EROSION OF REFLECTORS AND SANDSTORM SIMULATION

SolarTwins 2nd Summer School – Next Generation CST Technologies

Standardized reflector testing and advanced optical characterization tools

SolarTwins

OPAC Ciemat DLR

DLR

Dr. Florian Wiesinger, Institute of Solar Research, 2. September 2022

- Theoretically 1% of the area of the Sahara used for CSP would be sufficient to supply for all global energy.
- The current global installed CSP is at 6 GW, a bit less than 50% of it in Spain.
- IEA forecasts (2050) 4380 TWh CSP contribution which corresponds to 11% of worldwide electricity output.
- One technical problem → high material wear

MOTIVATION

[1]

Issues implementing CSP in desert environments

Deposited particles

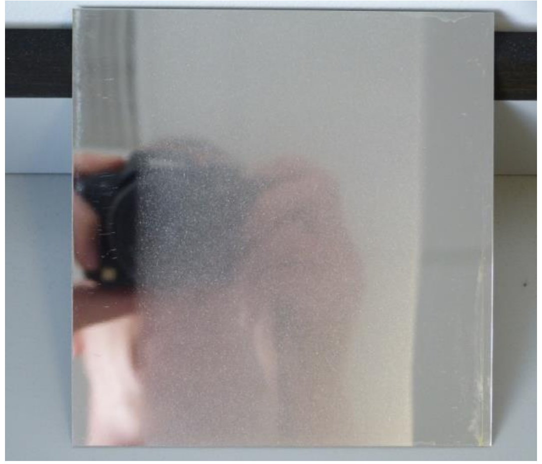
- Soiling of mirrors leads to losses of optical plant efficiency
- Permanent damage on mirrors and other materials

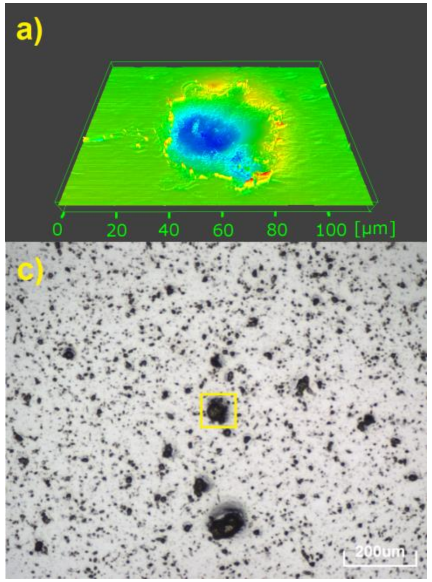
Suspended particles

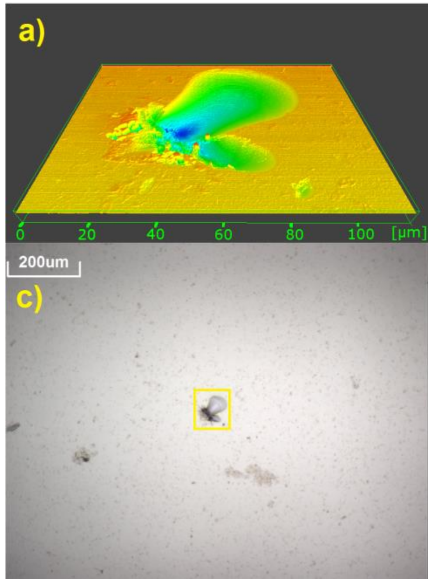
- Atmospheric dust load causes extinction of radiation in tower plants

[2]

Issues implementing CSP in desert environments

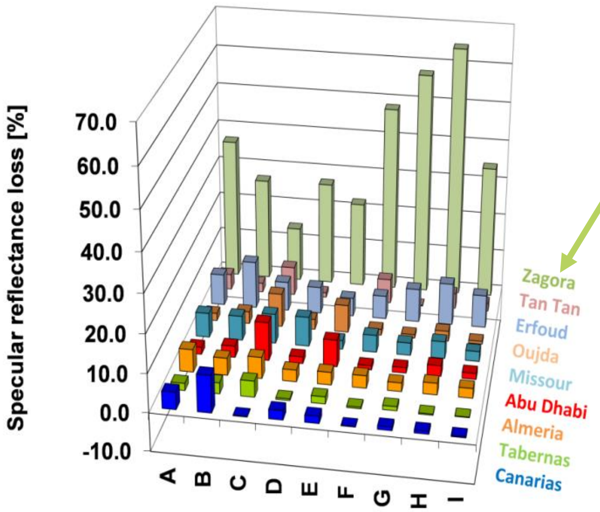






Aluminum mirror

Glass mirror



Specular reflectance drop after 20 months in Zagora:

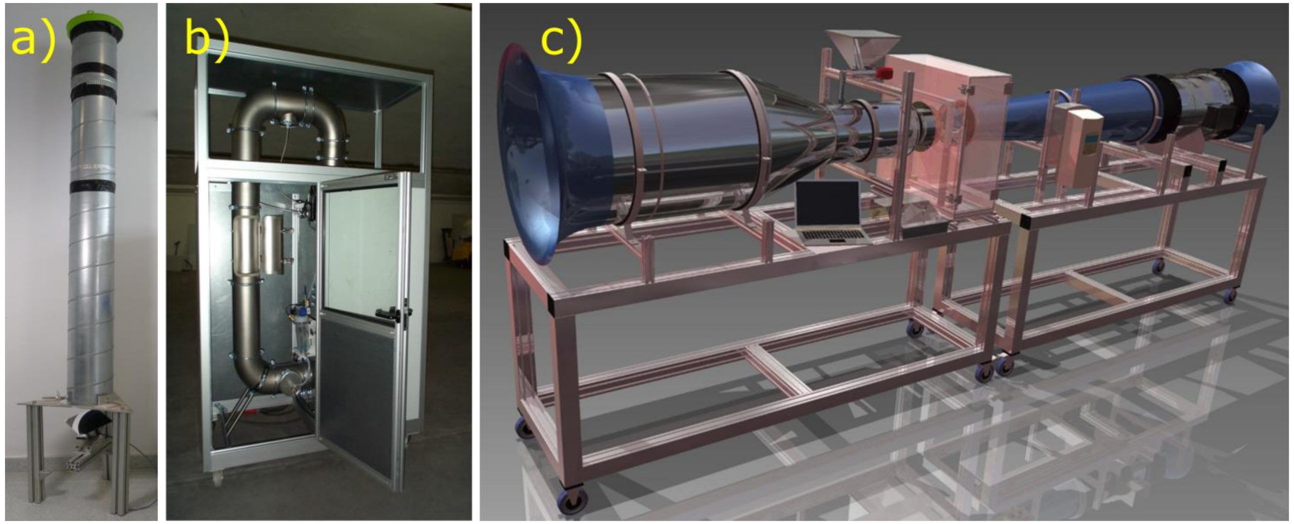
aluminum	glass
32,9%	5,2%

→ annual economical loss of average 50MW plant due to 1% reflectance drop = 600 000$

[3]

Objective

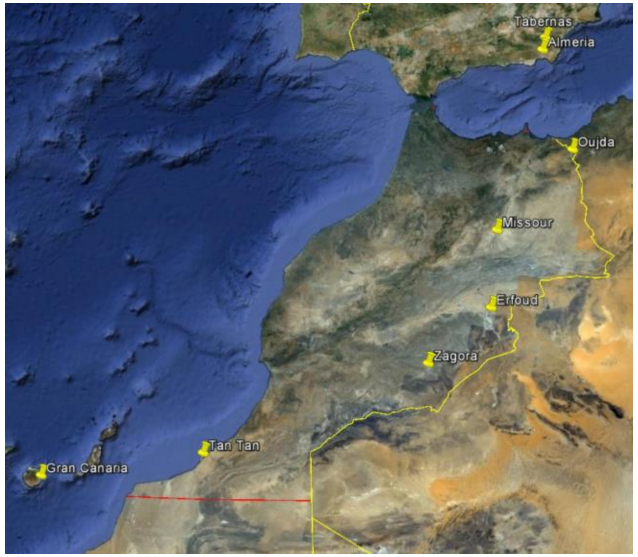
Three different erosion simulation setups: a) soil pipe, b) closed loop wind tunnel and c) open loop wind tunnel.

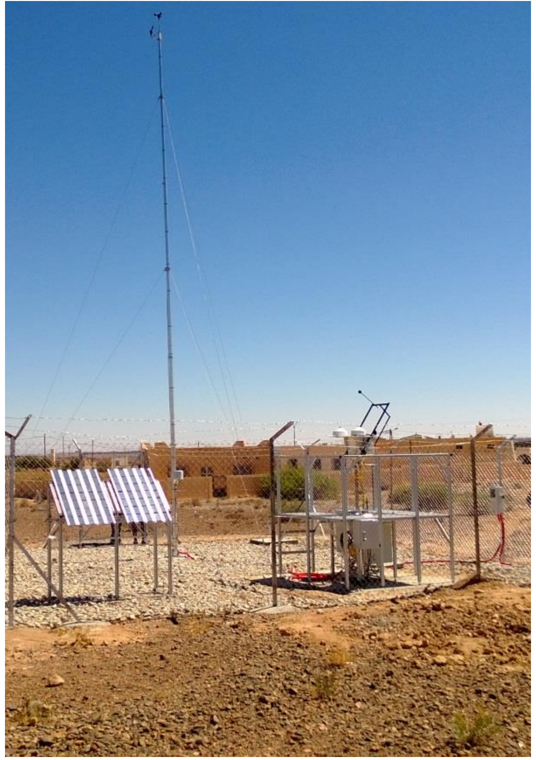


[4]

Outdoor campaign

- Extensive outdoor exposure campaign on 13 sites: Almeria, Tabernas, Gran Canaria, Abu Dhabi, Oujda, Missour, Erfoud, Zagora, Tan Tan, Maan, Tatauine, Adrar, Cairo
- Variety of site conditions, from urban over coastal to desert
- On-site measurements of parameters (temperature, wind, irradiation, humidity, particles, etc.)





Dust measurements

Operation of severall passive sampling devices.

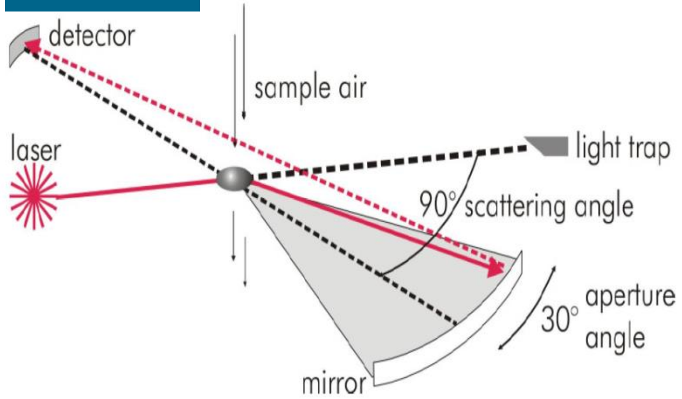
→particle size distribution, maximum particle size, mineralogical details, mean dust flux

Dust measurements

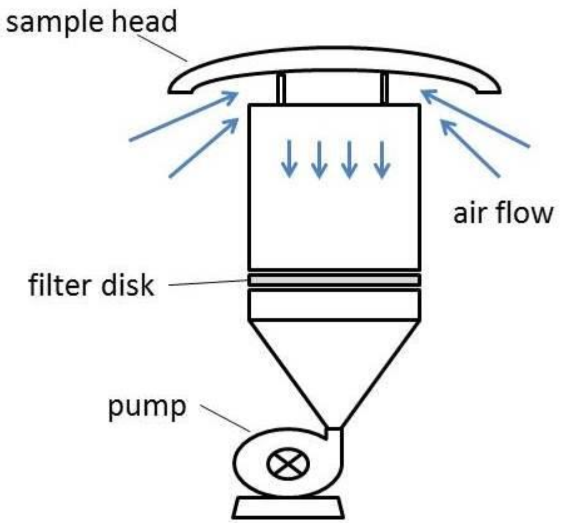
Three different active dust measurements samplers:

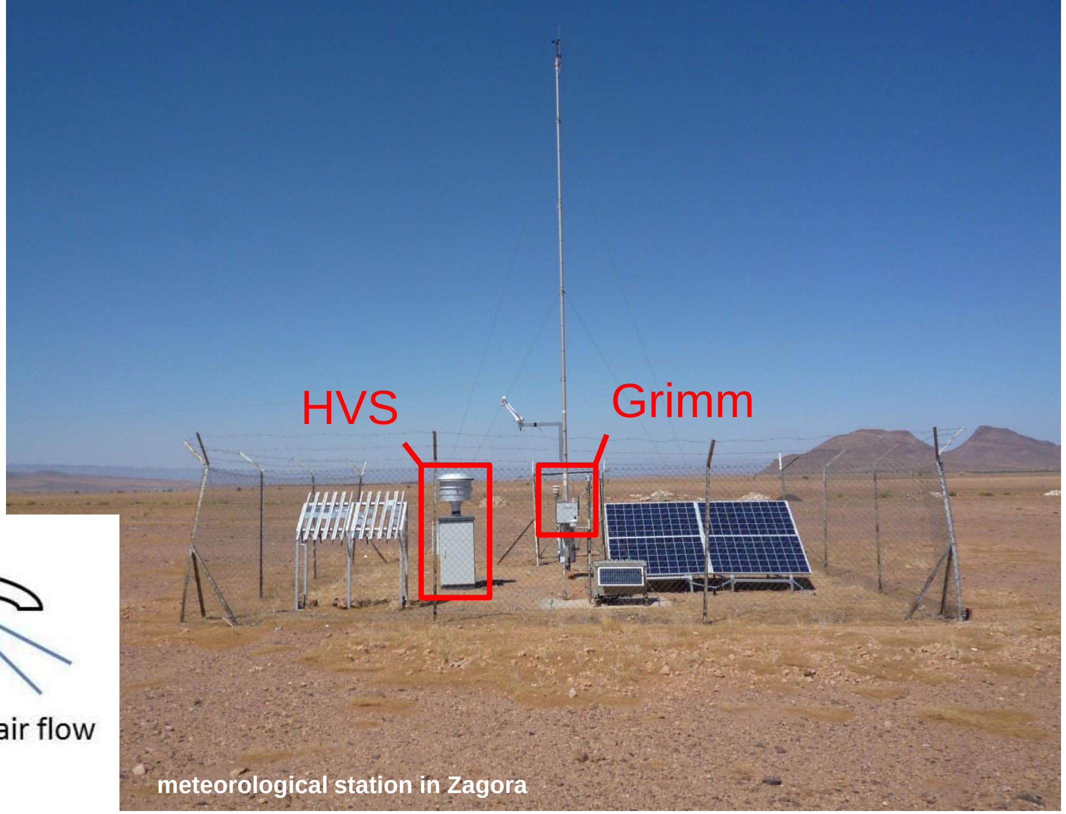
- Dusttrak 8533 from TSI (optical)
- EDM164 from Grimm (optical)
- HVS-TSP16 from MCZ (gravimetrical)

