Emissivity of Black Coatings from Ambient to Cryogenic Temperatures: How Spectrally Flat Black Coatings Can Enhance Performance of Space Systems

Tamas Rev & Dina Katsir - **Acktar Ltd.**
Tomáš Králík & Jiří Frolec – **ISI Brno**

Presented by

Dr Tamas Rev

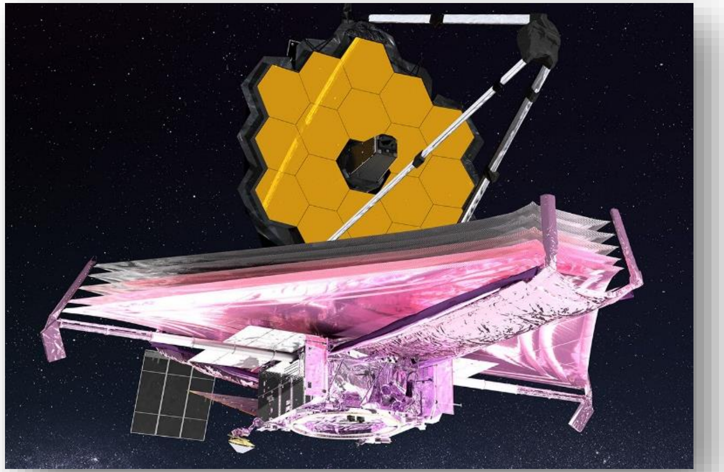
Outline

- **Introduction**
- **Acktar Space Heritage**
- **Objectives**
- **Experimental**
  - Acktar Black Coatings - Sample Design
  - Apparatus for Emissivity Measurements
  - Case Study – Black Body Reference
- **Results & Discussion**
  - Acktar Fractal Black Emissivity
  - Effective Coating Thickness
  - Supplementary cryogenic tests
- **Conclusions**

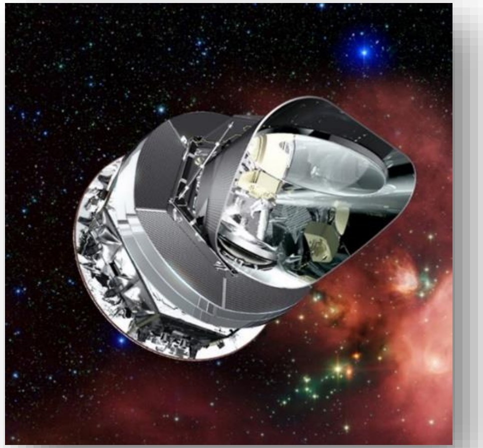
Introduction

- Thermal radiation has a significant influence on cryogenic systems, especially in vacuum environment
- In cryogenic systems, achieving high emissivity is essential to facilitate the effective removal of heat through radiation heat transfer
- Low emissivity is necessary to minimize radiation heat transfer and prevent heat leakage into the system

Credit: NASA

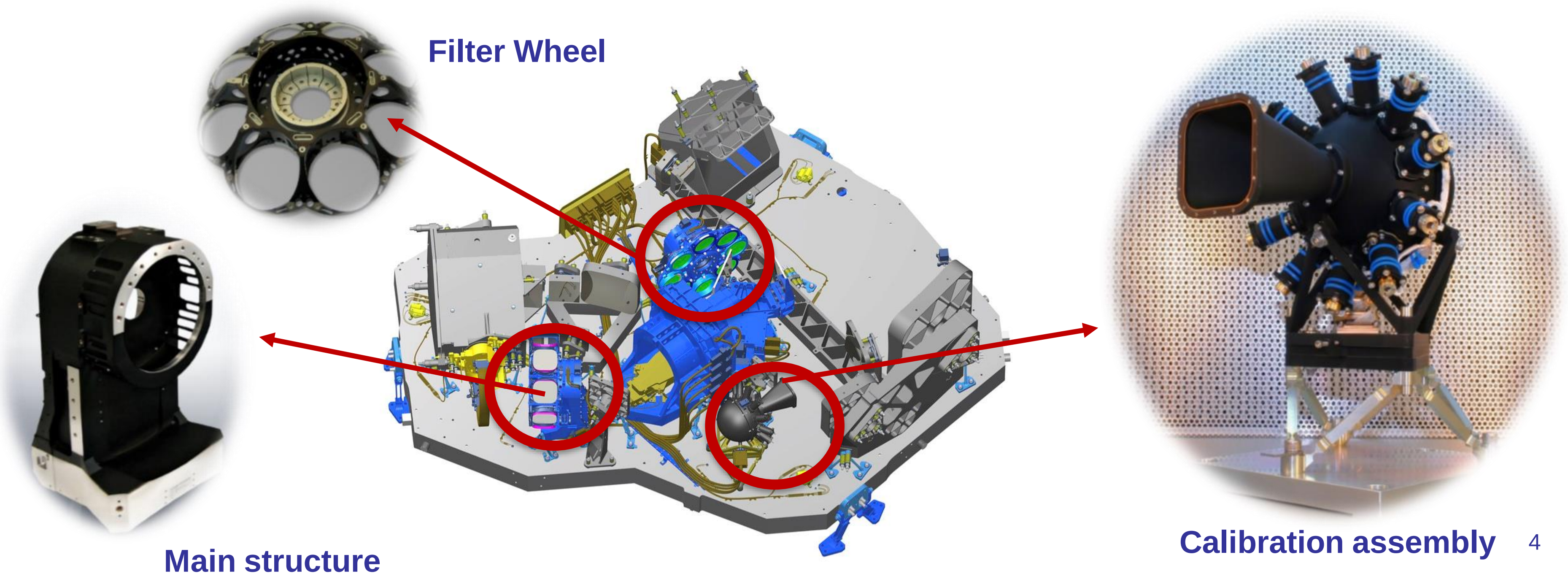


Credit: ESA



Introduction

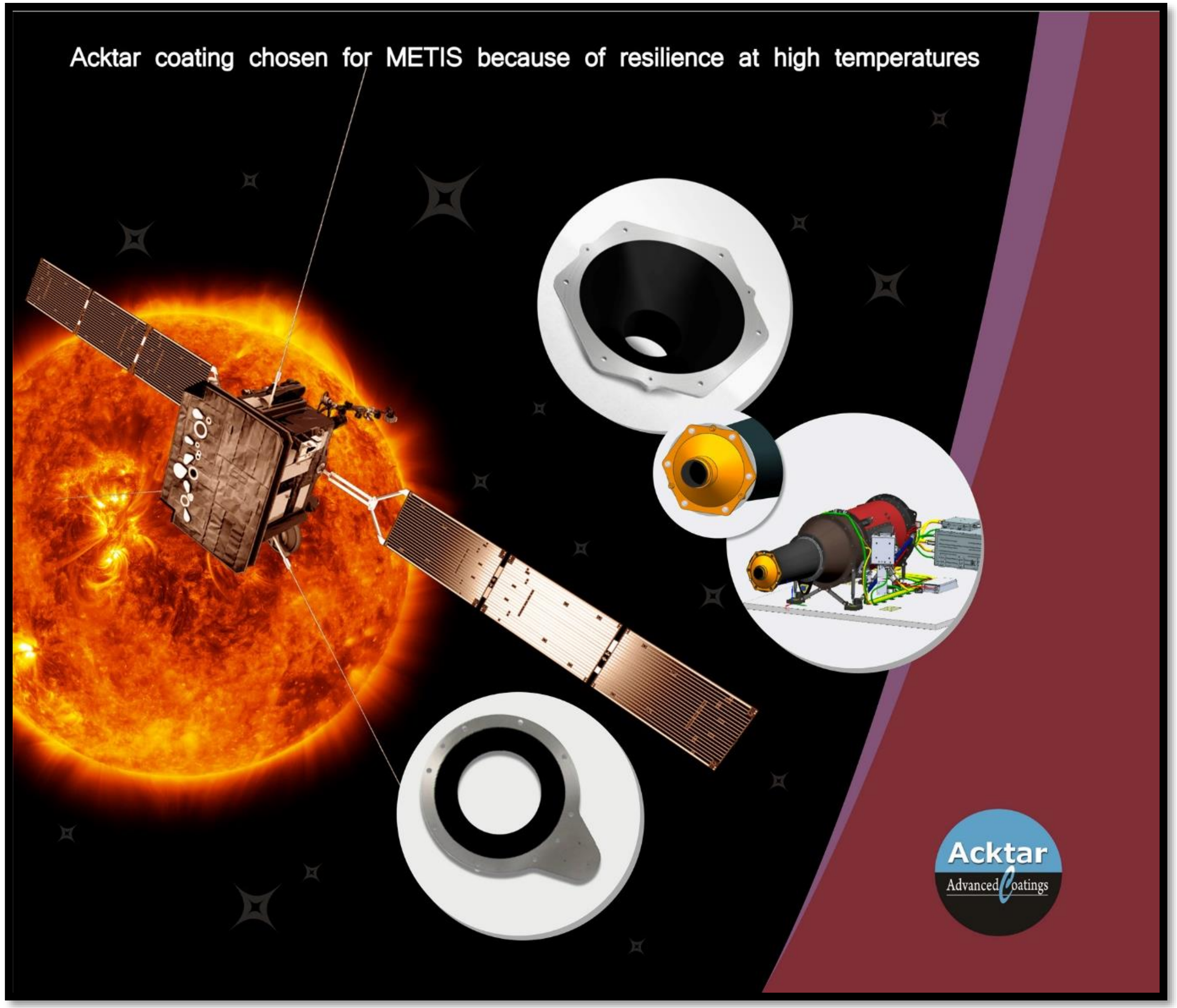
- Fractal Black is the chosen high-emissivity coating in over 30 space missions
  - More than 20,000 Fractal Black coated parts in space
  - 24 years of space heritage
  - LEO, GEO, Moon, L2, Mercury, Venus, Jupiter
  - JWST, Bepi Colombo, Solar Orbiter, Euclid, JUICE, NASA EOS, etc..



