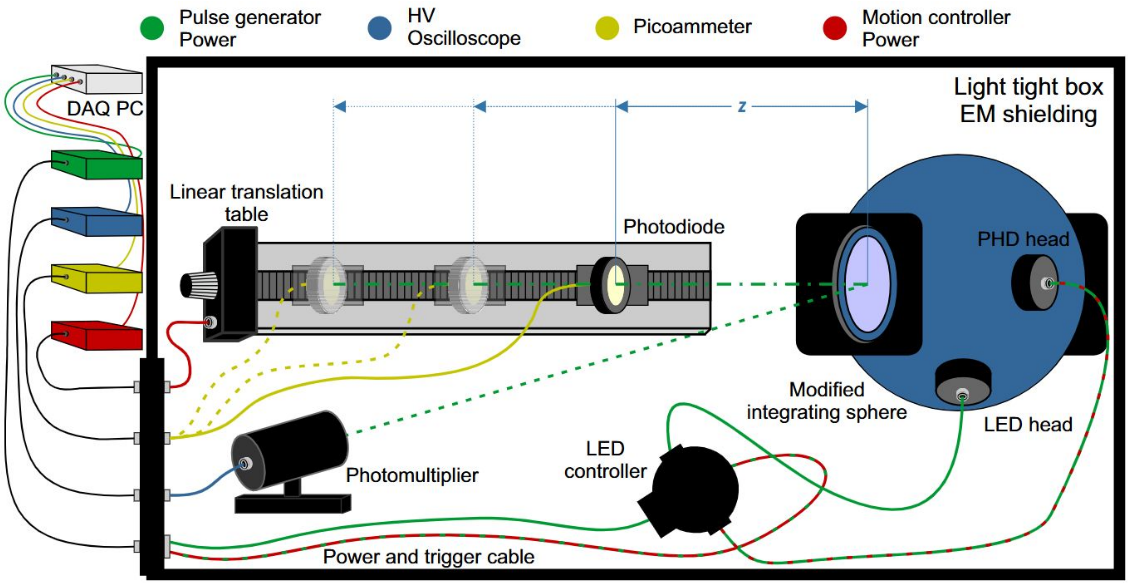
To determine the number of photons leaving the light source.

Based on the theory of radiative heat transfer.

Numerical calculation of formula known as a view factor.



$$F_{12} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos\phi \cos\theta}{\pi z^2} dA_2 dA_1$$



- Linear stage (540 mm range)
- Calibrated photodiode
- Total uncertainty within ~3 %
- PMT for 100 Hz/1 Hz conversion
- Pulse length – 5 μs
- LED current – 15.9 mA

Optics for astrophysics and particle physics

Design and construction of primary mirrors

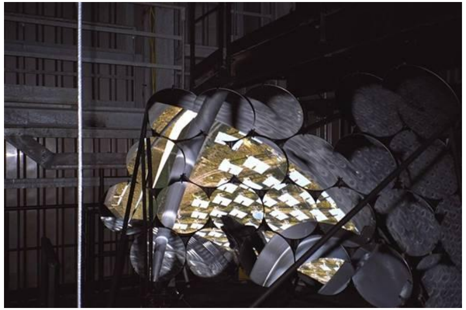
- Pierre Auger Observatory (PAO),
- Cherenkov Array at Thémis (CAT),
- Cherenkov Low Energy Sampling and Timing Experiment (Celeste),
- Single-mirror Small-sized Telescope (SST-1M),
- Fluorescence detector Array of Single-pixel Telescopes (FAST).

R&D of back-coated mirrors

- Cherenkov Telescope Array (CTA)

Mirror segments

- CBM/RICH detector



Involvement in selected projects

Large-sized Telescope (LST) of CTA - responsible for the optical system

- Active Mirror Control (AMC) - Compensation of mirror pointing with respect to the bending of the LST structure on different elevation angles in real time.

SST-1M

- Optical Alignment and Adjustment.
- Optical Simulation, Optimization, and Supporting Systems.
- Measurement and Calibration.