optical



gravimetrical

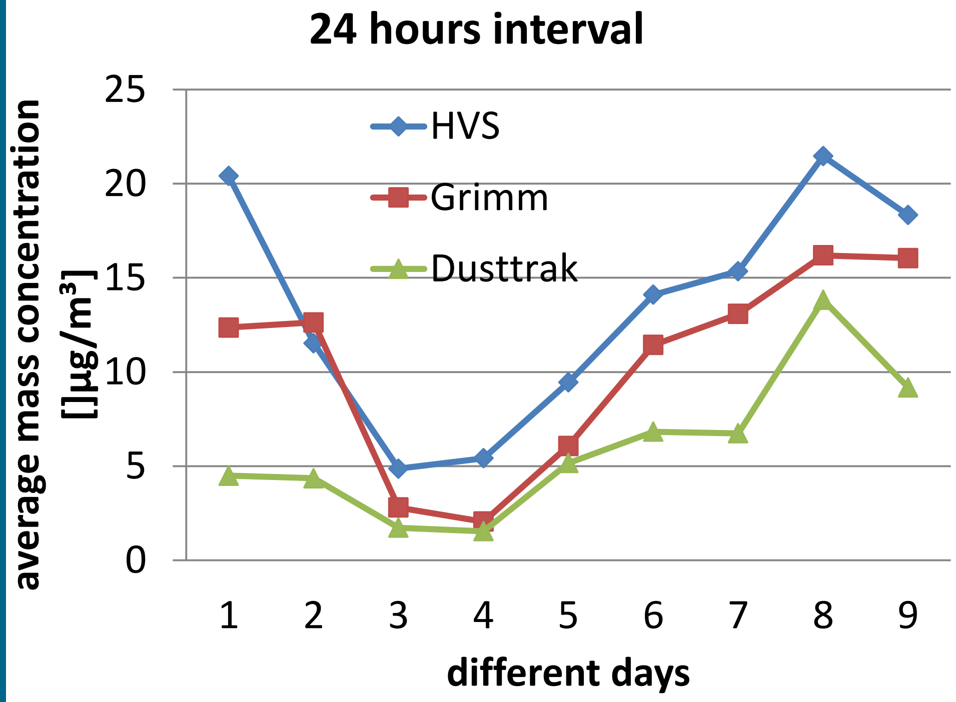


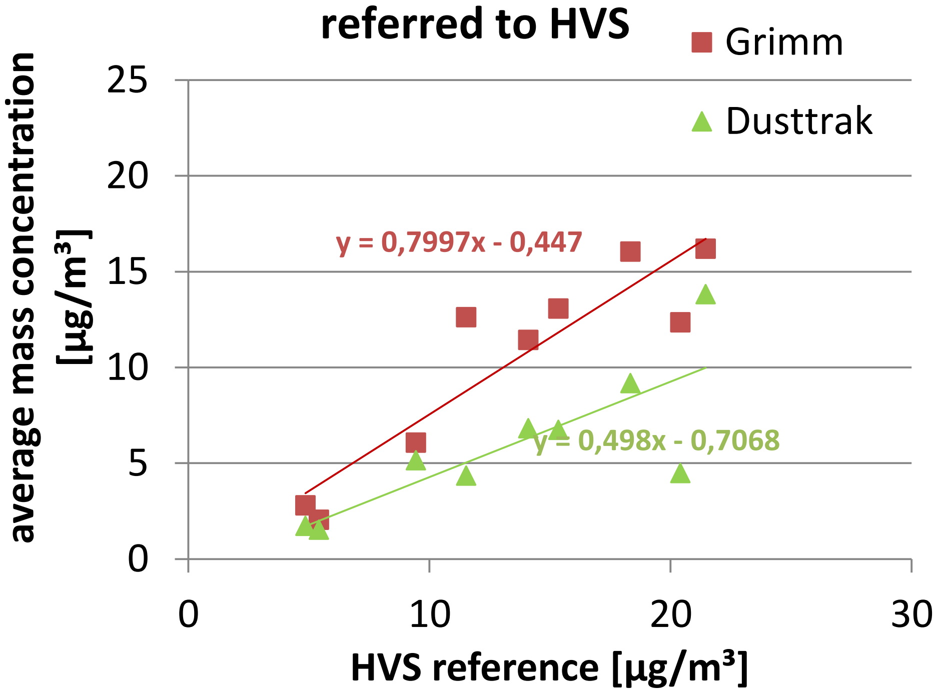


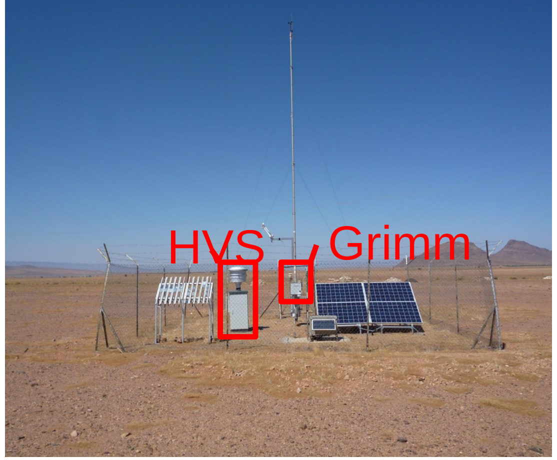
meteorological station in Zagora

→additional time resolution

Dust measurements

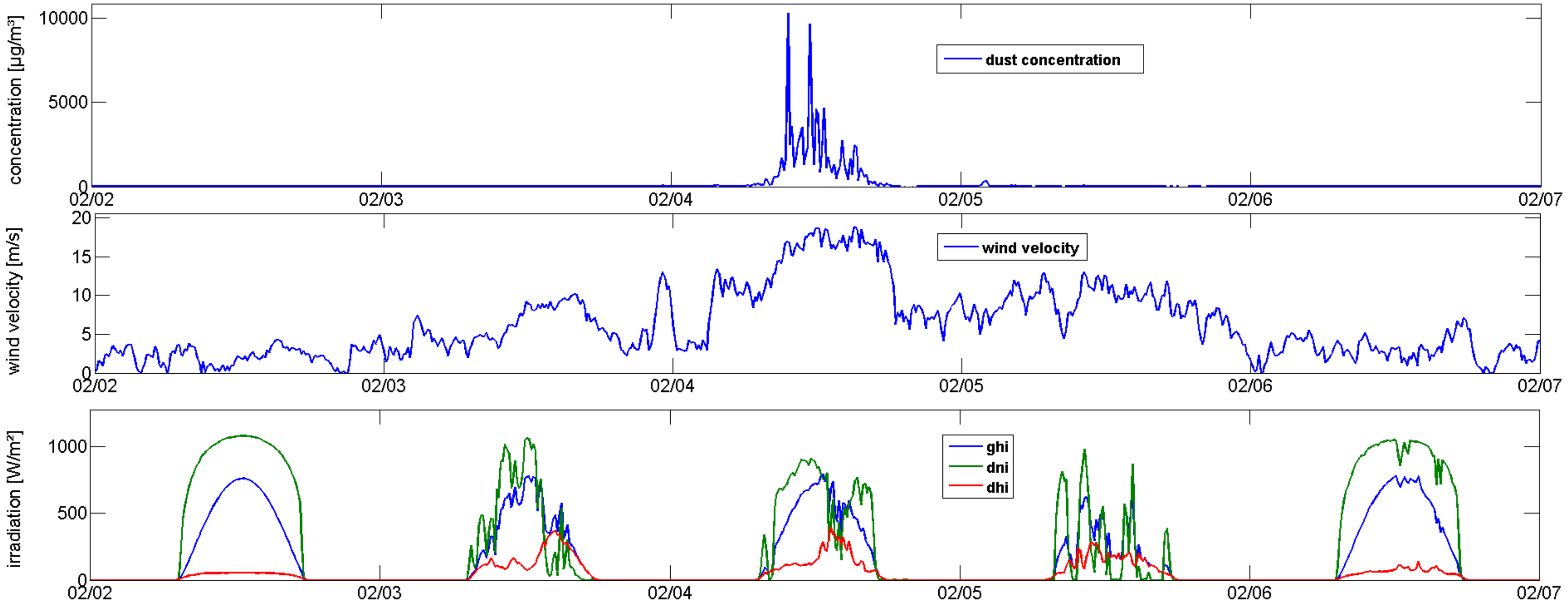


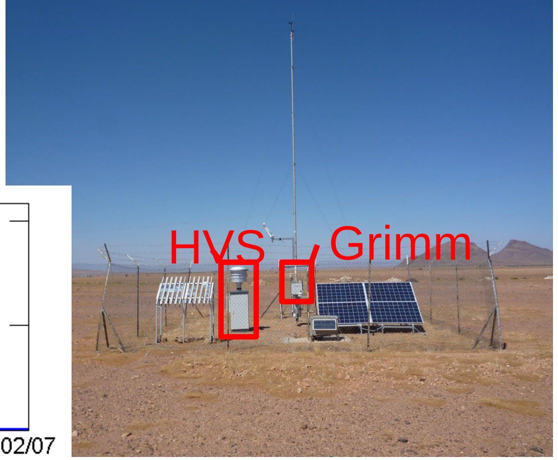




→additional time resolution

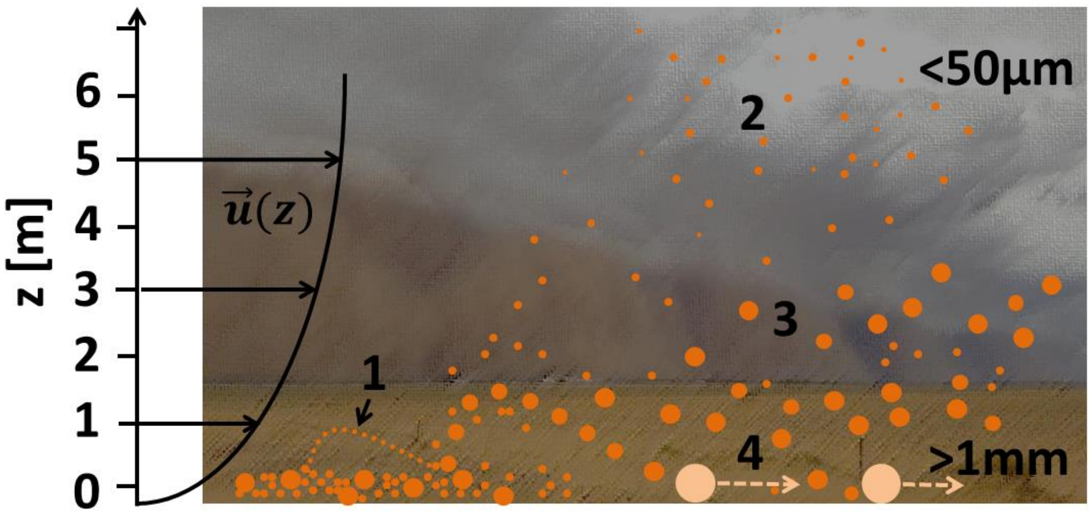
Dust measurements





→additional time resolution

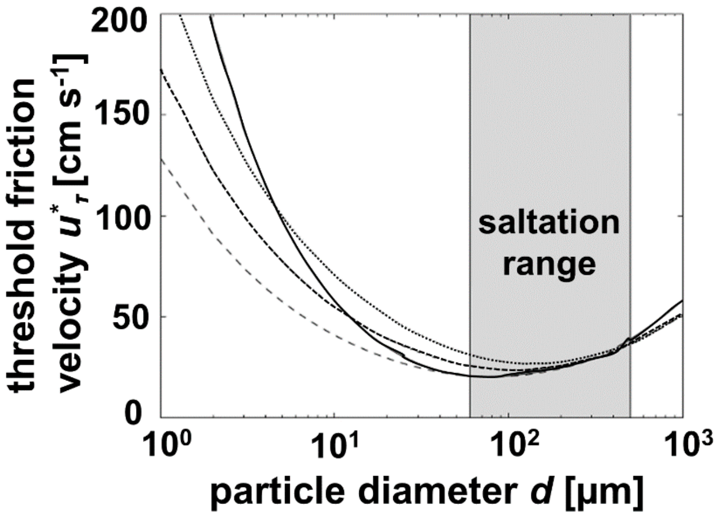
Dust movement



1) first particle dislodgement from the ground which later impacts the ground, releasing a new particle wave; 2) small particles in suspension mode; 3) the saltation cloud; 4) surface creep

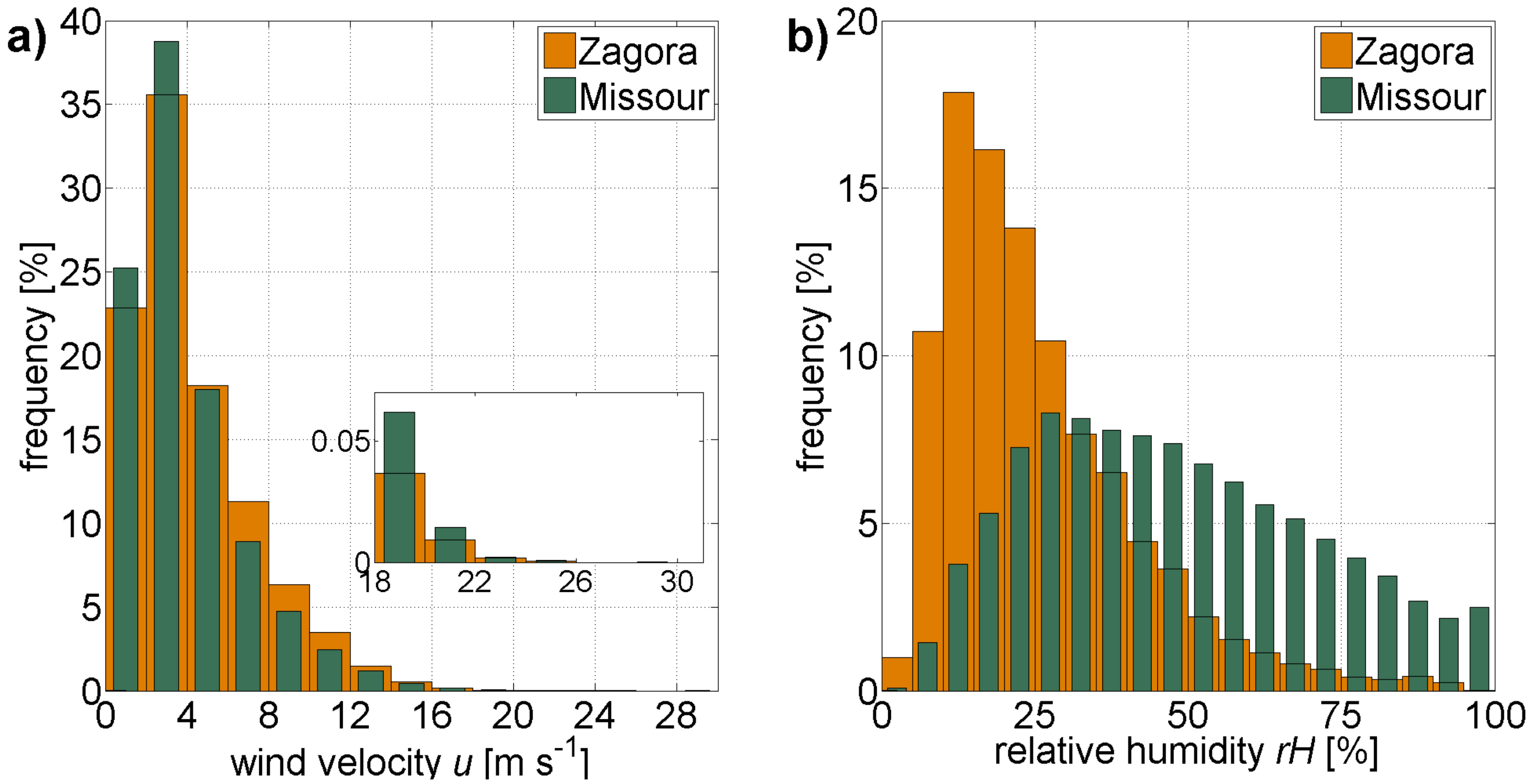
Dust movement is a complex, nonlinear process.