Fractal Black TM – Space Heritage

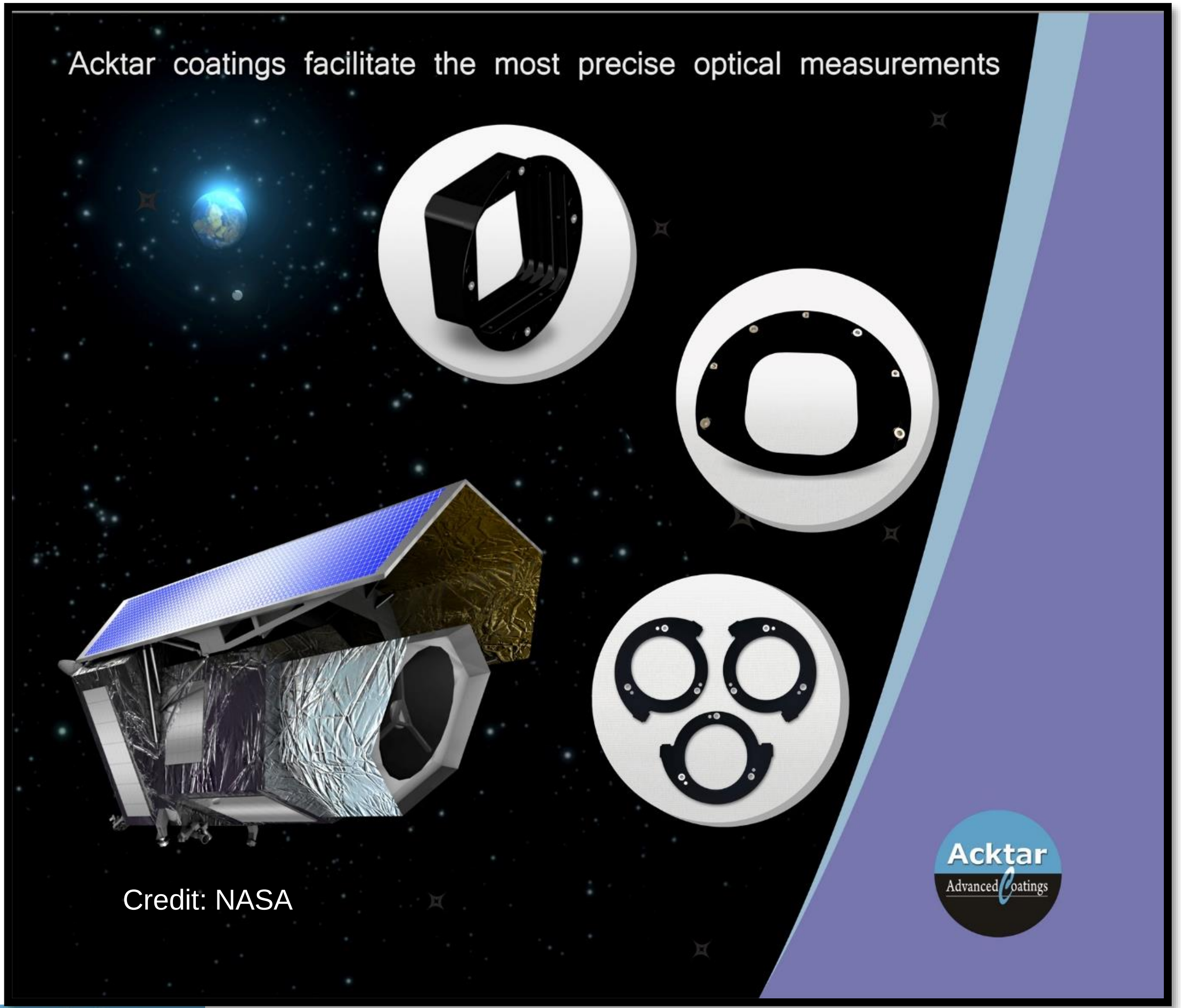
BEPI COLOMBO – A mission to Mercury

SOLAR ORBITER

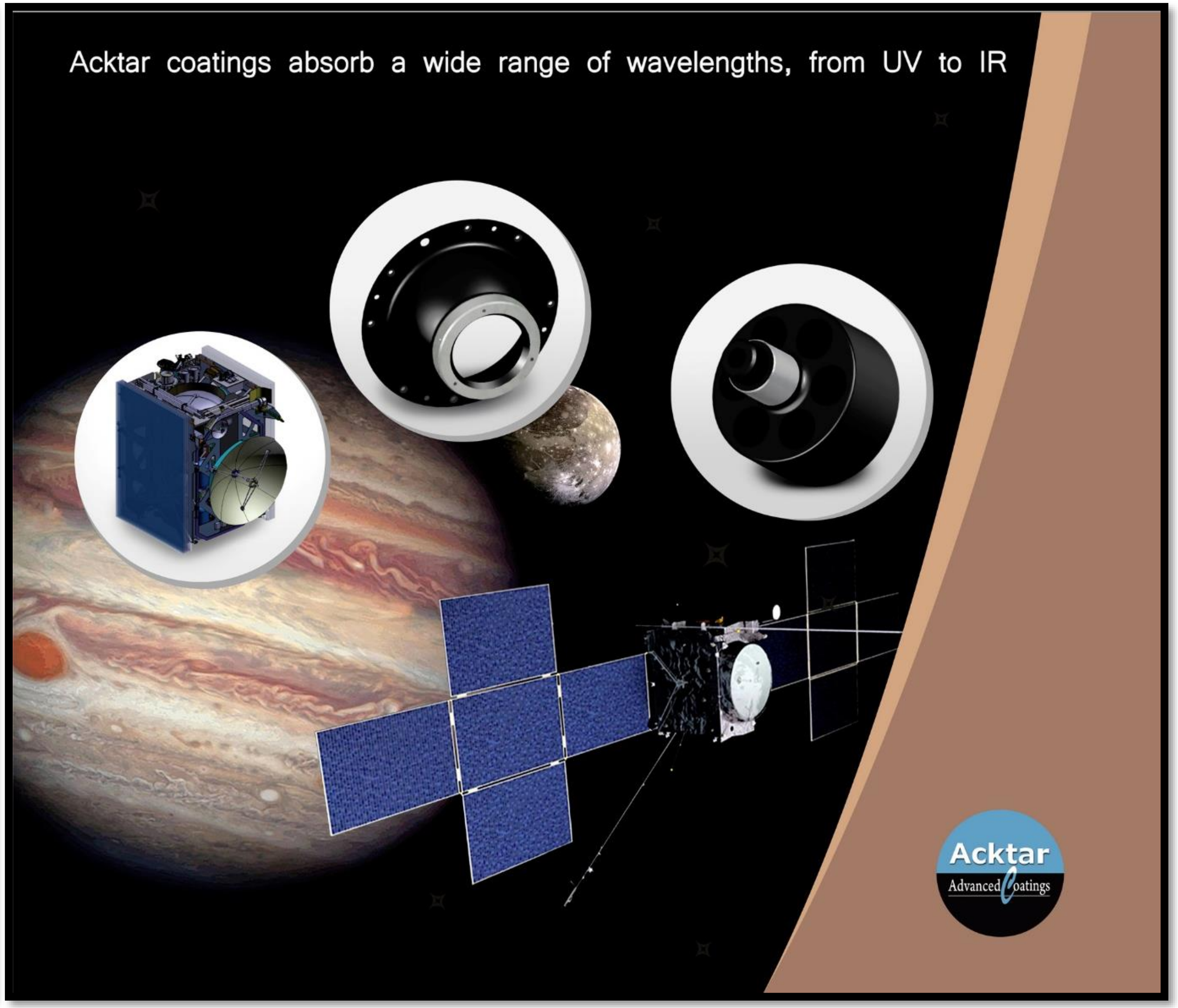


Fractal Black TM – Space Heritage

EUCLID

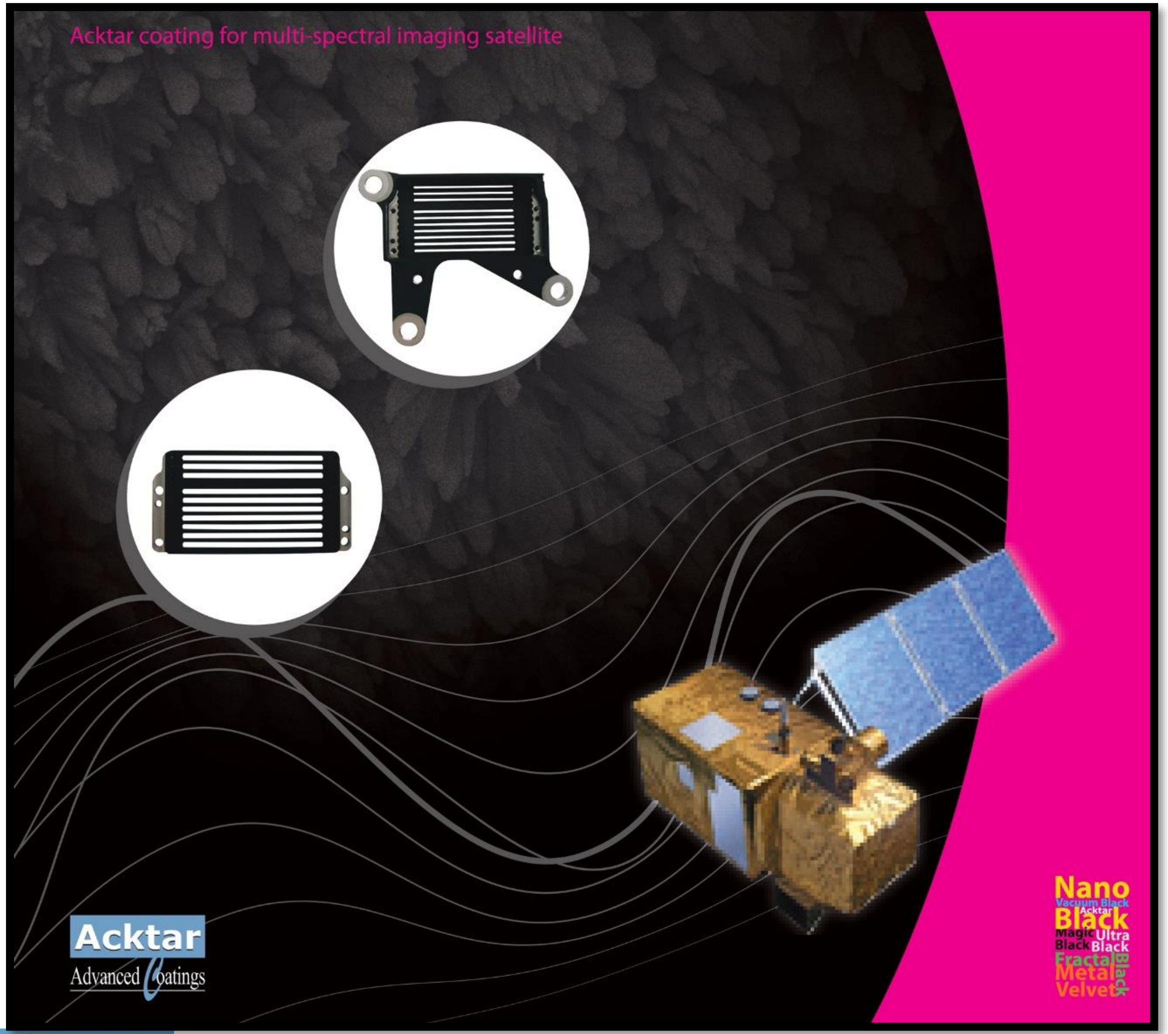


JUICE – Jupiter Moons Explorer

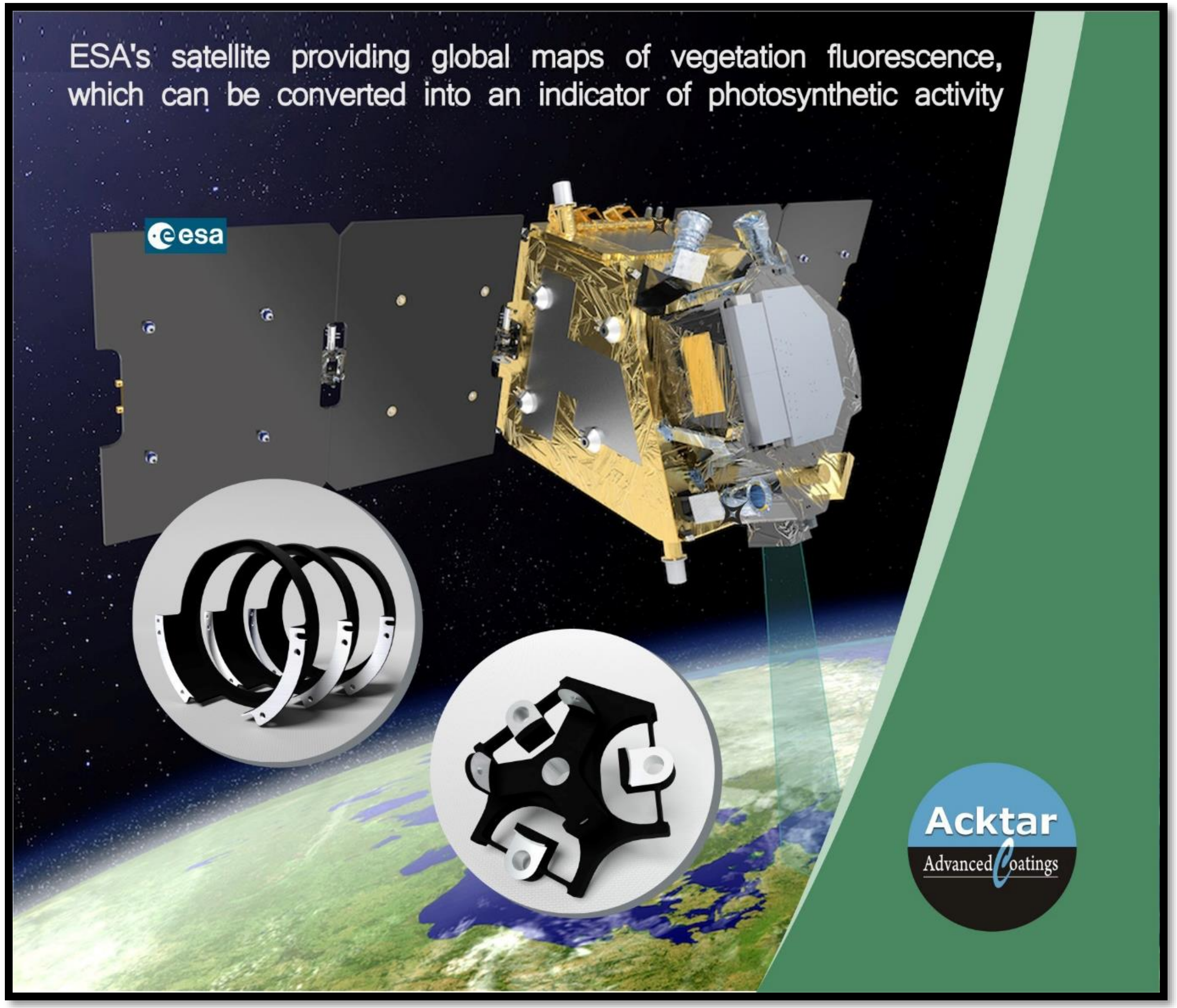


Fractal Black ™ – Space Heritage

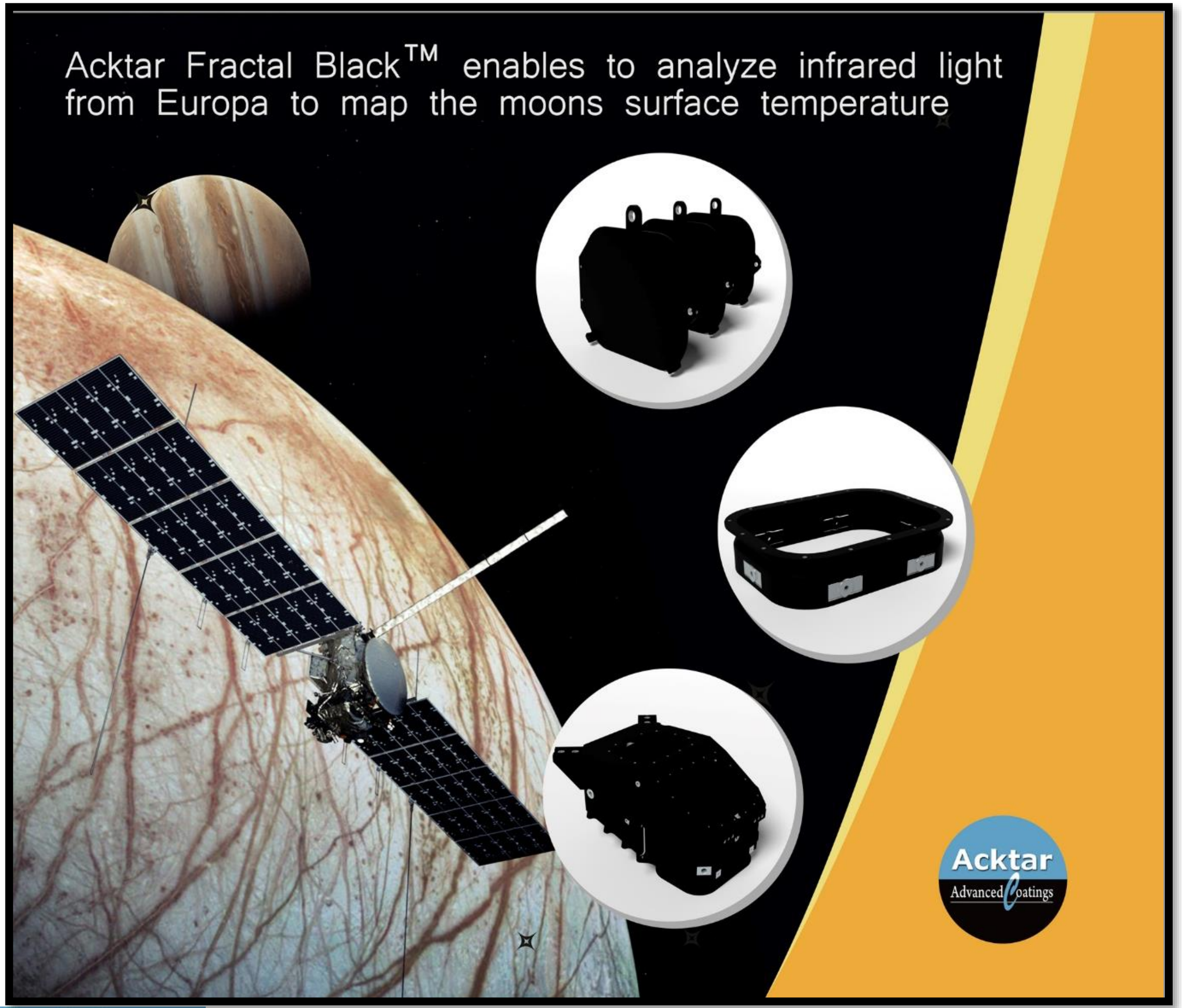
SENTINEL-2

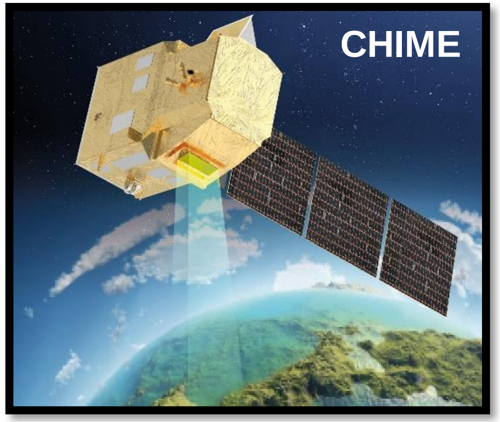


FLEX



E-THEMIS





Credit: ESA

Credit: ESA

Credit: NASA

Acktar Advanced Coatings
ISI CAS

The Challenge

Challenge 1: Difficult to rely on numerical/analytical predictions