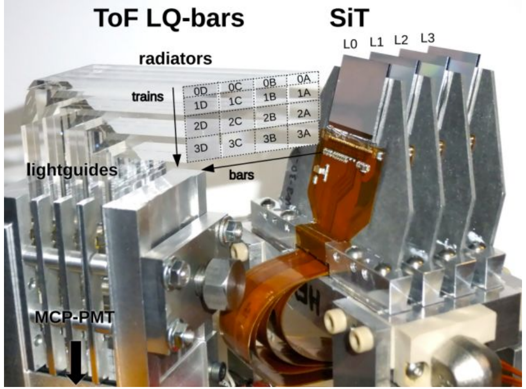
Auger

- Optical design of FD telescopes.
- Atmospheric monitoring: All-sky cameras to monitor cloud cover.
- Absolute end-to-end calibration of Auger FD telescopes.

The ATLAS Forward Proton (AFP)

- Full design and production.
- Measurement of protons diffractively deflected in collisions in ATLAS IP (direction, time of flight).

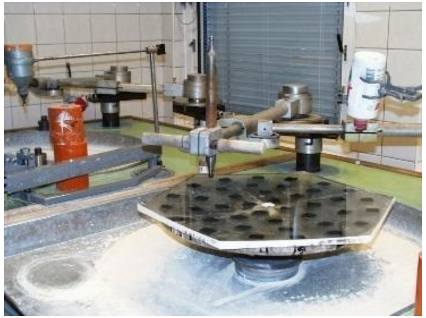
LST-1



AFP

Optics production facilities at JLO

Classical optical workshop, spherical optics up to 620mm in diameter.



Development of new CNC technology for manufacturing of sphere, sphere and freeform optics up to 1,2m in diameter. Grinding, polishing machine and measuring system for error correcting machine feedback.

Vacuum chamber – deposition facility for deposition of thin layers (Al, SiO_2, TiO_2 , HfO_2, MgF_2).

New method for chemical removing of the mirror layers without influence on mirror substrate.

Measurement facilities at JLO

SwingArm profilometer – large optics surface measurement.

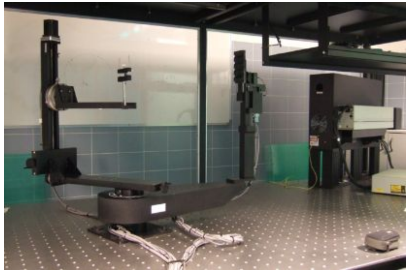
CASI – precise scatterometer of optical elements, scatter reflected light component, roughness measurement up to 1 nm.

Nanoindenter – Thin films mechanical testing, indentation and scratch test.

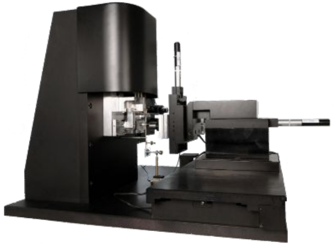
Digital interferometer Zygo Verifire – Fizeau type interferometer, 3D shape and waviness contactless measurement, for interoperational or final inspections.
1 - main interferometric unit, 2 - phase shifting unit, 3 - reference optic, 4 - five axis holder with sample, 5 - anti-vibration table

Taylor Hobson PGI Optics profilometer – contact 2D and 3D profilometer, shape, waviness and roughness measurement.
1 - sliding unit on vertical column, 2 - sensor, 3 - stylus, 4 - granite base, 5 - cross table, 6 - sample table with fine manual shifting and tilting

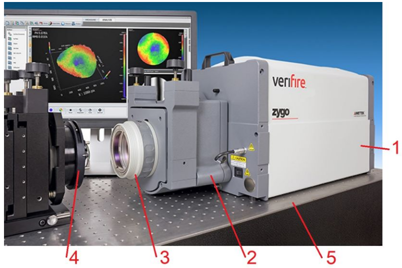
SwingArm profilometer



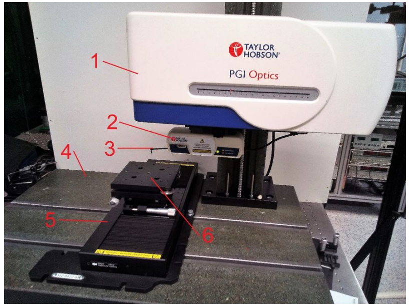
CASI



Nanoindenter



Digital interferometer



Taylor Hobson PGI Optics profilometer

Fluorescence detector Array of Single-pixel Telescopes

Low-cost next-generation fluorescence telescope array

- unified technology on both Earth hemispheres,
- target $E > 10^{19.5}$ eV, ultrahigh-energy cosmic rays.