One key parameter is threshold friction velocity u^*_T = minimum velocity to initiate soil particle motion (meteorological and land surface conditions)



[5]

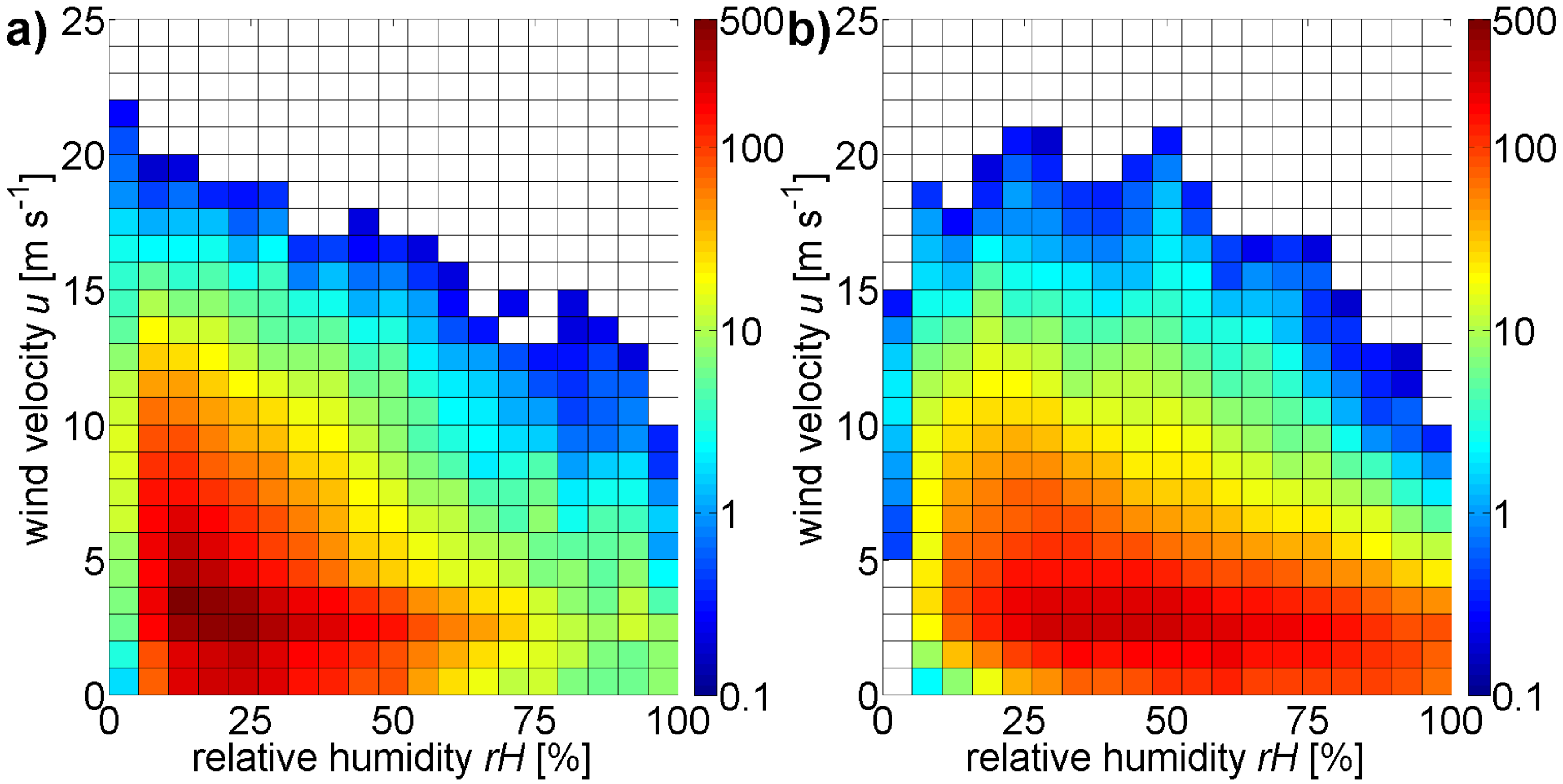
Dust movement



- Zagora high erosion, Missour low erosion
- Strong wind ≠ Strong dust movement/erosion

[6]

Dust movement

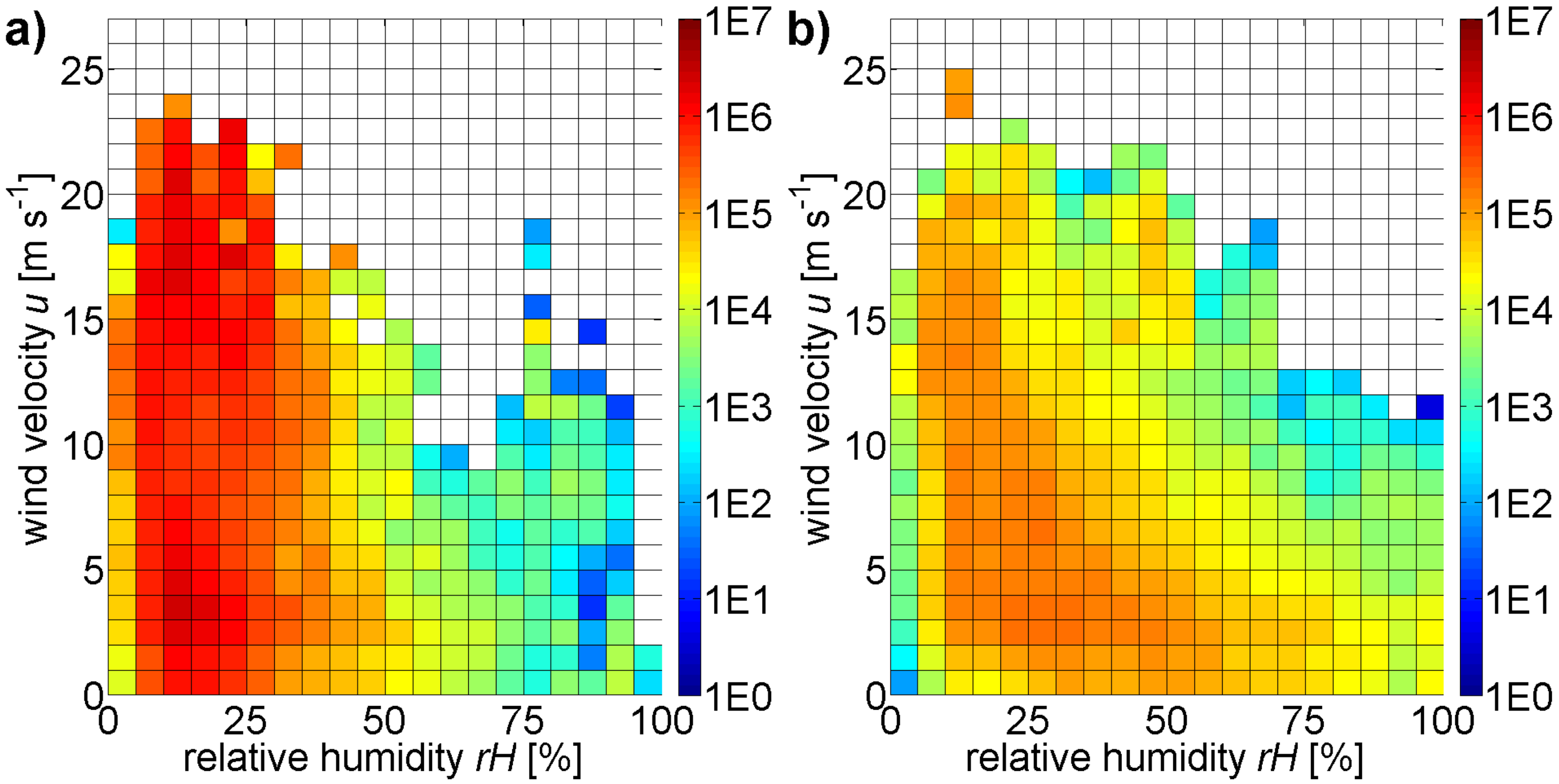


Absolute hours of u/rh couples

Zagora (a) high erosion, Missour (b) low erosion

[7]

Dust movement

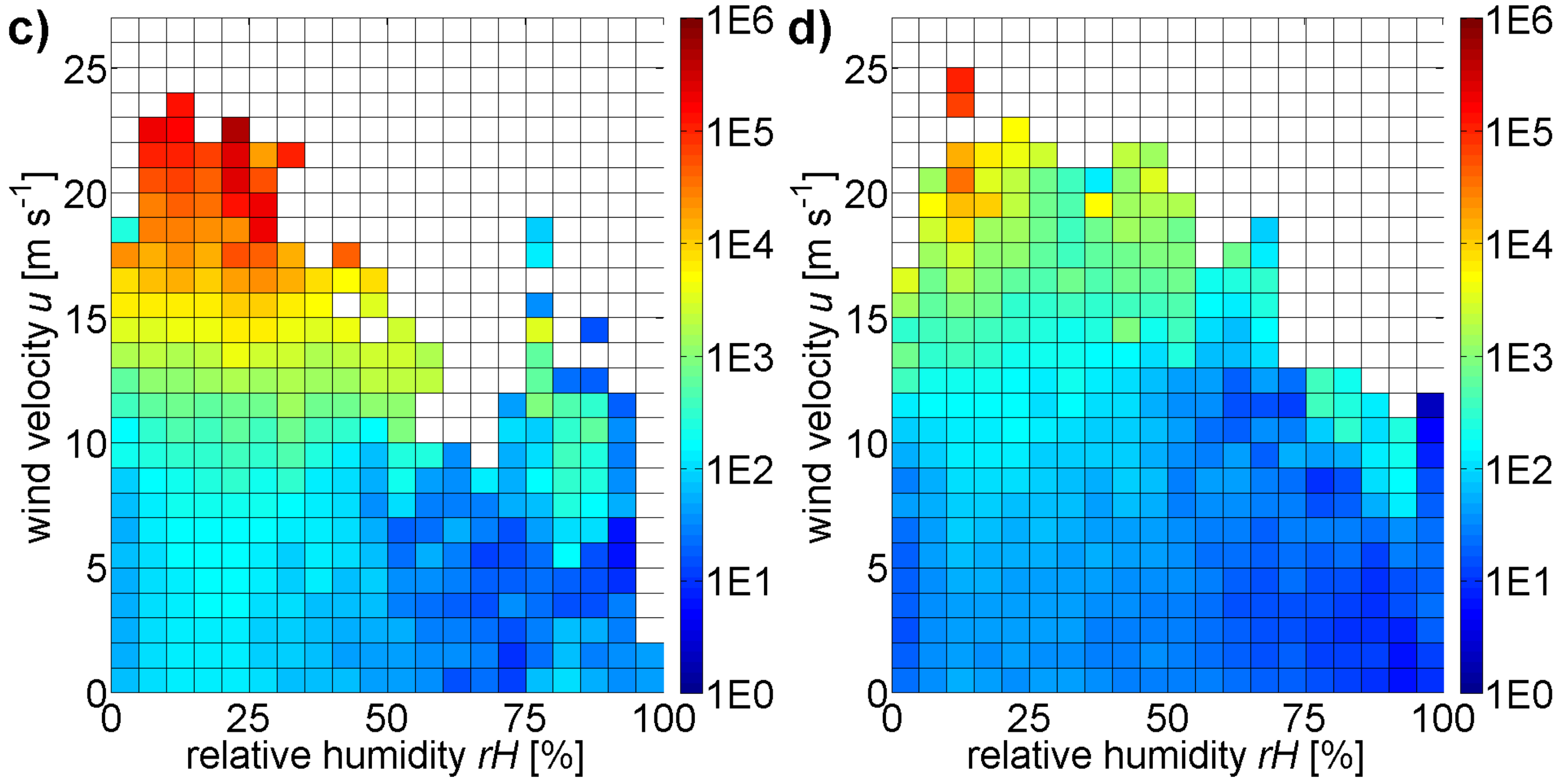


Cumulated dust concentration [µg/m³]

Zagora (a) high erosion, Missour (b) low erosion

[7]

Dust movement

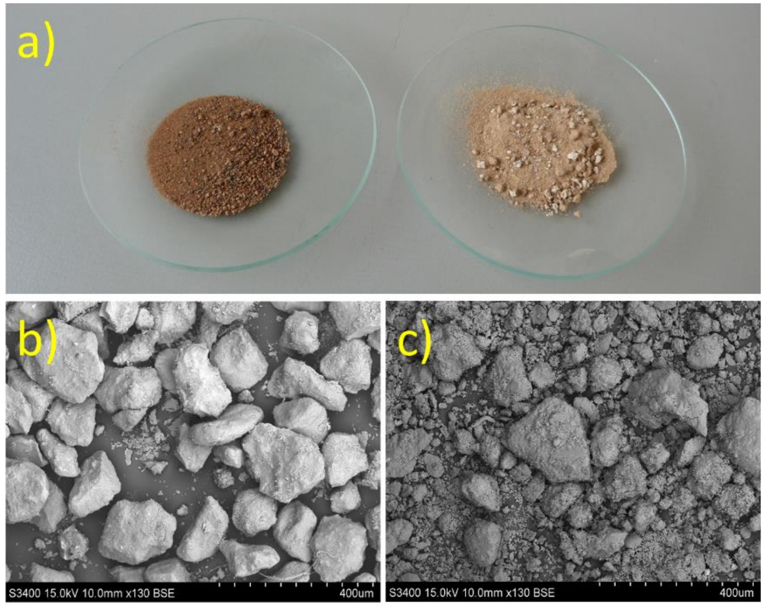


Cumulated dust concentration divided by frequency of u-rh couple = Dust activity

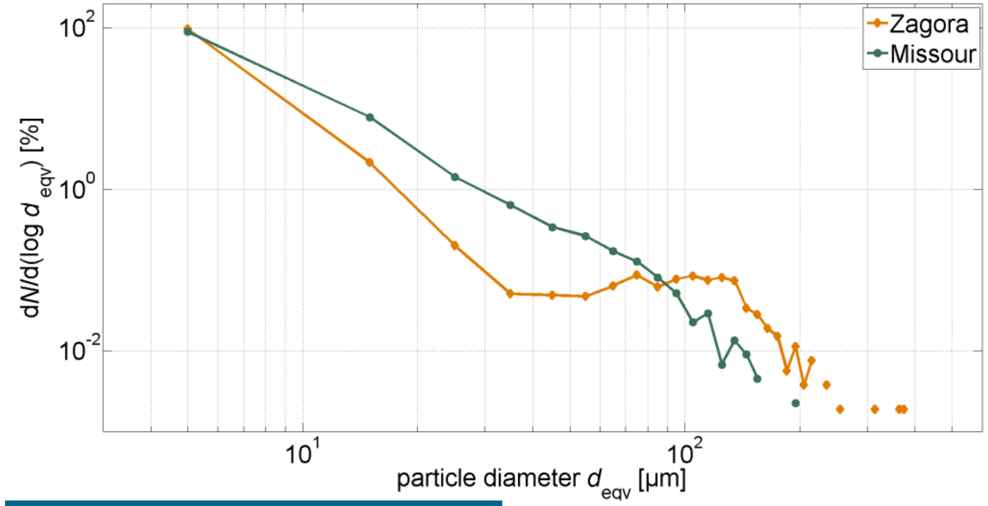
Zagora (a) high erosion, Missour (b) low erosion

[7]

Dust damage potential



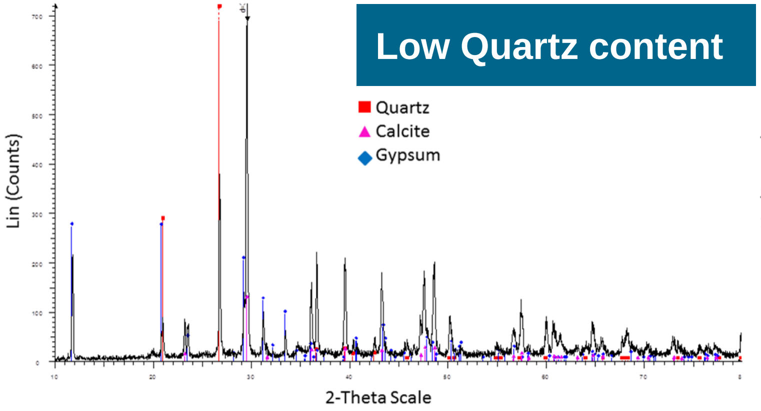
Particle size distribution



Particle mineralogy

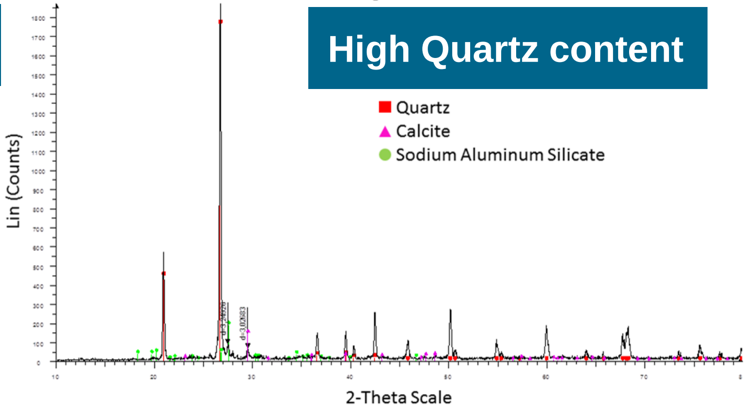
Missour

Low Quartz content



Zagora

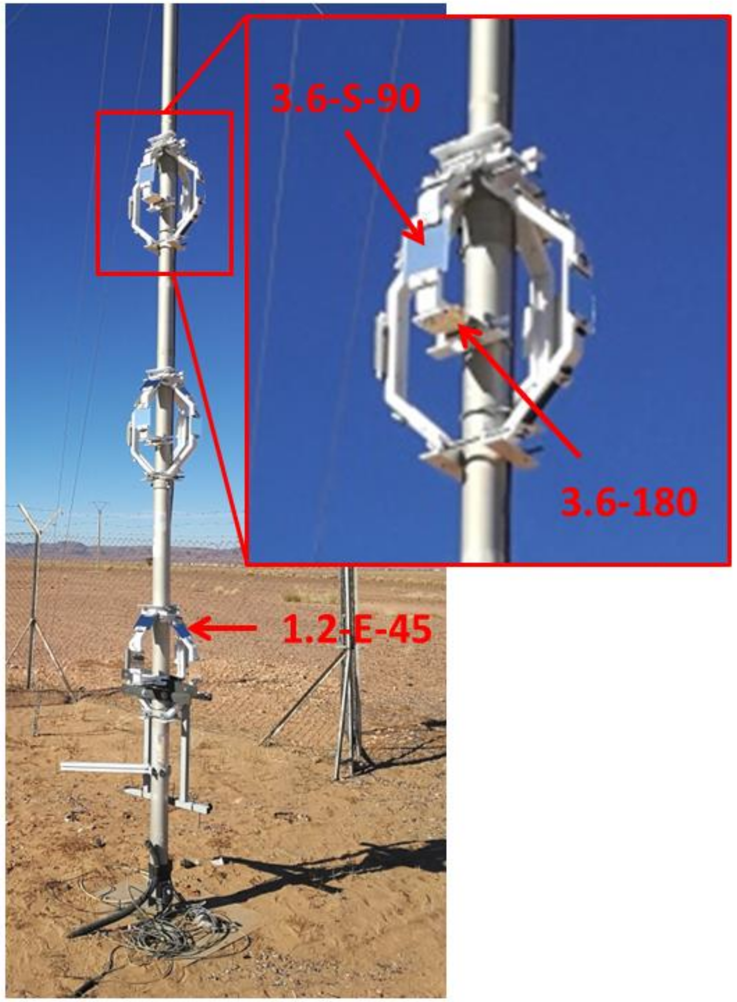
High Quartz content



Outdoor campaign – dust movement identified risks

- PSD maximum at 65-200µm
- PSD bimodal
- Open terrain with winds larger than 10m/s
- Low relative humidity and high wind present at the same time
- Low clay content
- High Quartz content