Vital to **experimentally** determine absorptivity/emissivity in an accurate and repeatable way

Challenge 2: Measuring thermal emissivity at cryogenic temperatures

- → Operational challenge
- → Engineering challenge
- → Performance

Challenge 3: Finding a material that in addition to the required emissivity can operate under the demanding environmental conditions

Cryogenic space environment, vacuum, ATOX, radiation, thermal cycling, UV, etc..

Objectives

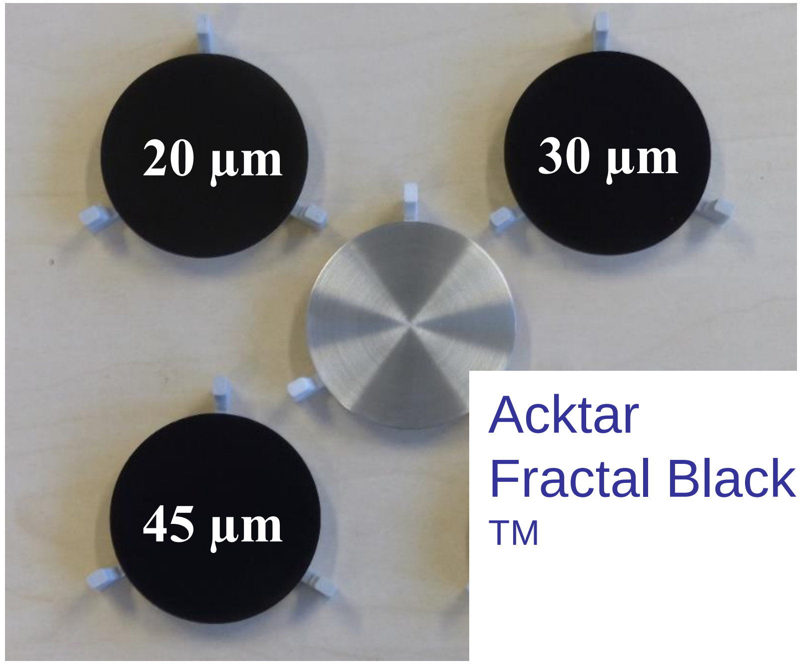
I. Measuring hemispherical emissivity (ε) of Fractal Black™ at cryogenic temperatures in the range of 5-300 K