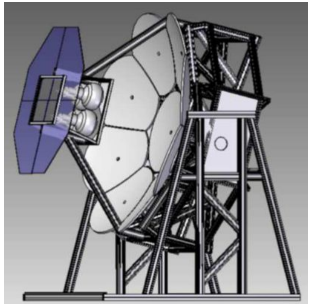
Prototypes installed

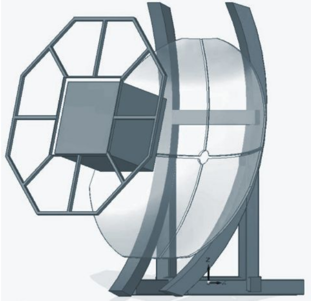
- 3 telescopes at BRM, TA, Utah,
- 2 telescopes (1 in operation) at LL, PAO, Argentina.

Second generation for FAST mini array

- mirrors: 9 → 4 segments, hot slumping
- new enclosure to easier maintenance and transport
- fully autonomous - solar system, sensors, electronics

Being considered as a potential part of the Global Cosmic Ray Observatory (GCOS).





Summary

Expertise

- JLO develops and manufactures advanced optical systems for astrophysical and particle experiments.

Unique technologies

- CNC machining, hot slumping, composite and sandwich mirrors, thin films, and precision metrology.

Applications

- Direct involvement in major international projects (CTA, Auger, FAST, AFP, ATLAS).