Outdoor erosion – field study on height and orientation

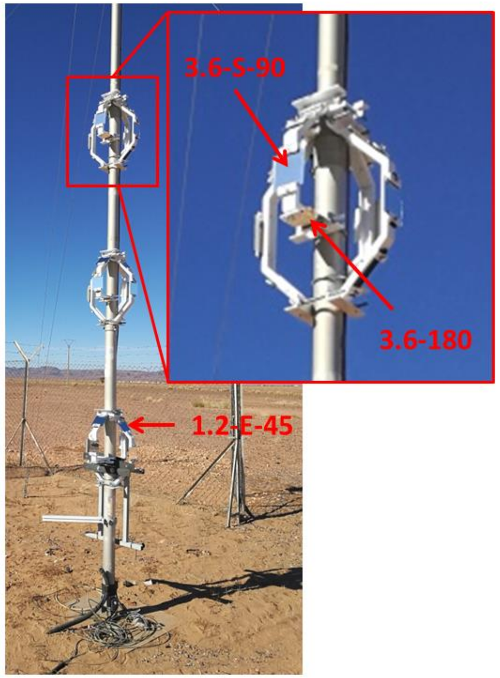


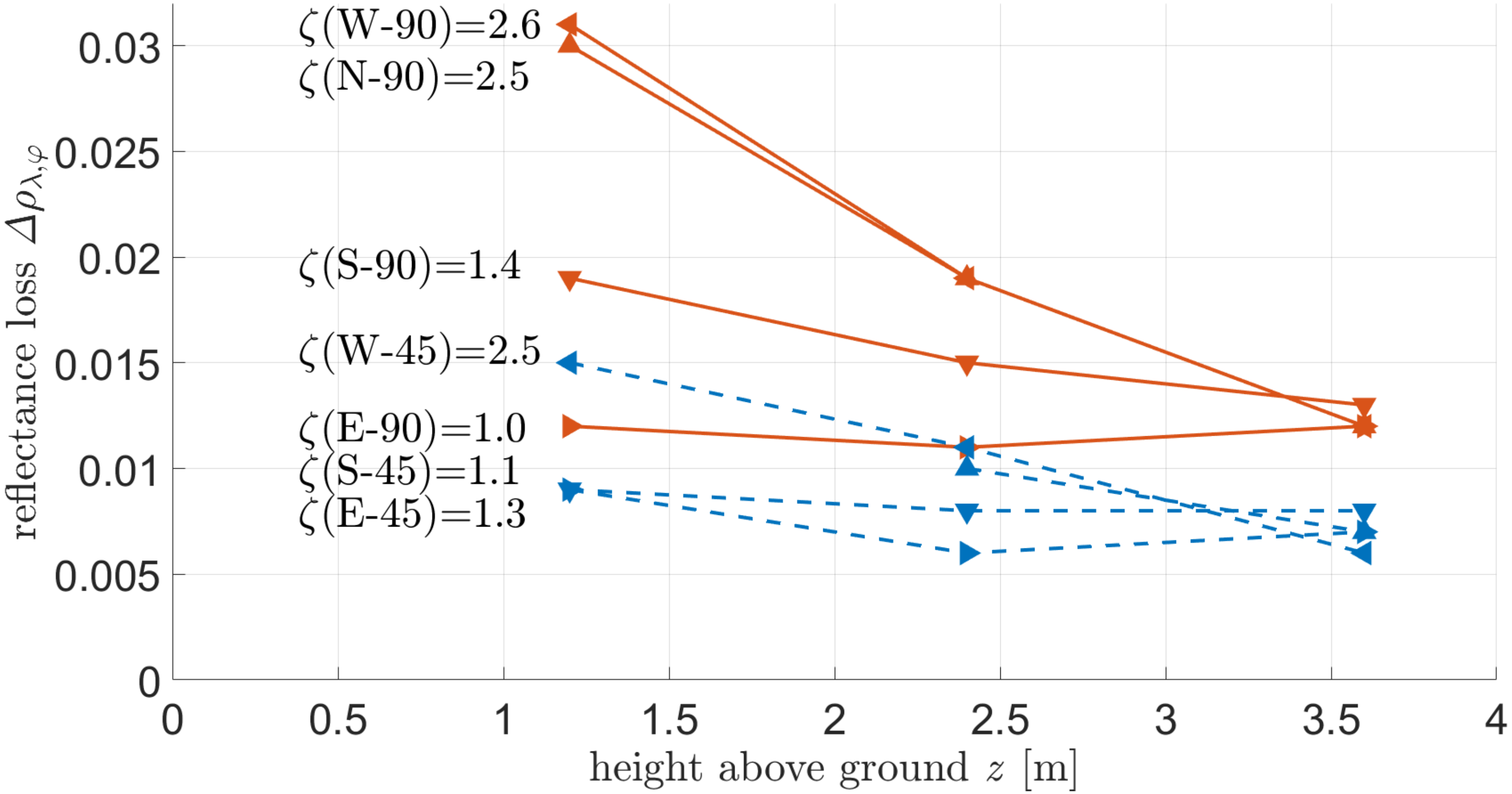
Erosion tree in Zagora equipped with 27 reflectors.

- Exposure on three different heights ***z*** above ground (**1.2**, **2.4** and **3.6**m).
- For every ***z***, four principal orientations (North, East, South and West).
- For every orientation, two elevation angles ϑ (45° and 90°). In addition one elevation at 180° per ***z.***
- In addition wind measurement
- Reflector characterization after 1 year.

[8]

Outdoor erosion – field study on height and orientation

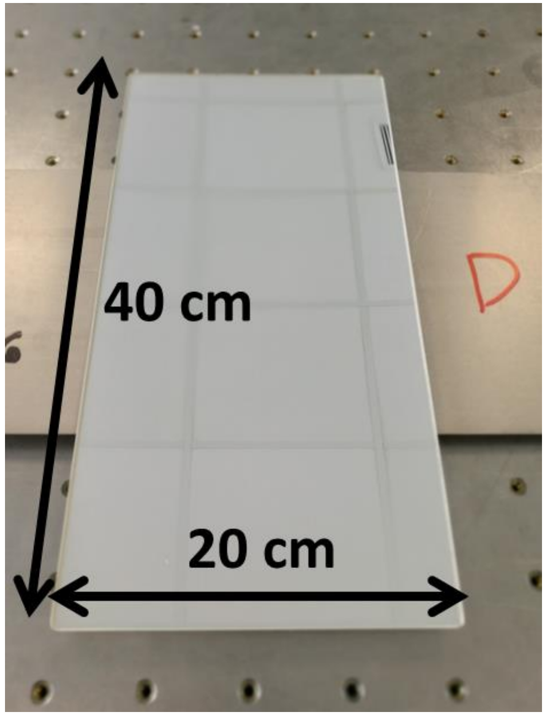


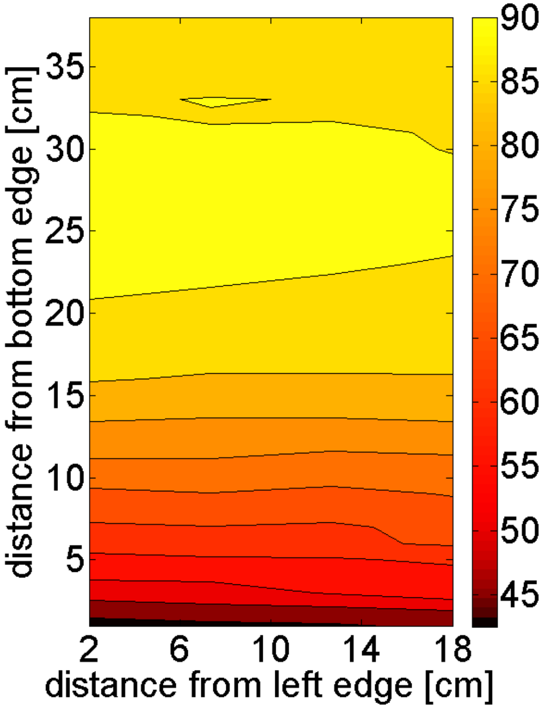


→ Erosion damage decreases with increasing height *z*, but different proportionality factor ζ

[8]

Outdoor erosion – field study on height and orientation

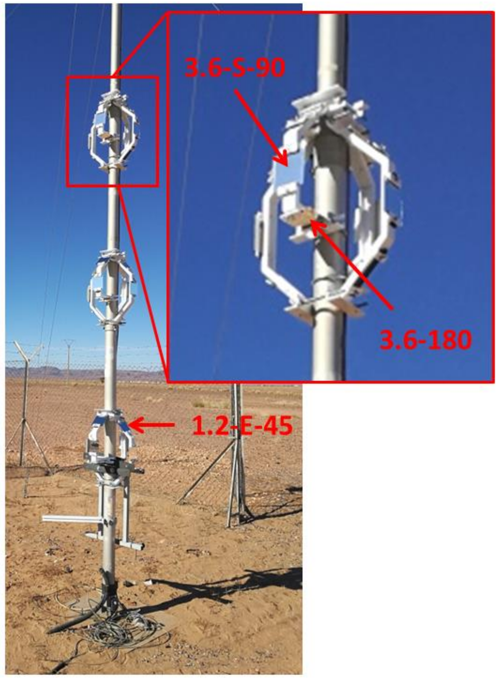


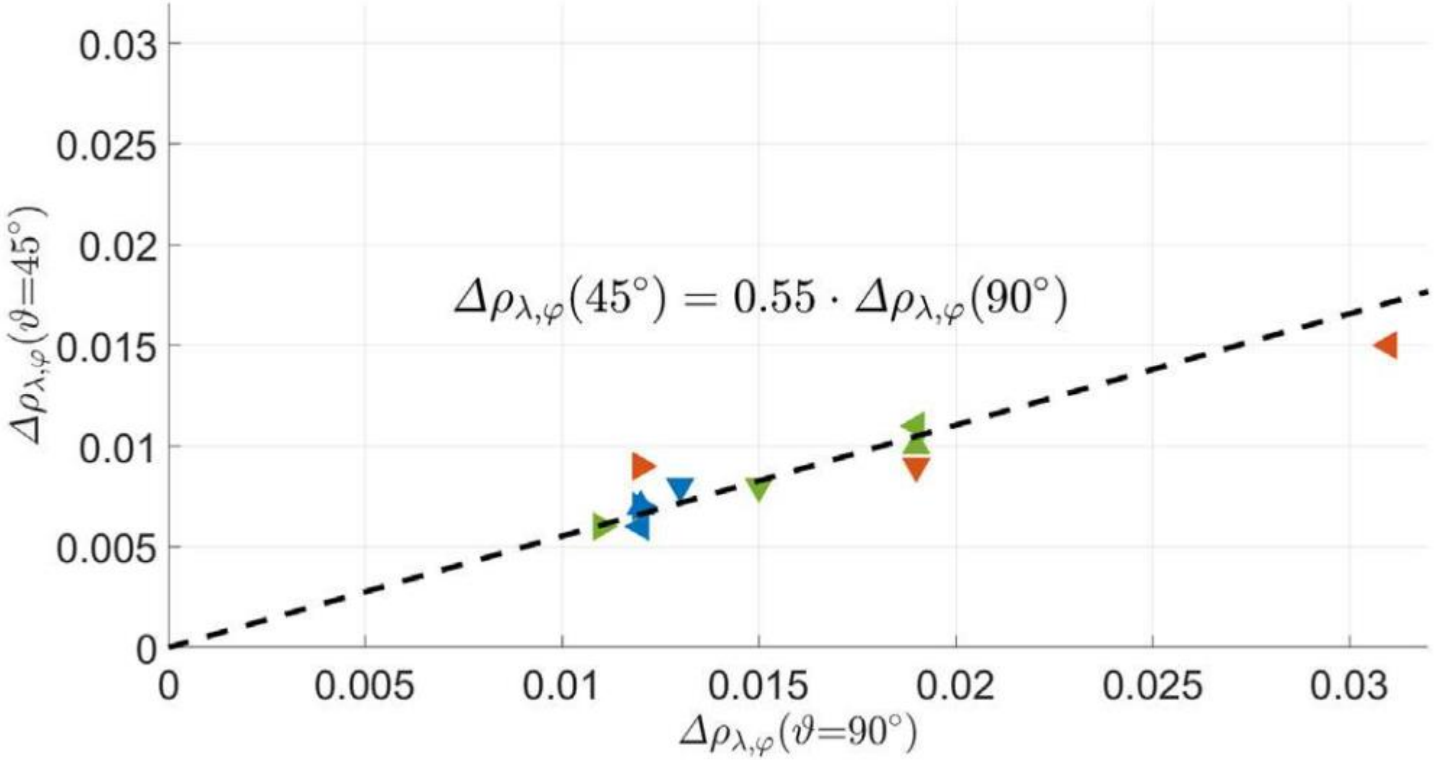


→ Erosion damage decreases with increasing height *z*, also confirmed in another outdoor campaign (more severe site)

[8]

Outdoor erosion – field study on height and inclination

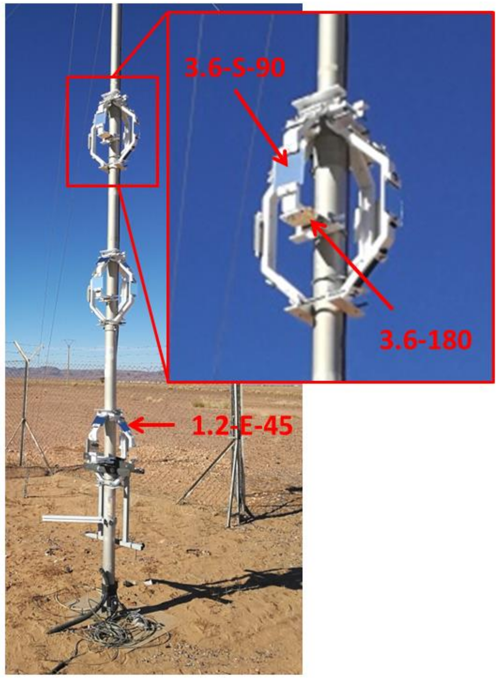


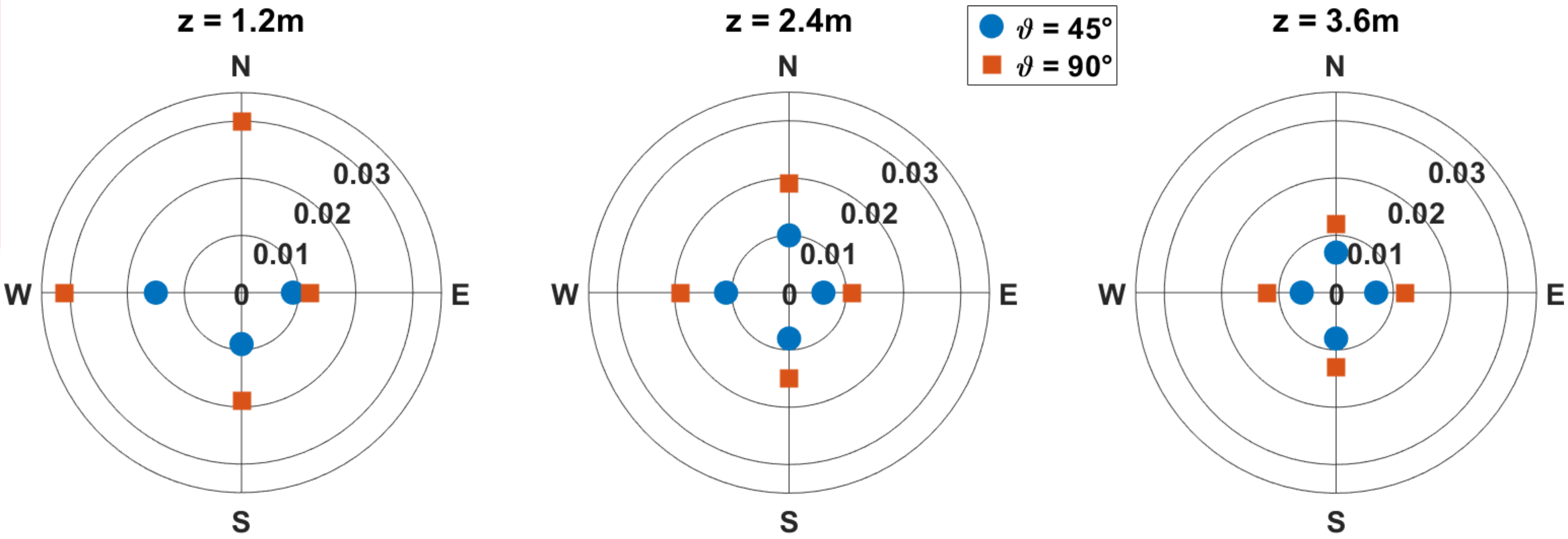


→ For all orientations samples exposed at ϑ=45° are less degraded than corresponding reflectors at ϑ=90°. Kinetic impact energy ∝ (sin α)²