II. Selecting the optimal coating thickness: to deliver required emissivity at a minimum coating thickness

III. Studying the temperature dependence of Fractal Black™'s emissivity

IV. Delta qualification to 30µm Fractal Black™ vs typical coating thickness of 15µm

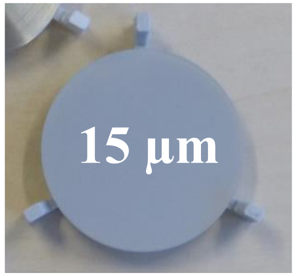
Experimental – Materials & Sample Design



Acktar Fractal Black TM

- Ø 40 mm Al 6061 substrate disk
- Acktar Fractal Black TM applied using Acktar's proprietary coating technology
- Fractal Black TM applied in 3 different thicknesses
- Acktar Diffusive White TM

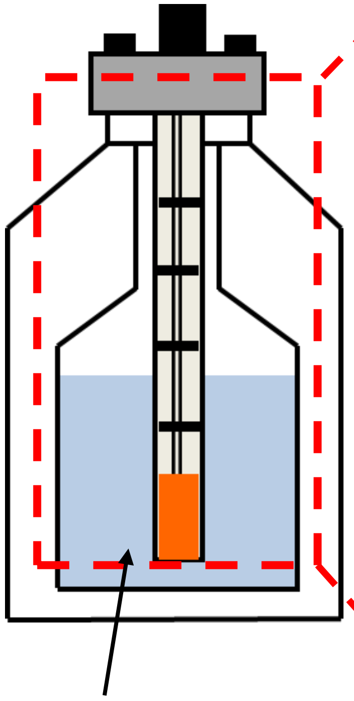
Acktar Diffusive White TM

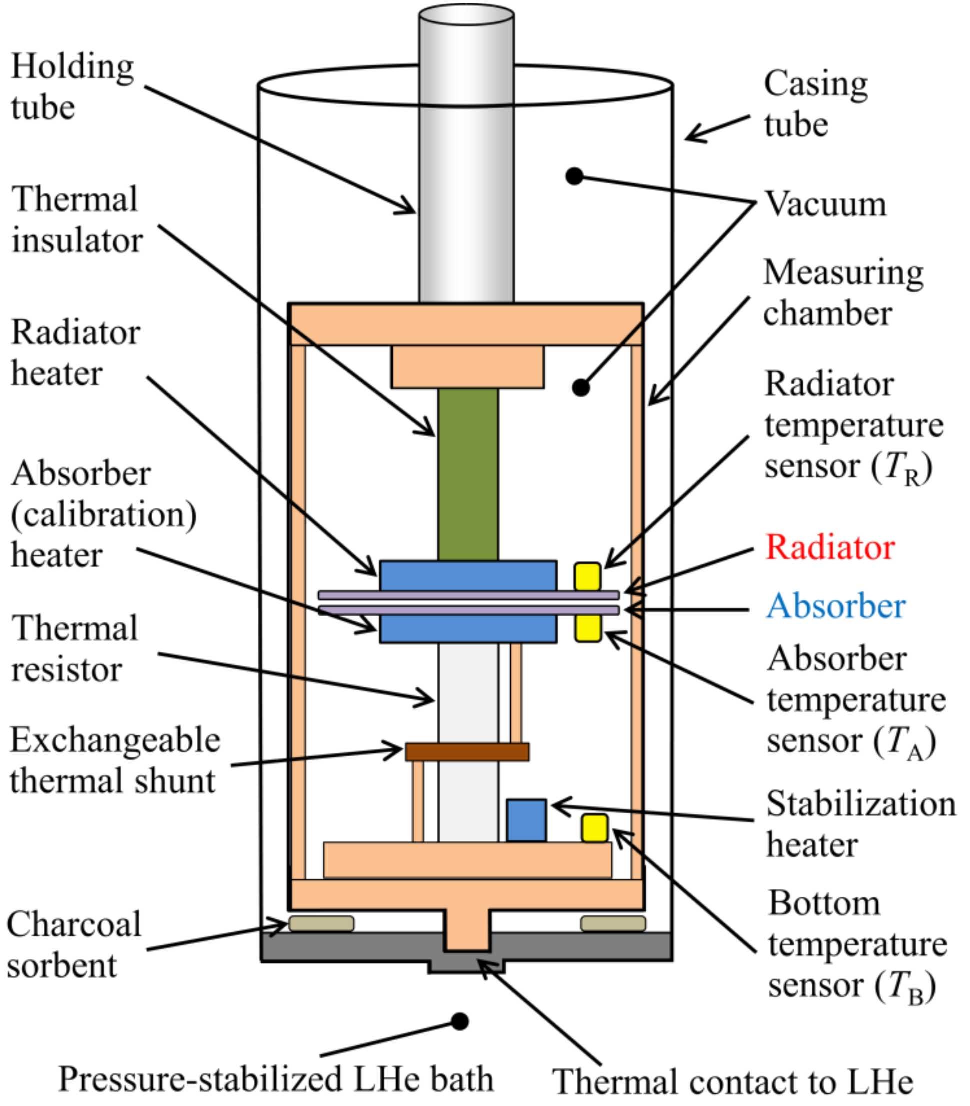


Sample ID	Sample format	Substrate material	Coating type and thickness
P#14062_2	Disc	Aluminum alloy 6061	Fractal Black™ 20 µm
P#14062_3			Fractal Black™ 30 µm
P#14062_4			Fractal Black™ 45 µm
P#14062_5			Acktar Diffusive White™ 15 µm

Experimental – Apparatus 'Emister' chamber

Apparatus in Dewar vessel



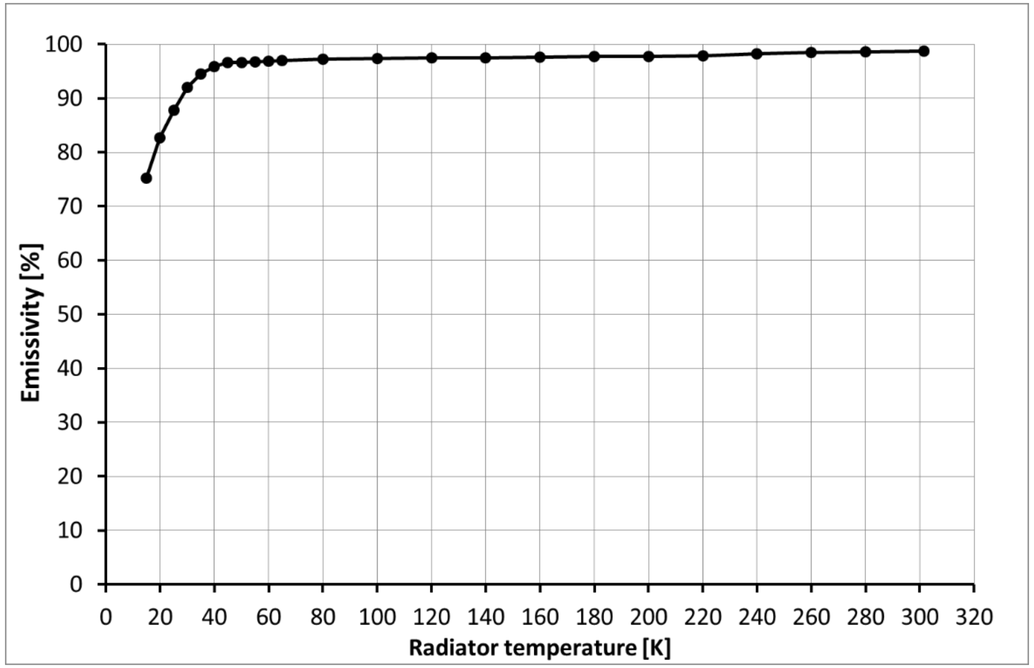


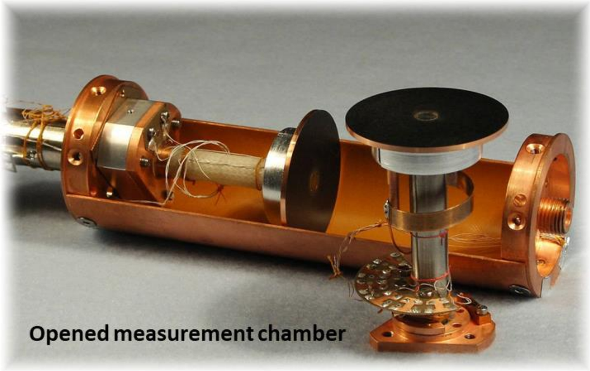
[Králík et al., 2016]