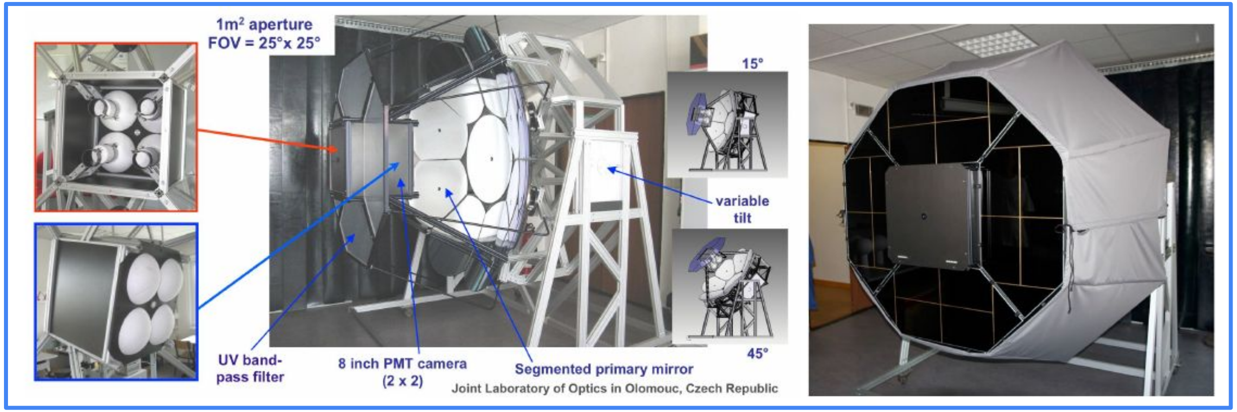
Impact

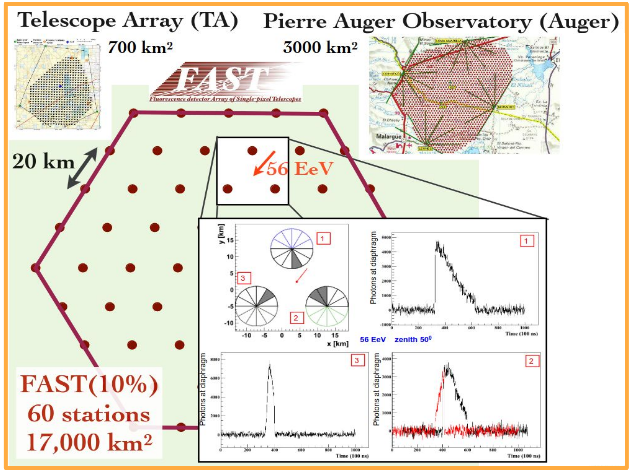
- We contribute to the development of next-generation detectors for observing cosmic phenomena and high-energy experiments.

Future work

- Further optimization of manufacturing processes, new materials, collaboration in international projects.

backup


1m² aperture
FOV = 25°x 25°
15°
variable tilt
45°
UV band-pass filter
8 inch PMT camera (2 x 2)
Segmented primary mirror
Joint Laboratory of Optics in Olomouc, Czech Republic


Telescope Array (TA)
Pierre Auger Observatory (Auger)
700 km²
3000 km²
FAST
Fluorescence detector Array of Single-pixel Telescopes
20 km
56 EeV
56 EeV zenith 50°
FAST(10%)
60 stations
17,000 km²

Large Sized Telescope - LST

- LST-1 operational since 2018
- LST-2, LST-3, and LST-4 under installation
  - Mirror installation finished on September 2025
- **LST parameters:**
  - 23-meter diameter parabolic reflective surface
  - Reflective surface of 400 square meters
  - Structure is 45 meters tall, weighs around 100 tonnes
  - Ability to re-position anywhere within 20 seconds
  - Camera comprises of 1855 photomultiplier tubes
  - LST array will cover gamma-ray from 20 to 150 GeV

- **Olomouc team is responsible for the optical system of LST:**
  - Mirrors
  - AMC - Active Mirror Control
    - Compensation of mirror pointing with respect to the bending of the LST structure on different elevation angles in real time

Simplifying of the mirror production chain

Current production chain:

1) Glass sheets
2) Wather conture cutting
3) Hot slumping
4) Glueing + grinding
5) Polishing + unglueing
6) Mirror substrate cleaning
7) Al-SiO2 deposition

\+

- Very precise and proven technology
- Easy to correct scratches with polishing (grinding)

\-

- Polishing and grinding is most time consuming processes
- Grinding/polishing processes is critical for sharp (0-90deg) contur angles
- Mirror production time and surface quality strongly depends on mirror diameter

Hot replication production chain:

1) Glass sheets
2) Wather conture cutting
3) Hot slumping replication

~~4) Glueing + grinding~~

~~5) Polishing + unglueing~~

3) Mirror substrate cleaning
4) Al-SiO2 deposition

\+

- We can skip polishing and grinding
- No limit for contur
- Production time, surface shape quality is almost independent on surface diameter
- Deposition errors correction with chemical way (acid solution) possible