[8]

Outdoor erosion – field study on height and orientation



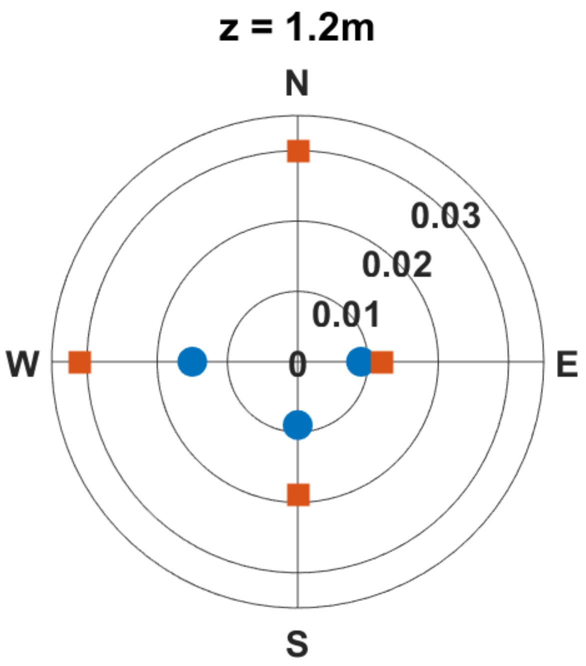


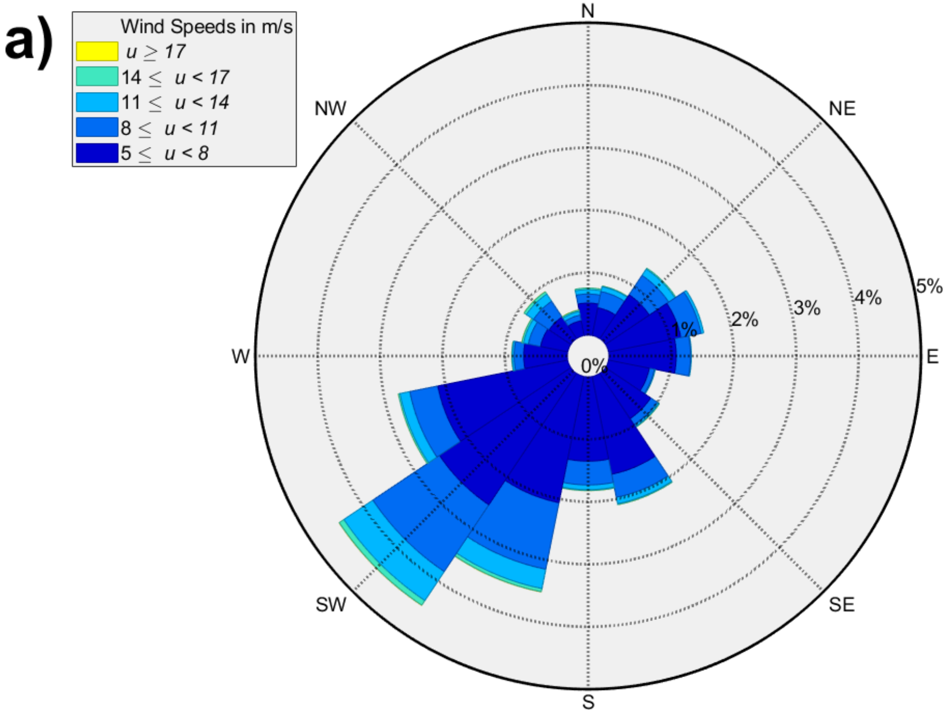
→ Different orientations lead to different optical degradation.

?Where does this anisotropic effect come from?

[8]

Outdoor erosion – field study on height and orientation



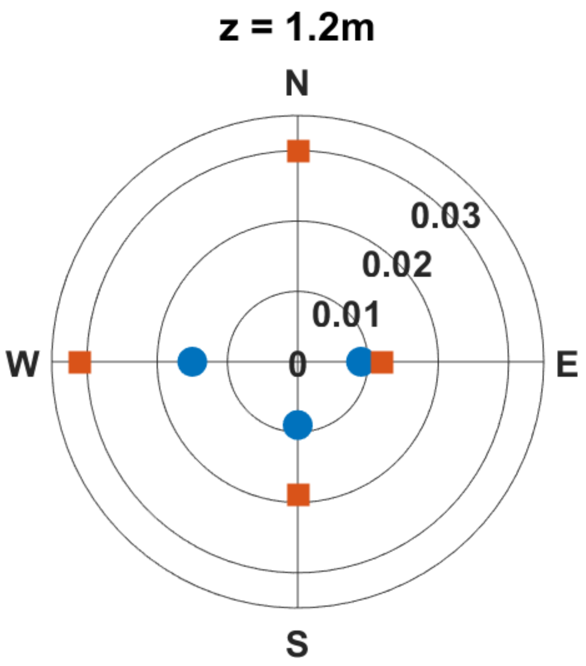


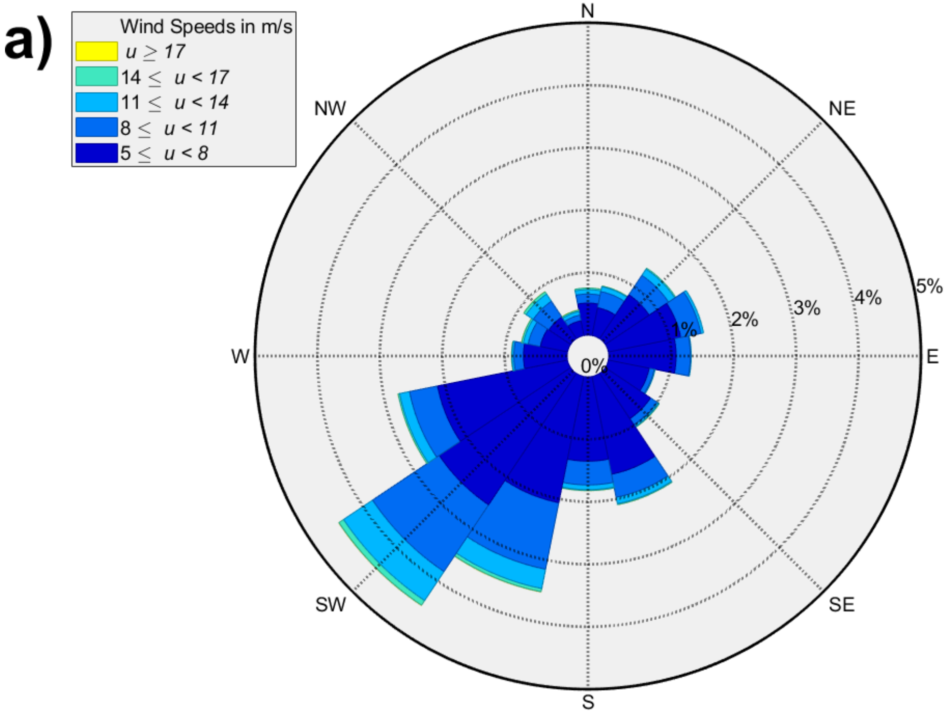
Wind velocities greater than 5 m/s are present over 25% of the time.

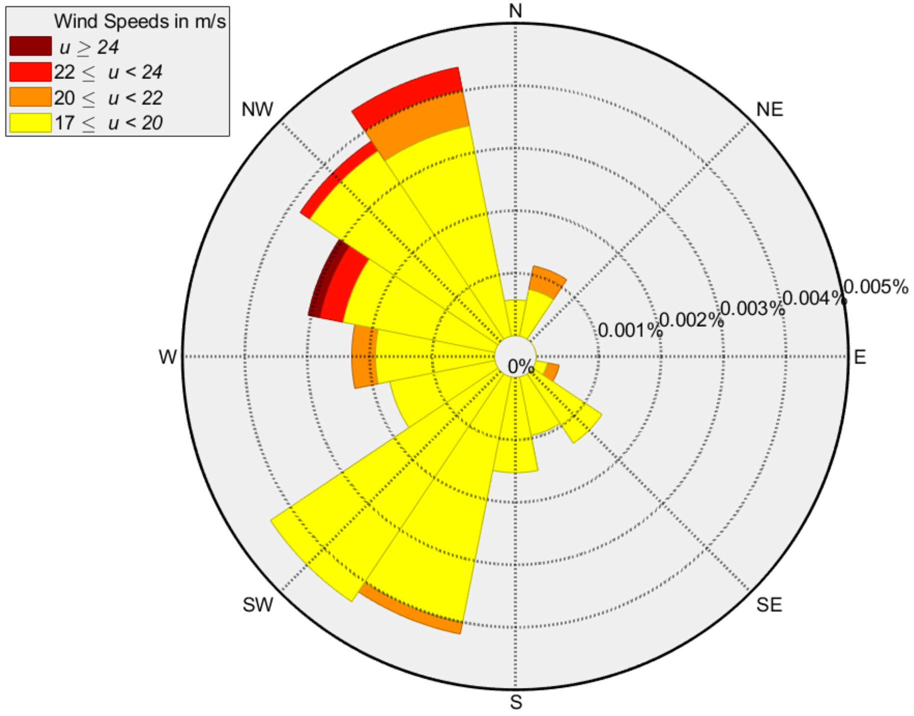
Most prominent direction is SW, ca. 10%.

[8]

Outdoor erosion – field study on height and orientation





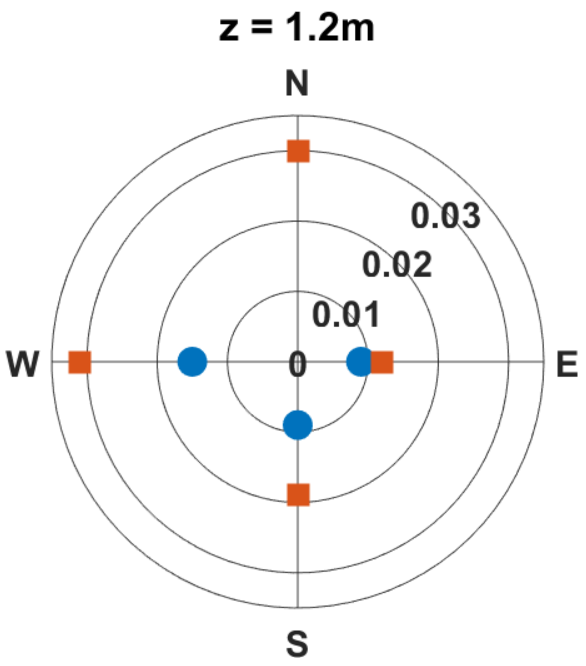


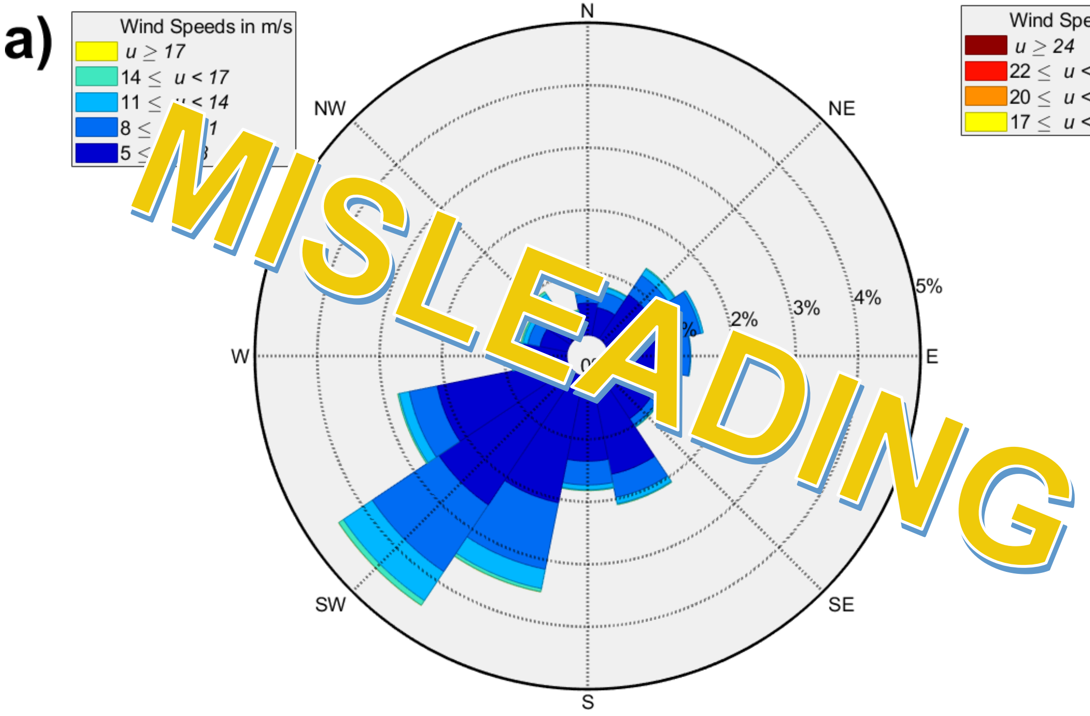
Only winds stronger than 17 m/s

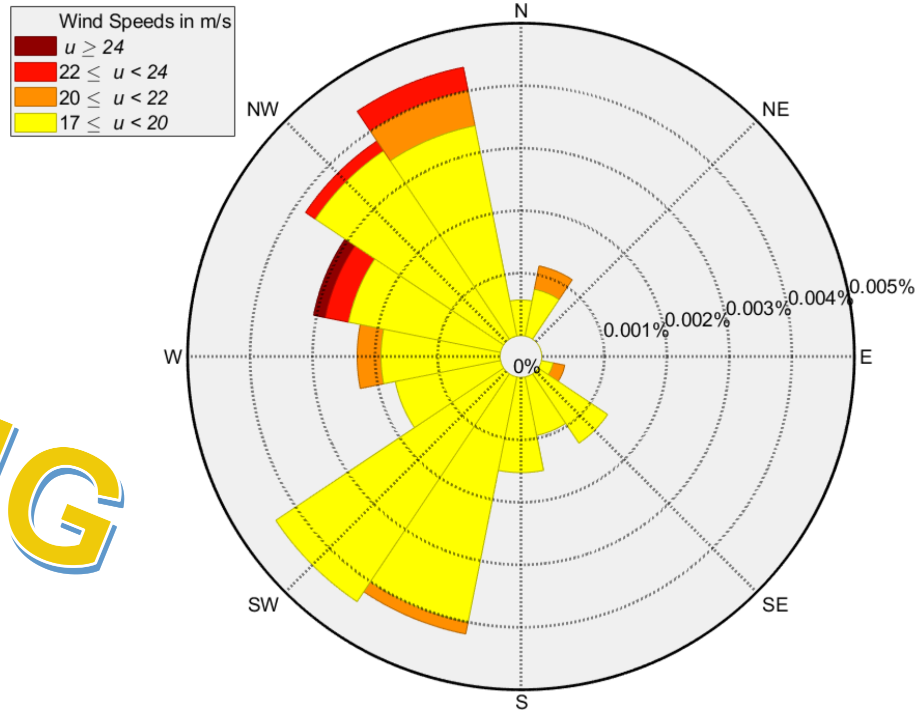
Strong winds (>22 m/s) exclusively from NW.