- Based on a calorimethric method
- Emissivity calculated from heat transfer between radiator and absorber disc (0.5 mm gap)
- Sample is at the position of radiator
- Absorber disk (reference) → very high α/ε 94% of T_R above 50 K

Case study - Black Body (Absorber)

Emissivity of the reference blacbody (2021)

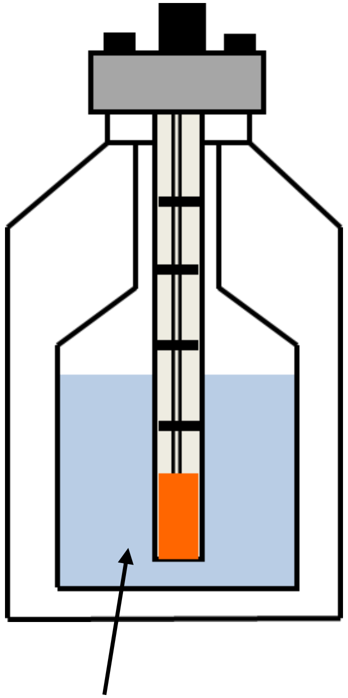




- Acktar Fractal Black ™ as reference
- In use since 2009
- It was used in **56** measurements (2009-2023)
  - Each measurement consists of several thermal cycles!
- Stored in open air or under vacuum in the apparatus
- Emissivity of samples show insignificant change over 14 years of usage!

Experimental - Evaluation

Apparatus in Dewar vessel



LHe

[Králík et al., 2016]

- Sample placed into Emister
- Emister, after evacuation, inserted in a wide neck LHe Dewar vessel
- Apparatus cool down to 5 K
- T_R, T_A and T_B is measured at various setpoints (after reaching thermal equilibrum)
- Heat flow $\mathbf{Q_R}$ **evaluated** from the temperature drop (T_A-T_B) on the **calibrated thermal resistor**.

Mutual emissivity

$$\varepsilon_{\mathrm{RA}} = \frac{Q_R}{A\sigma(T_R^{\ 4} - T_A^{\ 4})}$$

Emissivity

$$\frac{1}{\varepsilon_{\mathrm{R}}} = \frac{1}{\varepsilon_{\mathrm{RA}}} - \frac{1}{\alpha_{\mathrm{REF}}} + 1$$