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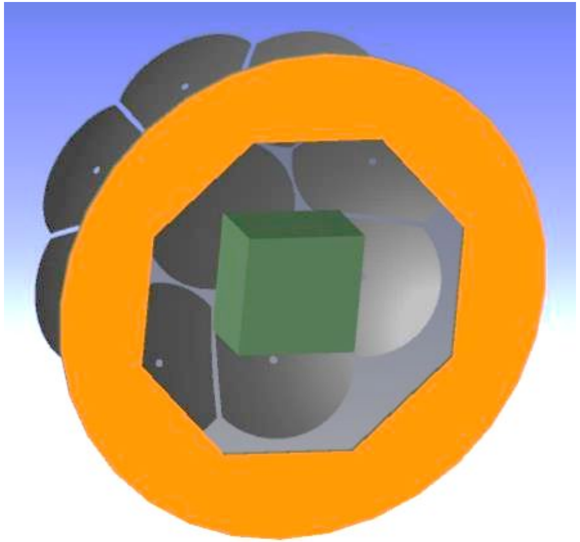
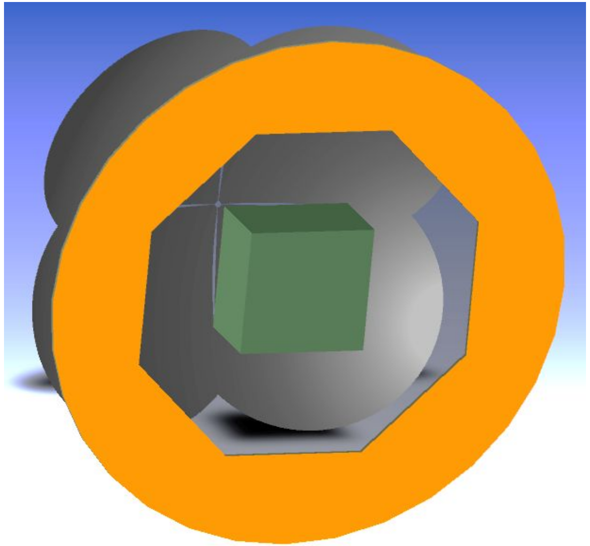
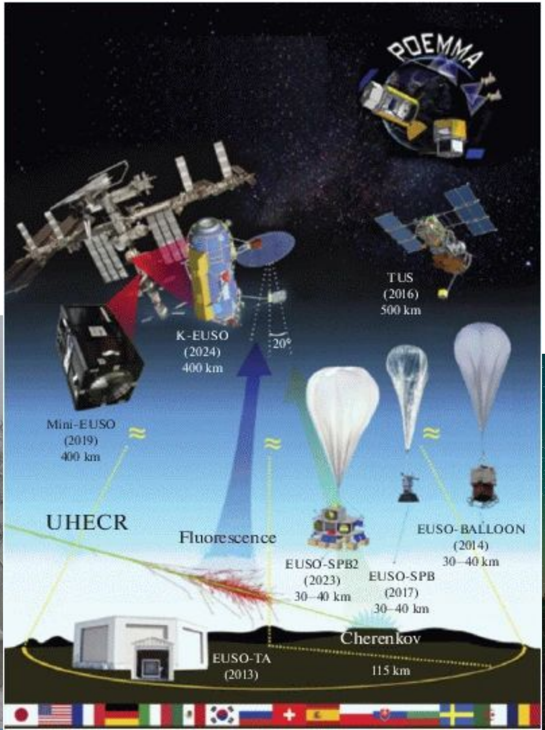
- Difficult scratches correction
- Layer adhesion?
- Surface quality for this mirror size and spherical depth?

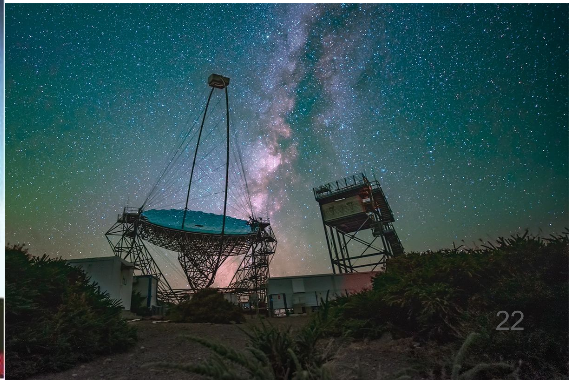




Sandwich back-reflective mirrors

Application of mirrors in telescopes for astroparticle projects, stratosphere, space -> high demands on mechanical resistance (stability of optical parameters)





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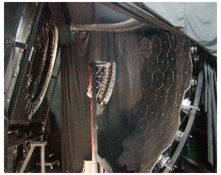
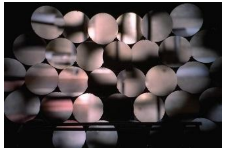
experiences in projects

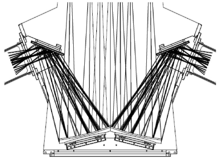
- **CAT** - **Cherenkov Array at Thémis -** 90 ultralight mirrors segments, diameter 500 mm