[8]

Outdoor erosion – field study on height and orientation







High velocities more important than duration

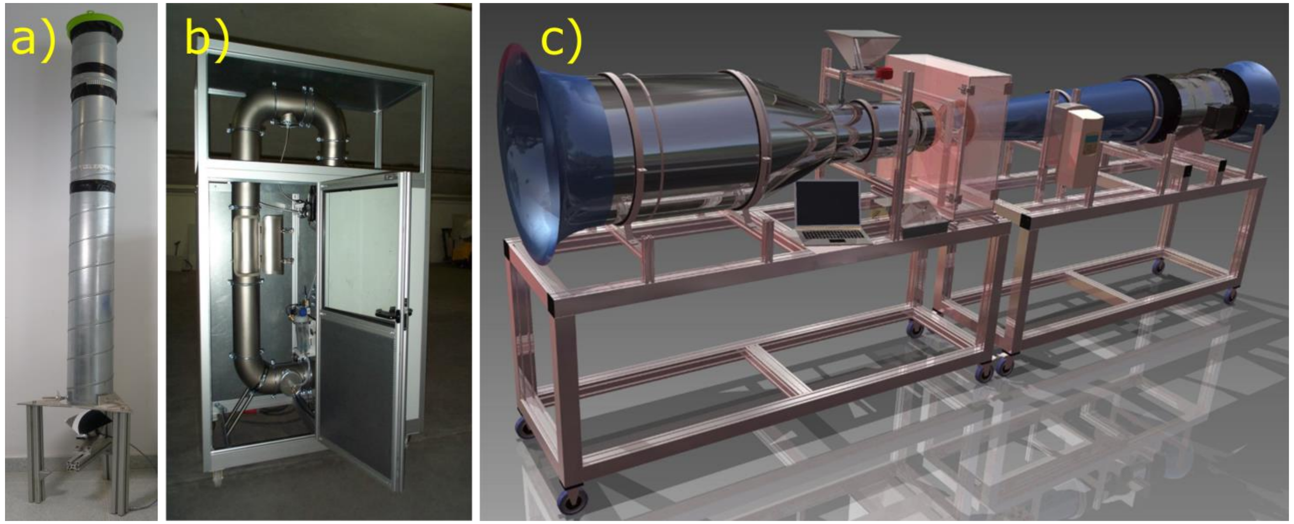
[8]

short break & discussion

afterwards: artificial erosion simulation

Objective

Three different erosion simulation setups: a) soil pipe, b) closed loop wind tunnel and c) open loop wind tunnel.



[4]

Erosion setup 1: soil pipe

sand container

meshes

Used erosive material: Silica particles (diameter between 300-625 µm).

rotating sample under impact angle α

According to DIN 52348

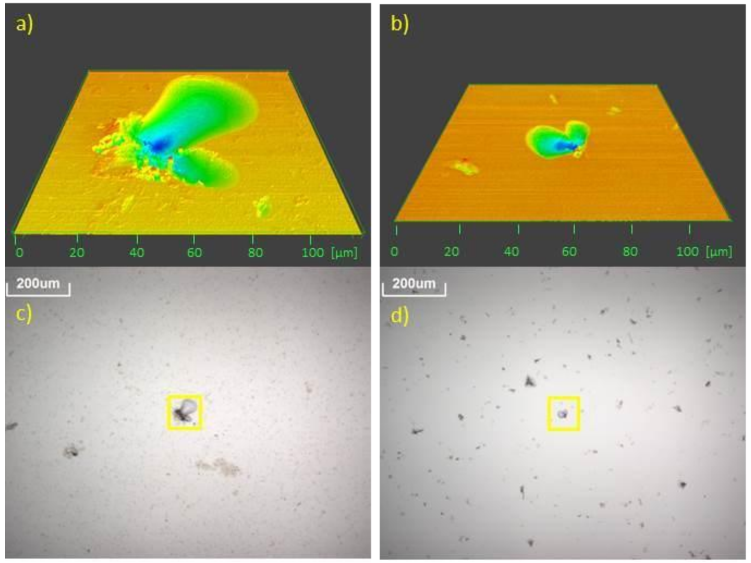
Investigated influences of:

- Total sand mass
- Impact angle
- Different reflector materials

- Impact speed
- Erosive material

Outdoor - Zagora

Laboratory – soil pipe



[3,9]

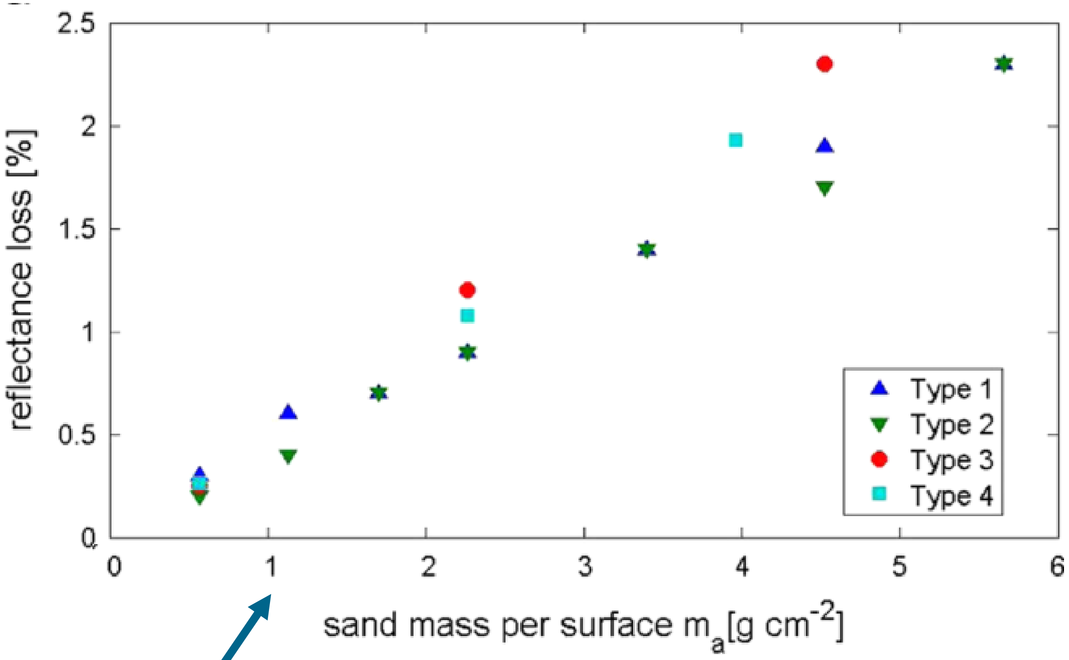
Erosion setup 1: soil pipe

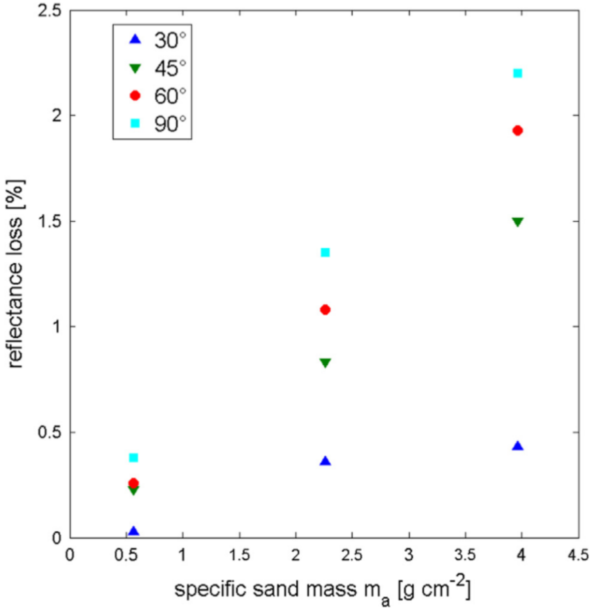
Used erosive material: Silica particles (diameter between 300-625 µm).

Investigated influences of:

- Total sand mass
- Impact angle
- Different reflector materials

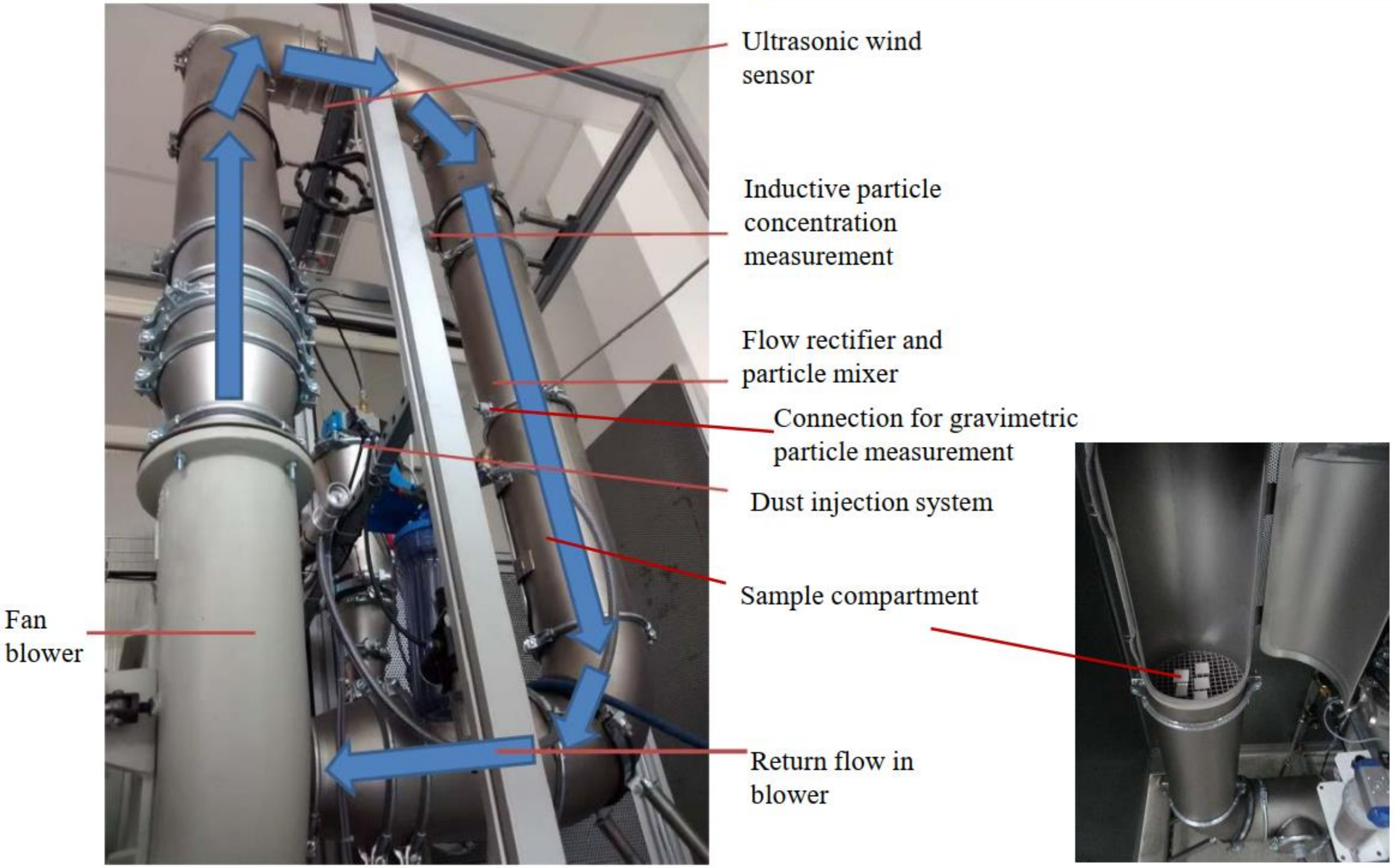
m_a :sand mass referred to tube cross section





[3]

Erosion setup 2: sandstorm chamber (closed loop)

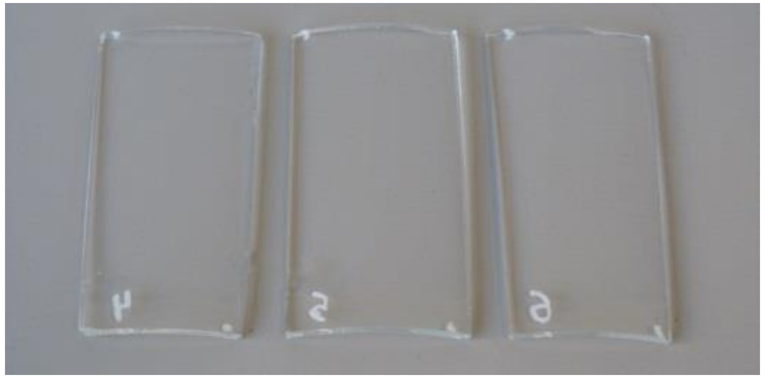


Erosion setup 2: sandstorm chamber (closed loop)

Technical parameters:

- Wind velocities from 5 m/s to 30 m/s.
- Various different test dust types possible (ISO 12103-1 A4 Arizona Quartz dust)
- Dust concentration ranges from 50 mg/m^3 to 3000 mg/m^3.
- Flexible test duration from few minutes to many hours.
- Homogeneous erosion on the sample.
- Requirement for sample dimension: around 6 x 6 cm

Erosion setup 2: sandstorm chamber (closed loop)



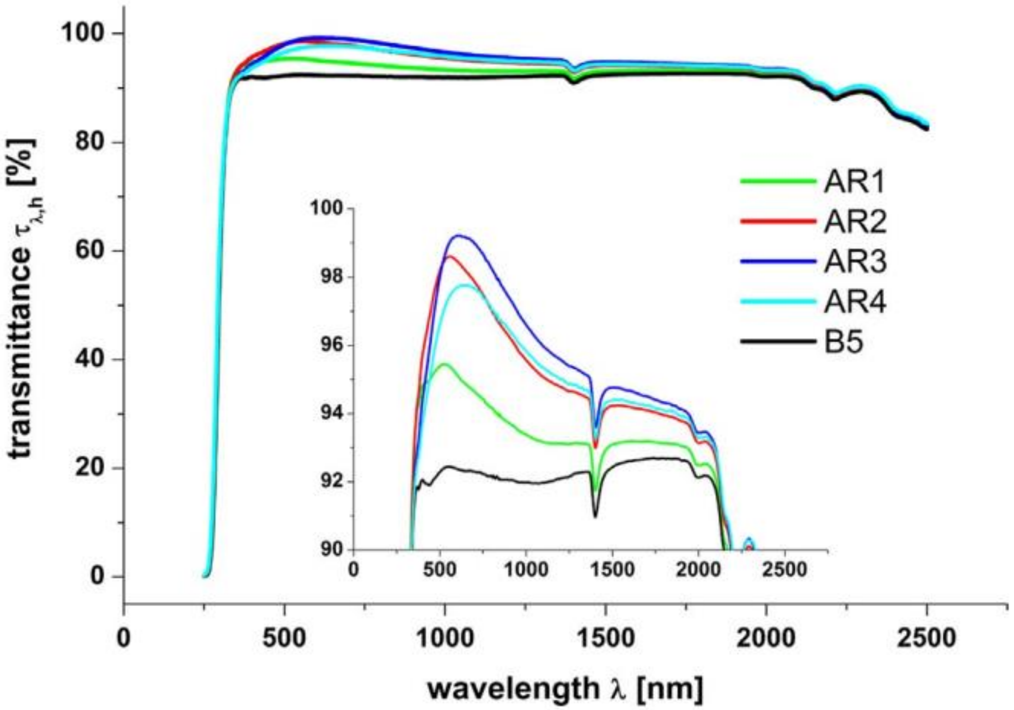
Glass envelope tubes, different anti-reflective (AR) coatings:

AR1-AR4 and B5 (without coating)

Values of $\tau_{s,h}$ for all the samples before testing in %.