Measured quantities

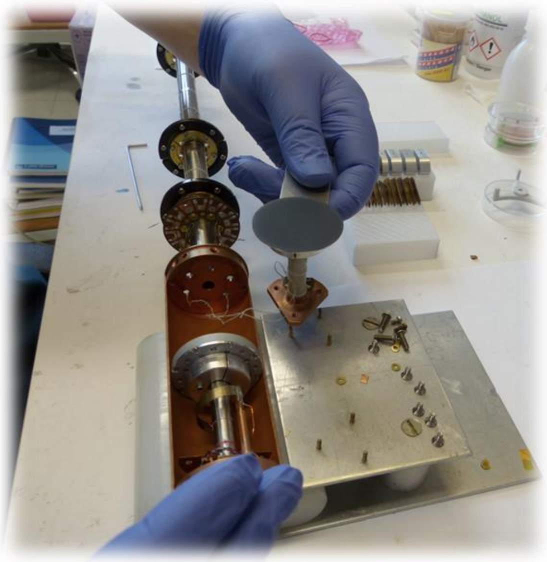
Q_R – Radiative heat flow

T_R – Radiator temperature

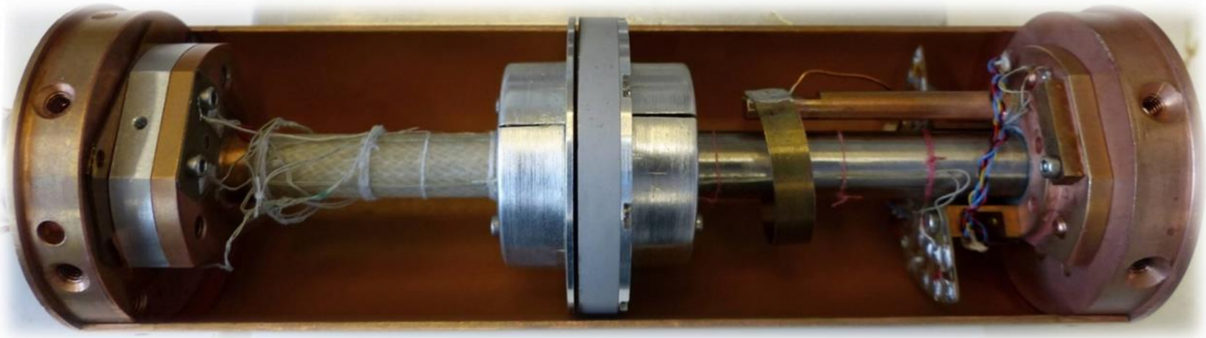
T_A – Absorber temperature

Experimental – Apparatus

Reference blackbody



Assembly



Installed sample as radiator, BB as absorber

Full inner part of apparatus

Experimental – Apparatus

Sample pre-cooled with liquid nitrogen