- **PAO - Pierre Auger observatory -** 1000 ultralight mirrors segments, diameter 600 mm



- **CELESTE - ChErenkov Low Energy Sampling and Timing Experiment -** 3 types of spherical mirrors segments total area 40 m^2



- **DIRAC in CERN DImeson Relativistic Atom Complex -** 12 extremely light glass segments, diameter 411mm

- **Lidar mirror for PAO -** 2 x segmented mirror (1m diameter)

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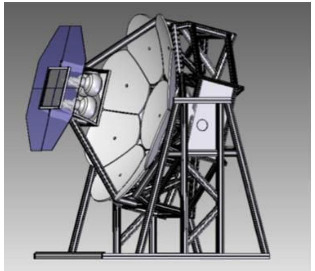
experiences in projects

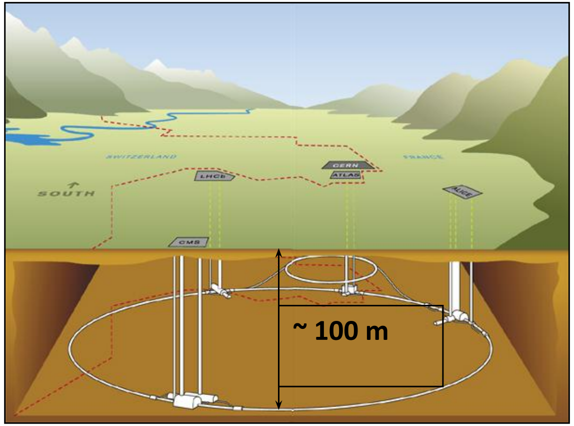
- **SST-1M 4m diameter Davies-cotton segmented mirrors**

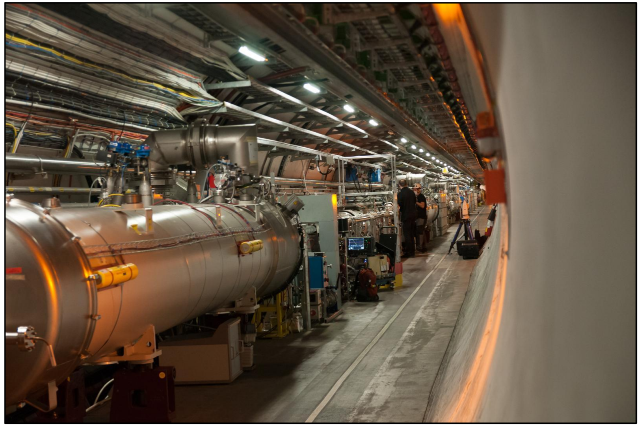


- **FAST - 7 segmented mirrors**
  - **5 - 9 segments**
  - **2 - 4 segments (hot replication technology)**

Project AFP

- Detector AFP (**A**TLAS **F**orward **P**roton), started in 2013
- International collaboration – USA, Canada, Germany, Spain, Serbia, Italy, Czech Republic (PU/JLO, CTU, CUNI, UWB)
- Installed in Large Hadron Collider (LHC) at CERN laboratories in Switzerland
- Operation at proton beams of the energy 6.8 TeV (for physics experiments at collision energies 13.6 TeV)