	AR1	AR2	AR3	AR4	B5
$\tau_{s,h}$	94.1 ± 0.1	96.5 ± 0.0	97.0 ± 0.0	96.0 ± 0.1	92.1 ± 0.0

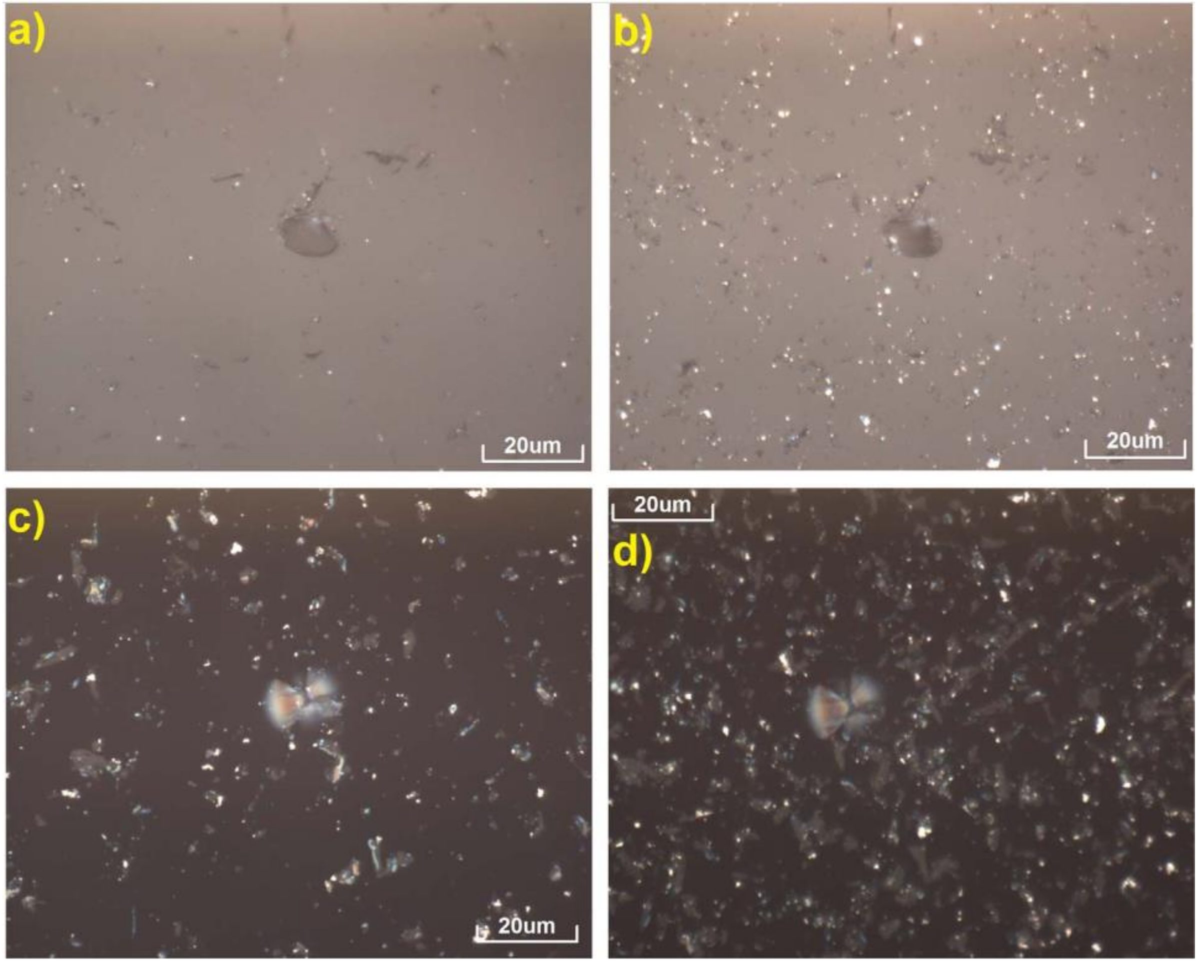
Initial transmittance



[10]

Erosion setup 2: sandstorm chamber (closed loop)

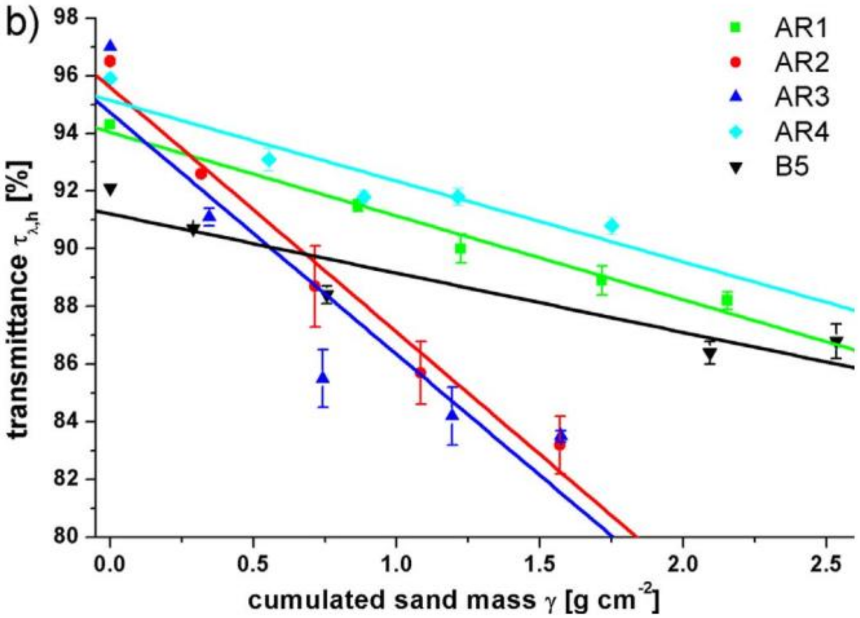
	after 10 min	after 40 min
uncoated (B5)		
coated (AR3)		

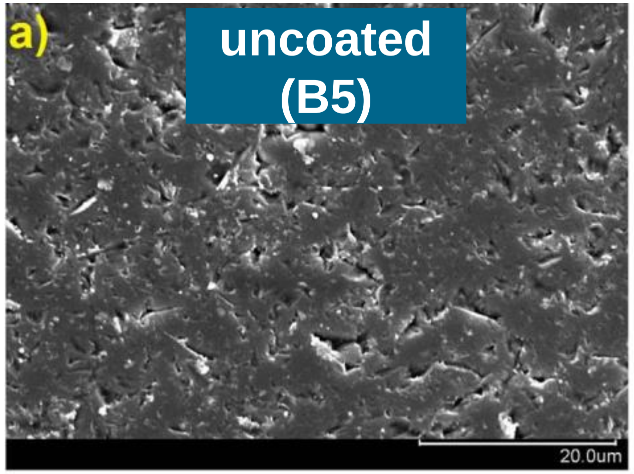


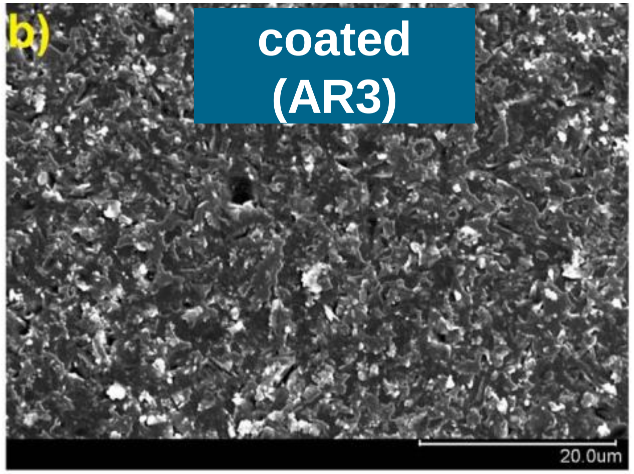
[10]

Erosion setup 2: sandstorm chamber (closed loop)

Decrease of solar-weighted transmittance with testing time

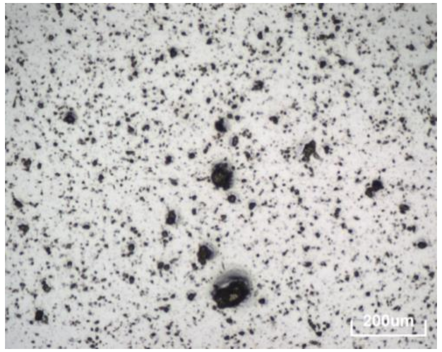




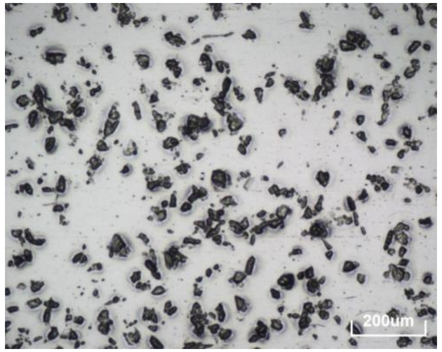


Erosion setup 2: sandstorm chamber (closed loop)

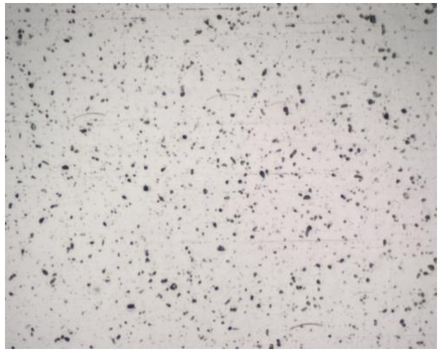
Zagora 20 month



Soil Pipe



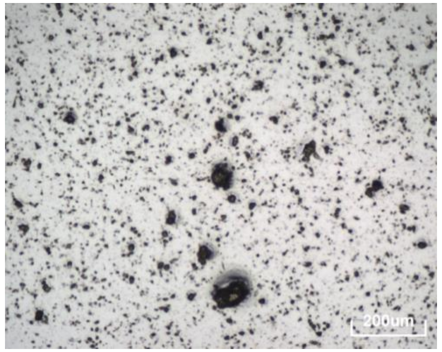
SSC



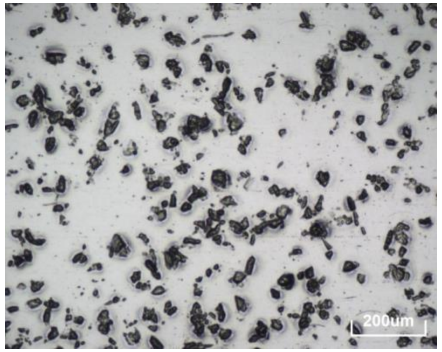
Disadvantages: no satisfying dust concentration control, no easy change of dust type, no complete adjustment of erosion results.

Erosion setup 2: sandstorm chamber (closed loop)

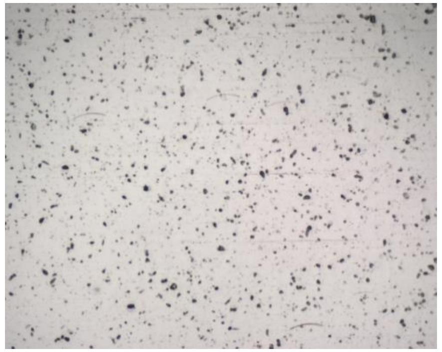
Zagora 20 month



Soil Pipe

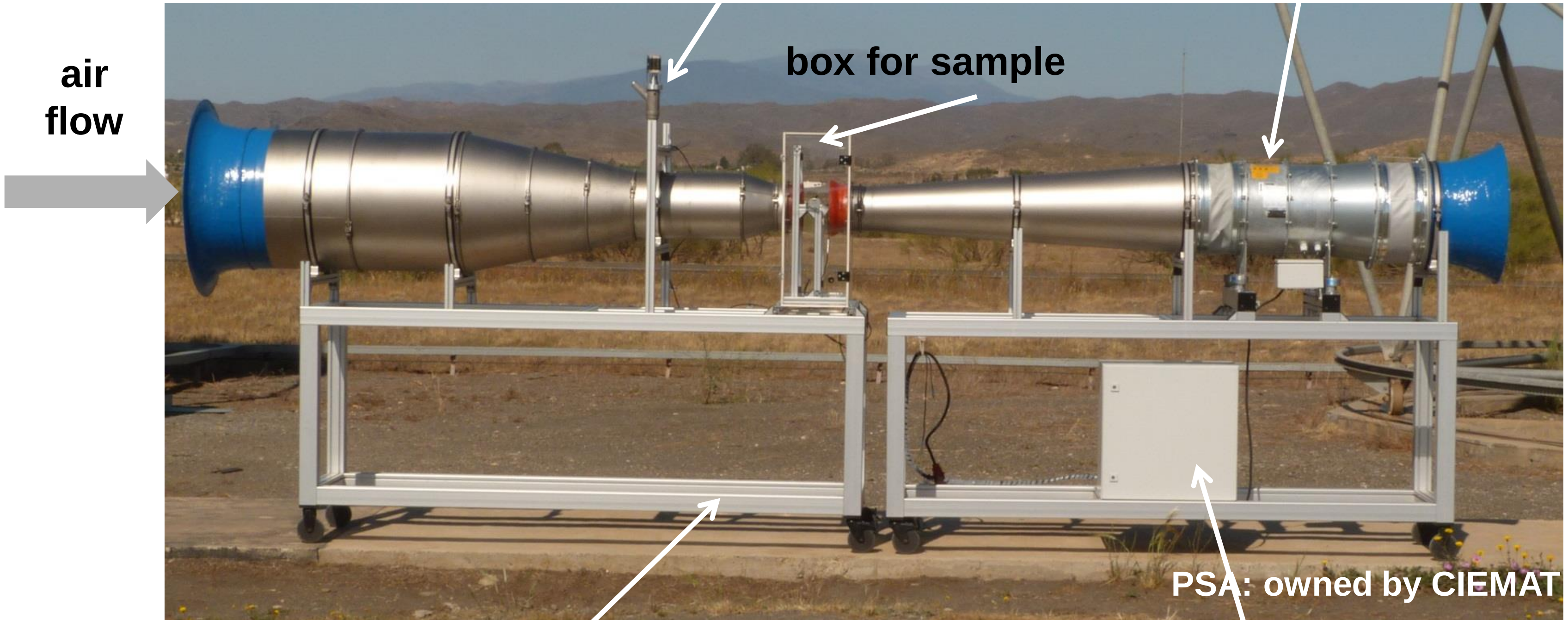


SSC

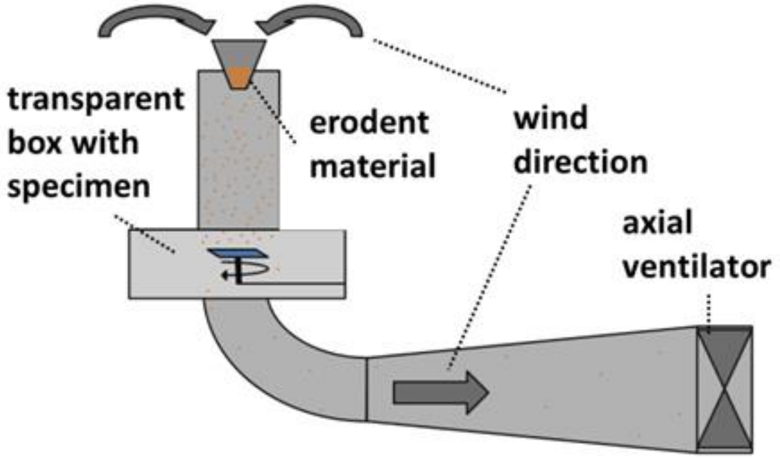


Search for a new parameterization that characterizes erosion defects more accurately than reflectance/transmittance losses.

Erosion setup 3: sandstorm chamber (open loop)

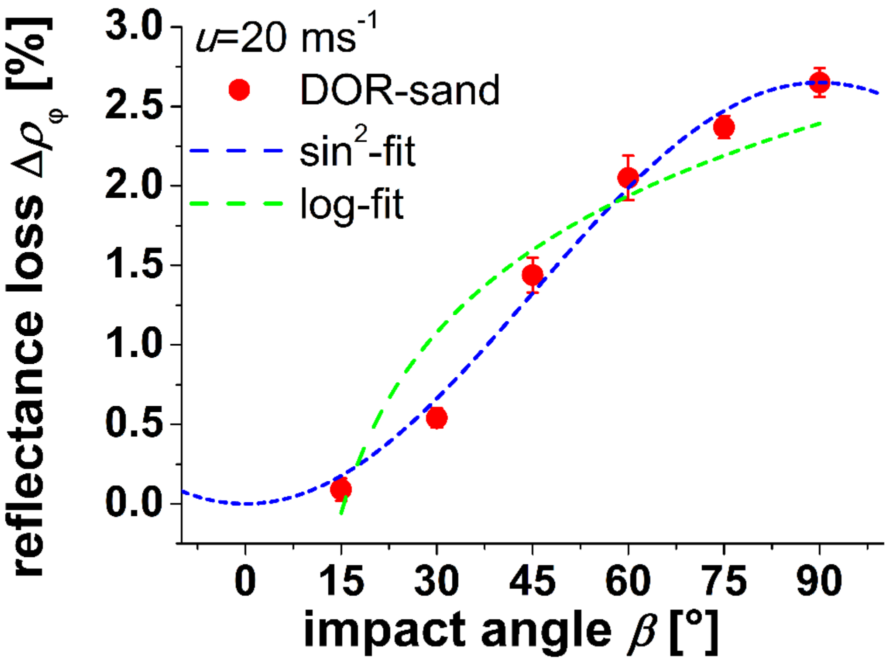


Erosion setup 3: sandstorm chamber (open loop)

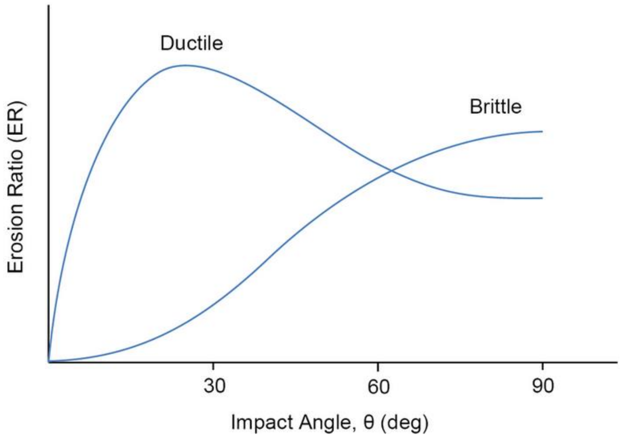


Open loop wind tunnel in suction mode with high variability of input parameters allowed for a comprehensive study of erosion determining influences coming from: **particle velocity, impact angle, erodent material**