Evacuation and placing Emister into Dewar vessel

Results & Discussion

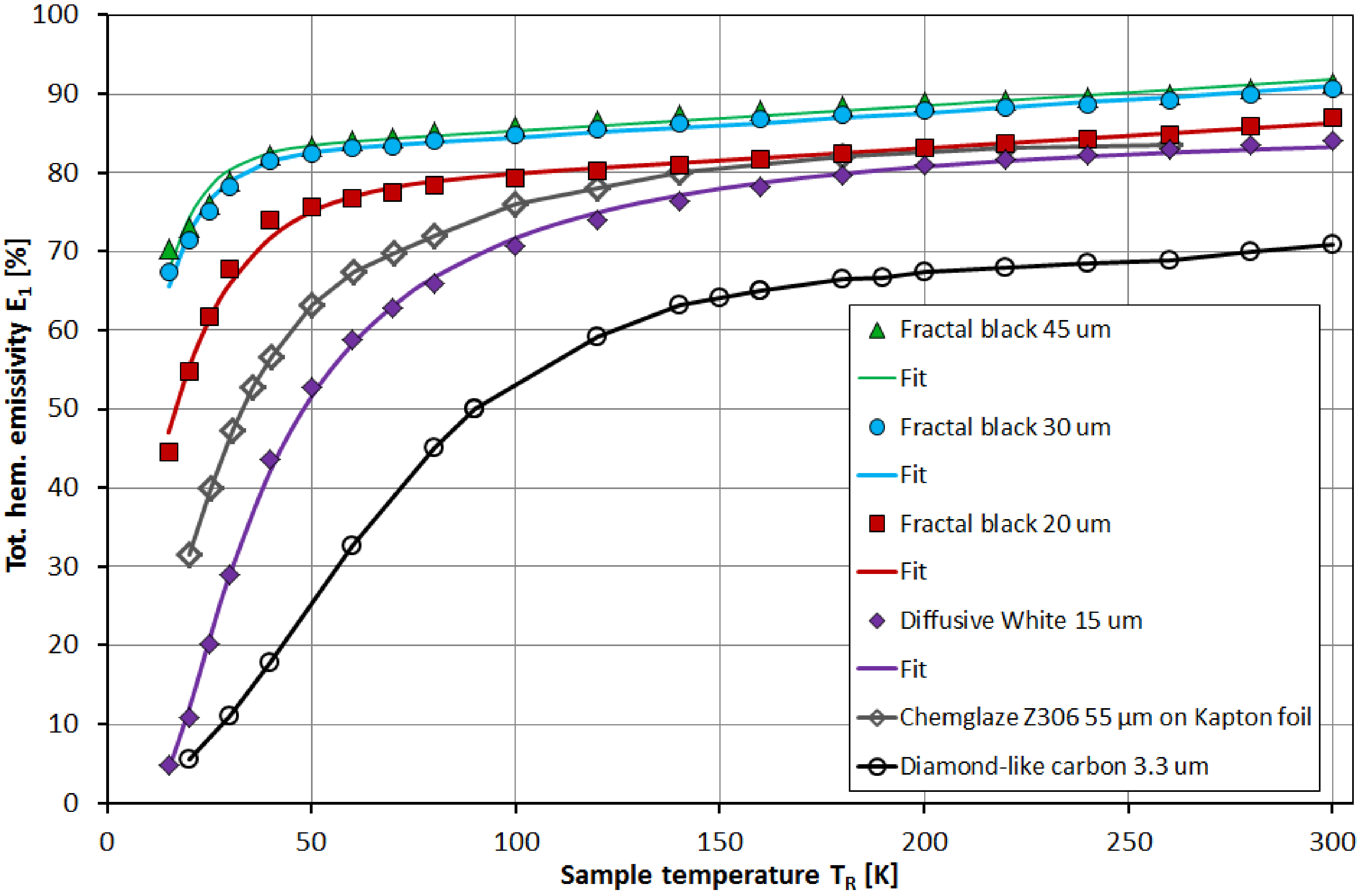
Fitting functions

Fractal Black ™

$$E_1 = -a\left(e^{-\frac{T_R}{b}} - e^{-\frac{T_R}{c}}\right)$$

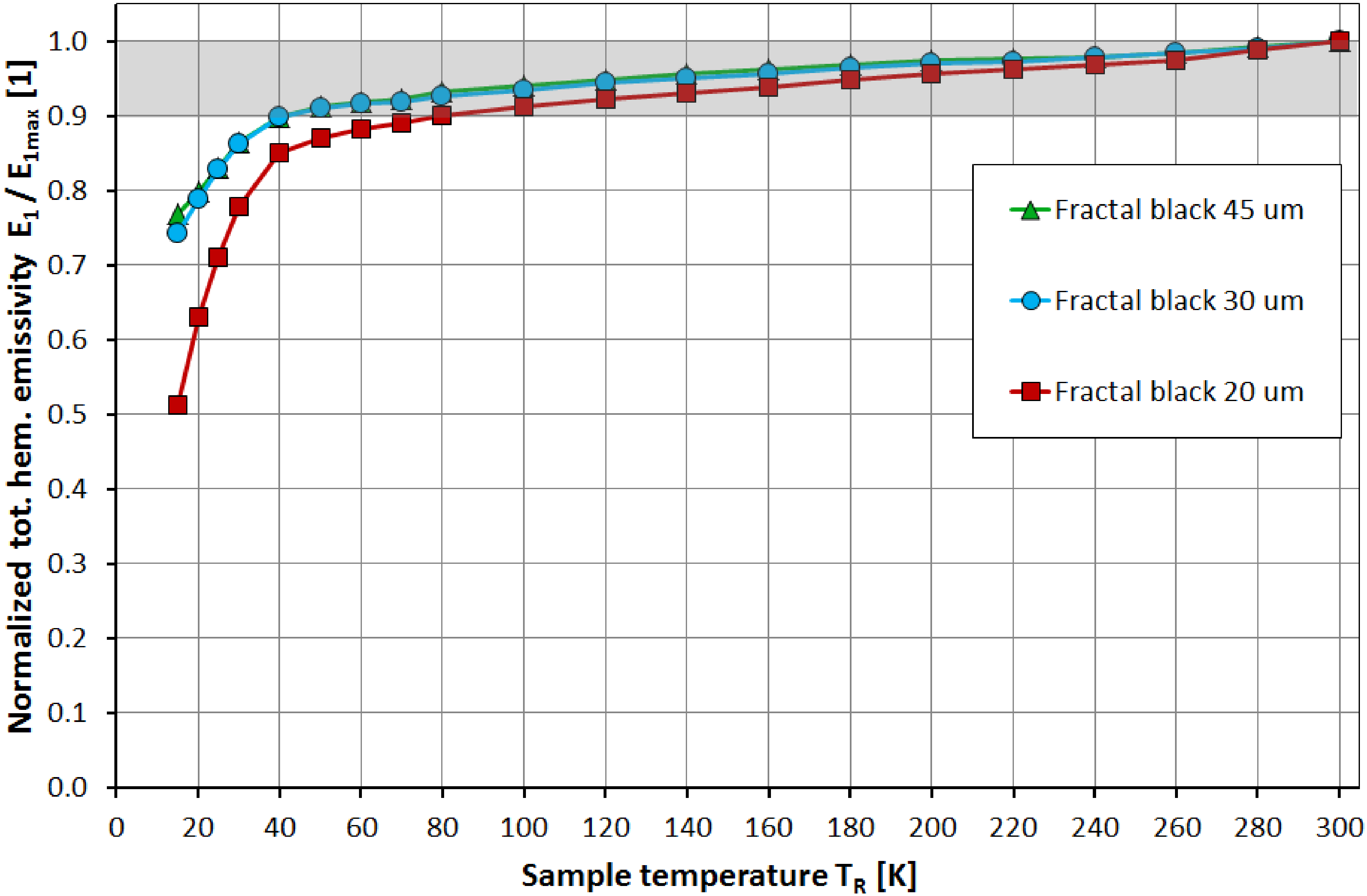
Diffusive White ™

$$E_1 = a\left(e^{bT^c}\right)$$



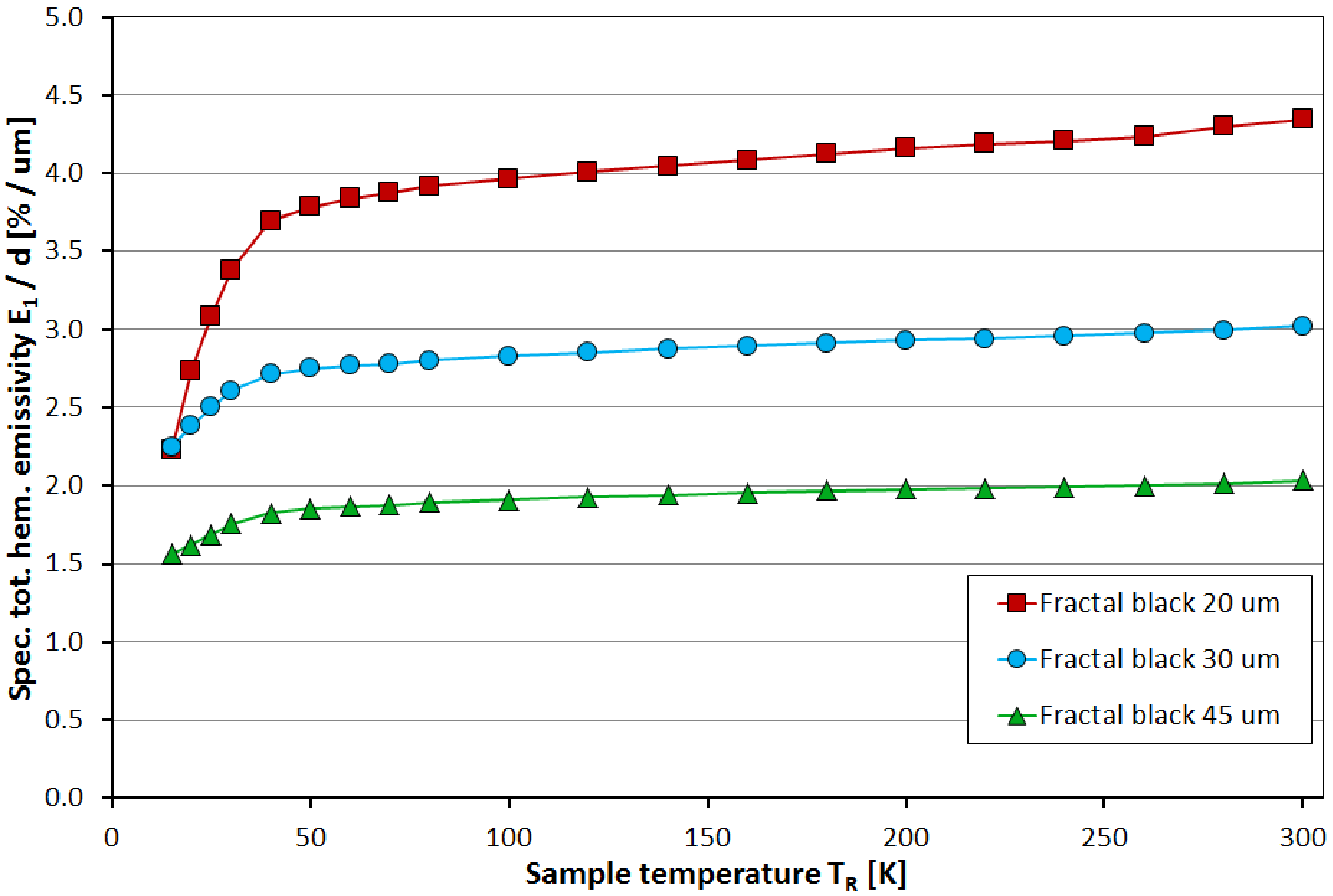
Effective (optimal) coating thickness for FB