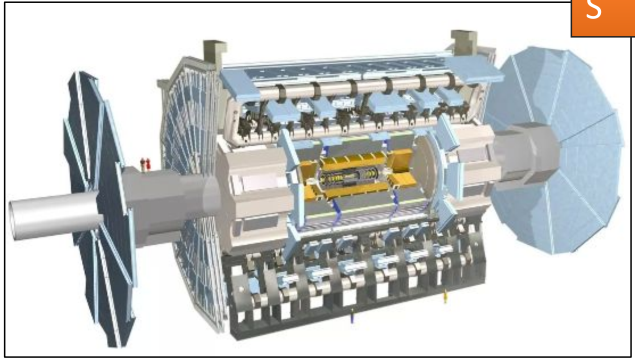


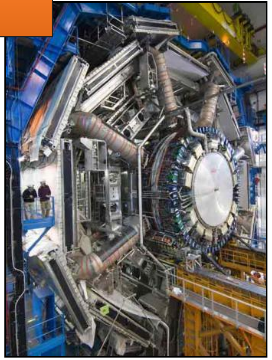


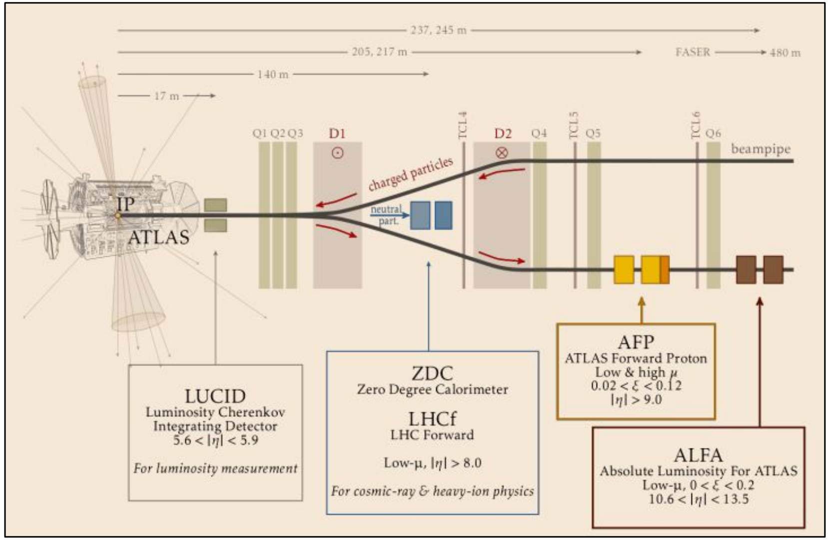
Detector AFP

- ❑ Part of the Forward Region of the detector ATLAS (a leading experiment in particle physics)
- ❑ Installed on **both** sides of the detector ATLAS at the distance of about 205 m from the ATLAS IP (Interaction Point)

ATLA
S

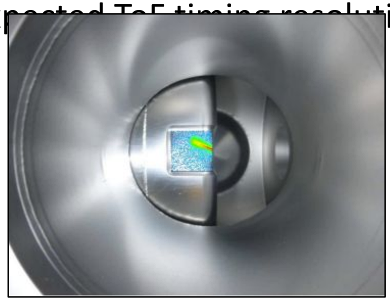


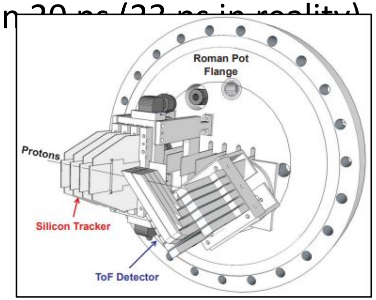


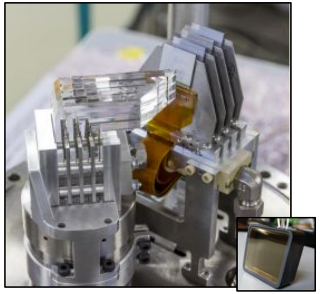


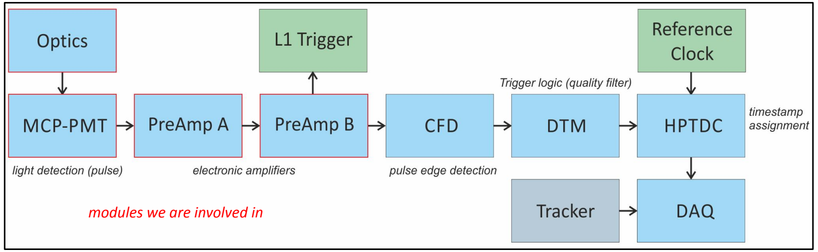
Detector AFP

- AFP detector measures protons diffractively deflected in collisions in ATLAS IP (direction, time of flight)
- It is very close to the main proton beam – just 1.5 mm from it => very high radiation (0.7 MGy at 5 mm from the beam)
- **All components must be radiation hard** (Silicon tracker and ToF)
- ToF (Time-of-Flight) detector is based on fast Cherenkov radiation generated in pure fused silica bars and detected by an MCP-PMT (microchannel photomultiplier)
- Expected ToF timing resolution 20 ps (23 ps in reality)