Normalized emissivity to its maximum →



Relative 10% decrease

Effective (optimal) coating thickness



- The higher the thickness, the lower the effect on making the coating "blacker"

Conclusions I

- Total hemispherical emissivity (ε) of Fractal Black™ was **successfully measured** at cryogenic temperatures in the range of 5-300 K
- The emissivity of Fractal Black^{TM} is spectrally flat in the temperature range of 40 - 300K and is approximately 80%-90%
- Fractal Black™ withstood thermal cycling between 5 K and 300 K without any measurable degradation
- The effective coating thickness of Fractal Black was established – 30 micron. Above this value, only a relatively small increase in emissivity was achieved by increasing the coating thickness

Conclusions II

- **Spectrally flat** like Black coatings are of high interest as they provide thermal stability which is essential in space applications
- **Long-term durability**, **high thermal stability** and **applicational versatility** of *Fractal Black™* was demonstrated →
- Makes it a perfect choice for space missions to various destinations
- Not only **minimizes reflectance** from UV, VIS through FIR
- **Effectively controls thermal radiation** across spacecraft components

Recent developments and qualifications

Fractal Black TM – Recent Qualifications

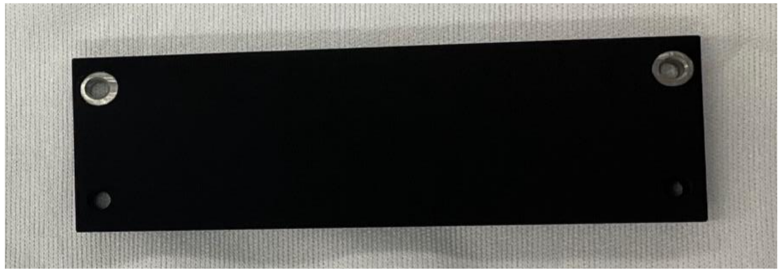
NASA SPHEREx

MTL qualified the Fractal Black[TM] for use on NASA's Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer mission (SPHEREx)

- Linear Variable Filter Mount
- Dual function application
- Shear failure
- Adhesion test (X-cut per ASTM D3359) + **Thermal shock**
  - 10 cycles
  - 110 ° C to LN_2
  - Ambient to LN_2

	Pre-thermal shock		Post-thermal shock	
	α	ε	α	ε
Avg.	0.988 ± 0.00	0.936 ± 0.03	0.988 ± 0.00	0.900 ± 0.01

[Blank et al., 2024]



Acktar – Recent qualifications for new substrate materials

Coating high-performance advanced ceramics for Kyocera Corporation

- Cordierite-based fine ceramics used in ground and space telescopes
  - Thermal expansion near zero at room temperature
  - Dimensional stability <4nm per meter per year
- Vacuum Black^{TM} was adapted to fit Kyocera's requirements
  - 98.5% light absorption in EUV-SWIR
  - Thermal stability 4K-723K
  - Protection from ATOX and accumulation of static electricity.

KYOCERA

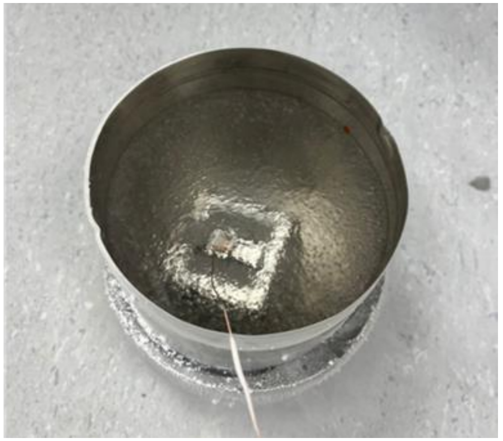
Acktar Advanced Coatings

ISI CAS

Acktar – Recent qualifications for new substrate materials

Aluminum Silicate

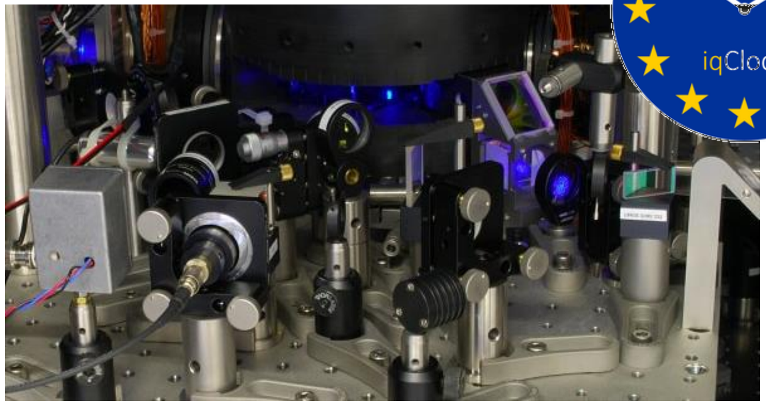
- Thermal shock cycling of Acktar Fractal Black™ on AlSi40
  - 3 cycles as per Stanford University procedures
  - Ambient to LN_2
- Adhesion test post-cryogenic cycling
  - 3M853 type crystal clear tape
  - The samples showed excellent adhesion



Acktar – non-space cryogenic use cases

Acktar - Key innovator in the iqClock project for the development of the world's most accurate atomic clock (precision of 10^{-17} seconds)

- The iqClock atoms' are **cooled to temperatures below 10nK**
- Acktar's contribution: absorbing straylight to improve signal (black coating with low reflectance) while preventing heat leakage to the detector chamber (black coating with relatively low emissivity)



Acktar – non-space cryogenic use cases

Cold shields for IR sensors

- Cold shields protect IR sensors from unwanted stray radiation by absorbing radiation indoors
- Commercial product of over 20 years
- Substrate materials: Invar, Copper, Kovar
- Acktar high emissivity Fractal Black™ inside, gold outside

Acktar – Forward to the moon!

<u>Lunar dust-resistant coating at cryogenic temperatures</u>

- The lunar black coatings challenge:
  - The moon's craters are amongst the coldest places in our Solar System
  - Durability to Lunar dust
- Initial tests according to NASA-STD-1008 using lunar regolith simulant

During lunar dust exposure

After lunar dust mitigation

Thank you for listening!

Any questions? :)

Dr Tamas Rev

tamas.rev@acktar.com

Thermal & Fluids Analysis Workshop
TFAWS 2023
August 21-25, 2023
NASA Goddard Space Flight Center
Greenbelt, MD