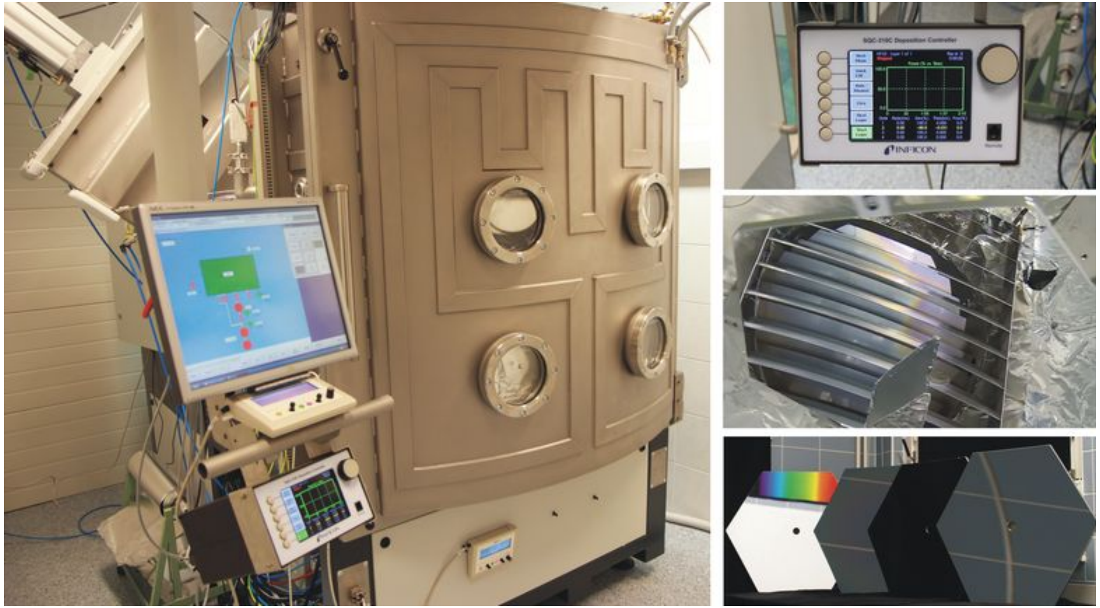


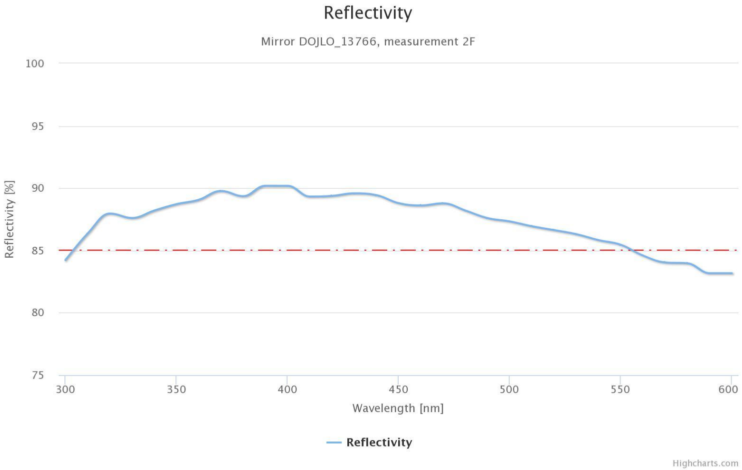






8) Coating





- Al – SiO_2 multilayer composite
- Standard reflectance > 85 % for 300 – 550 nm

We are able to characterize optical elements using parameters such as

- reflectance (hemispherical and 2F),
- transmittance,
- scattering properties,
- surface roughness,
- emission profile (in both far field and near field — the latter mainly for extended uniform light sources),
- hardness,
- elastic modulus,
- as well as absolute calibration of extended light sources.