Erosion setup 3: sandstorm chamber (open loop)



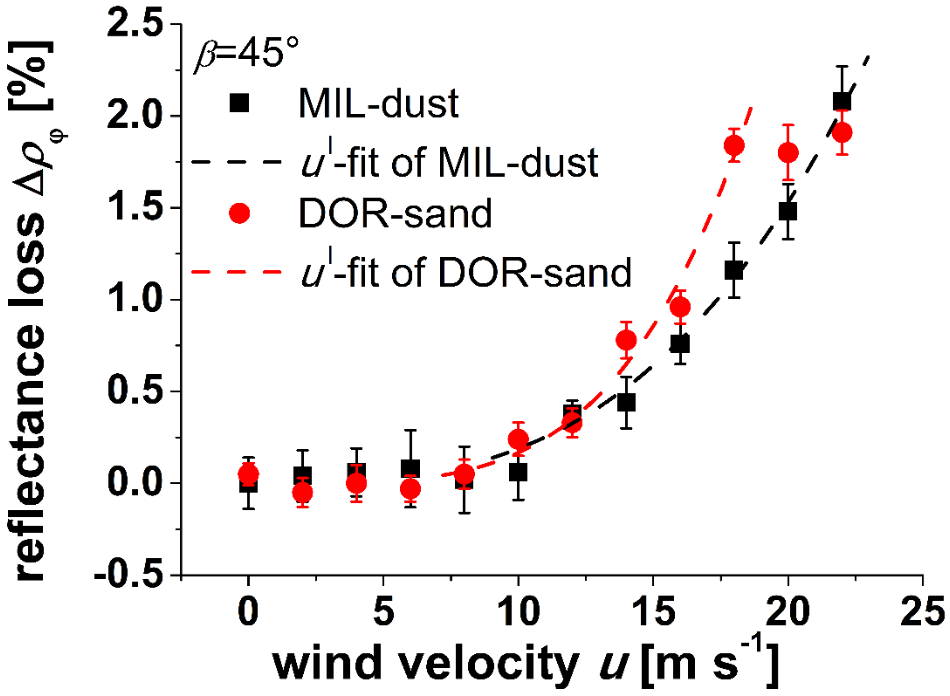
DOR-sand: 15-300µm



- Theory differentiate brittle and ductile materials.
- Fit because $E_g \approx \vec{u}^2 = (u \cdot \sin \beta)^2$

[11,12]

Erosion setup 3: sandstorm chamber (open loop)

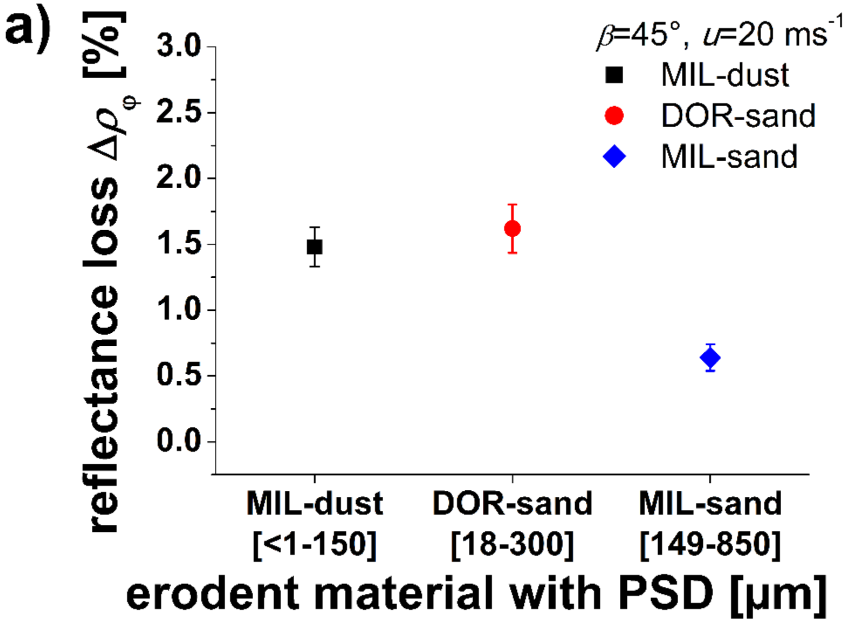


MIL-dust: <150µm
DOR-sand: 15-300µm

- Mechanical wear exhibits minimum threshold; below negligible.
- Relation between impact energy (E_g) and wear can be described as power law.
- For DOR-sand also maximum threshold observed →All particles do maximum damage.

[12]

Erosion setup 3: sandstorm chamber (open loop)

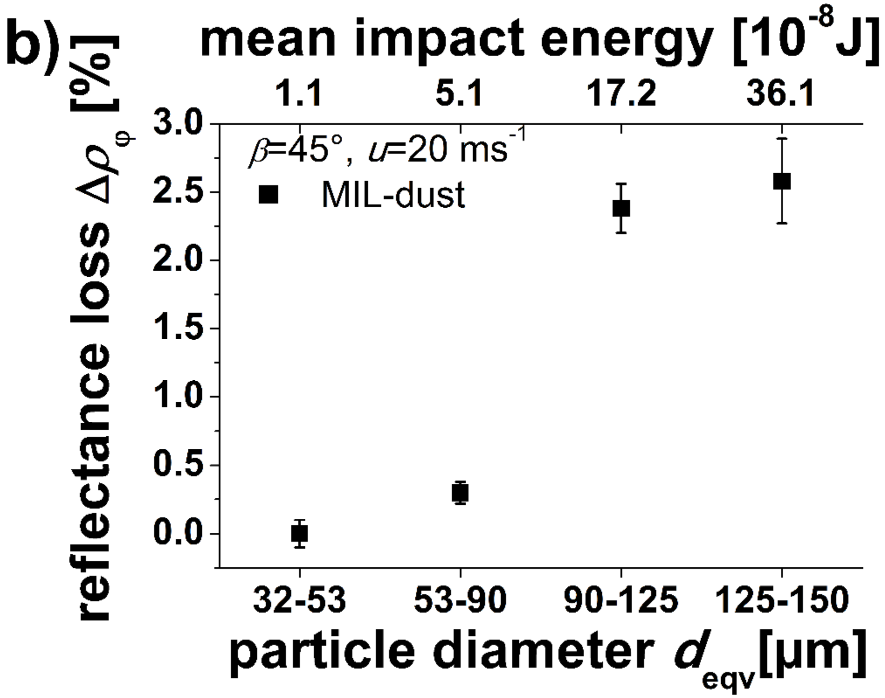


MIL-dust: <150µm
DOR-sand: 15-300µm
MIL-sand: 150-850µm

- MIL-sand largest particles and smallest Δρ.
  → Threshold effects and particle number per impact mass.
- Same investigation with higher resolution…

[12]

Erosion setup 3: sandstorm chamber (open loop)

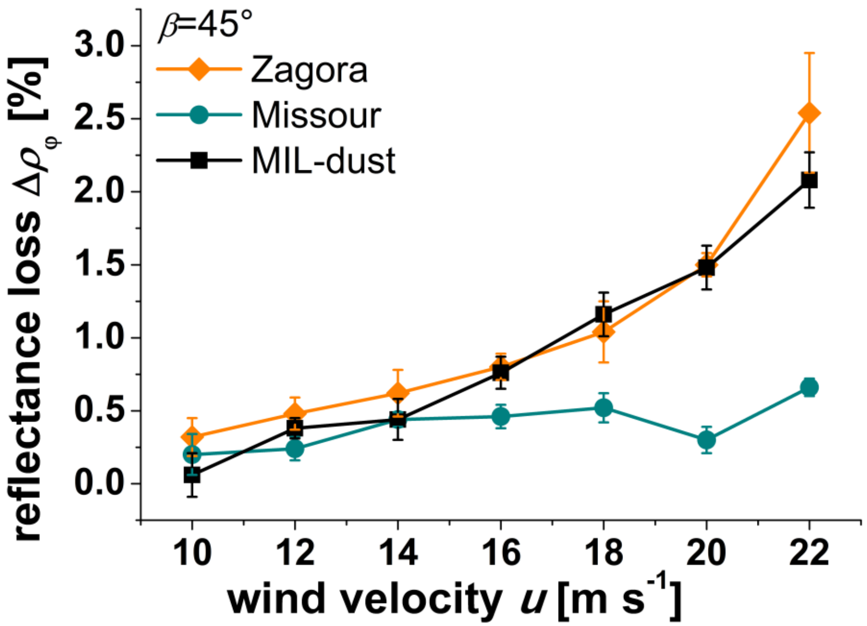


Sieve MIL-sand in four size fractions: see subscript range

→ Aeolian erosion at typical field conditions becomes inefficient for quartz particles smaller than 50µm.

[12]

Erosion setup 3: sandstorm chamber (open loop)

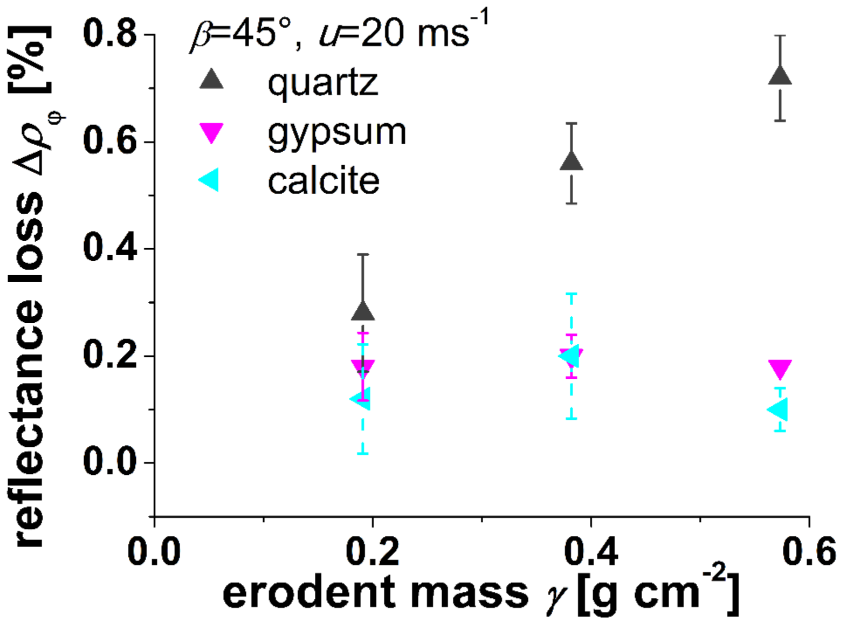


All particle types sieved to same size range.

→ Material from Zagora more aggressive than Missour material.
- Particle characteristics (shape, mineralogy)

[12]

Erosion setup 3: sandstorm chamber (open loop)



All particle types sieved to same size range.

→ Quartz highest erosion potential, due to its hardness. (quartz 7, gypsum 2, calcite 3)

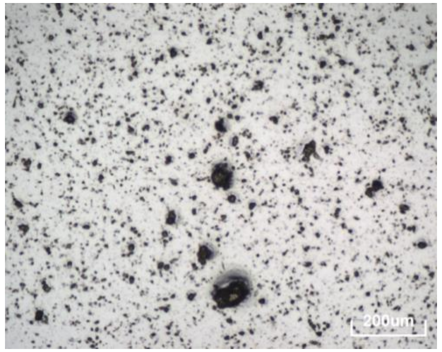
→ Gypsum and calcite contents in natural material not responsible for erosion effects under typical conditions.

[12]

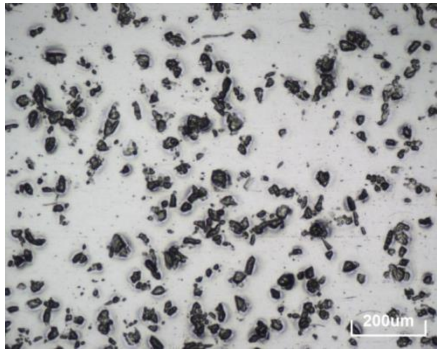
Erosion Testing – Standardization - DSDD

- How to quantify erosion ?
- Reflectance loss ρ not meaningful, since one large defect can cause similar Δρ as a lot of small defects while the consequences might be completely different.
- Instead of ρ use image analysis to obtain *defect size density distribution DSDD*.

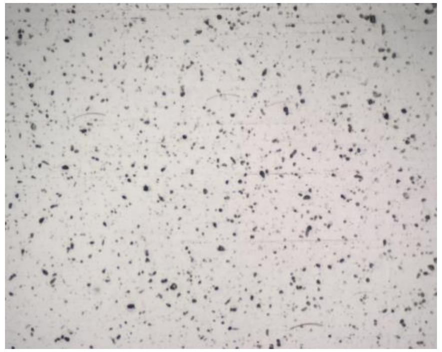
Zagora 20 month



Soil Pipe

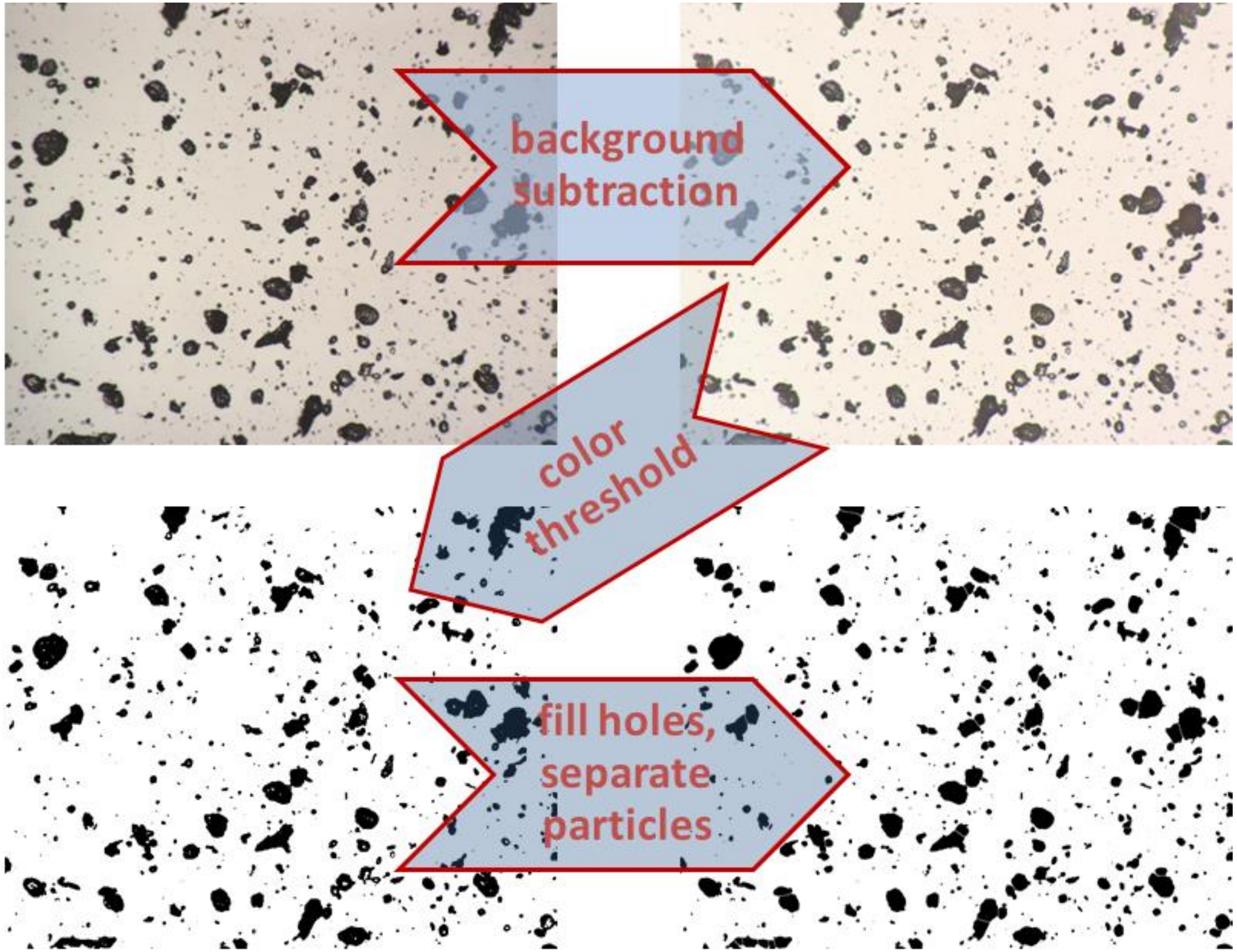


SSC



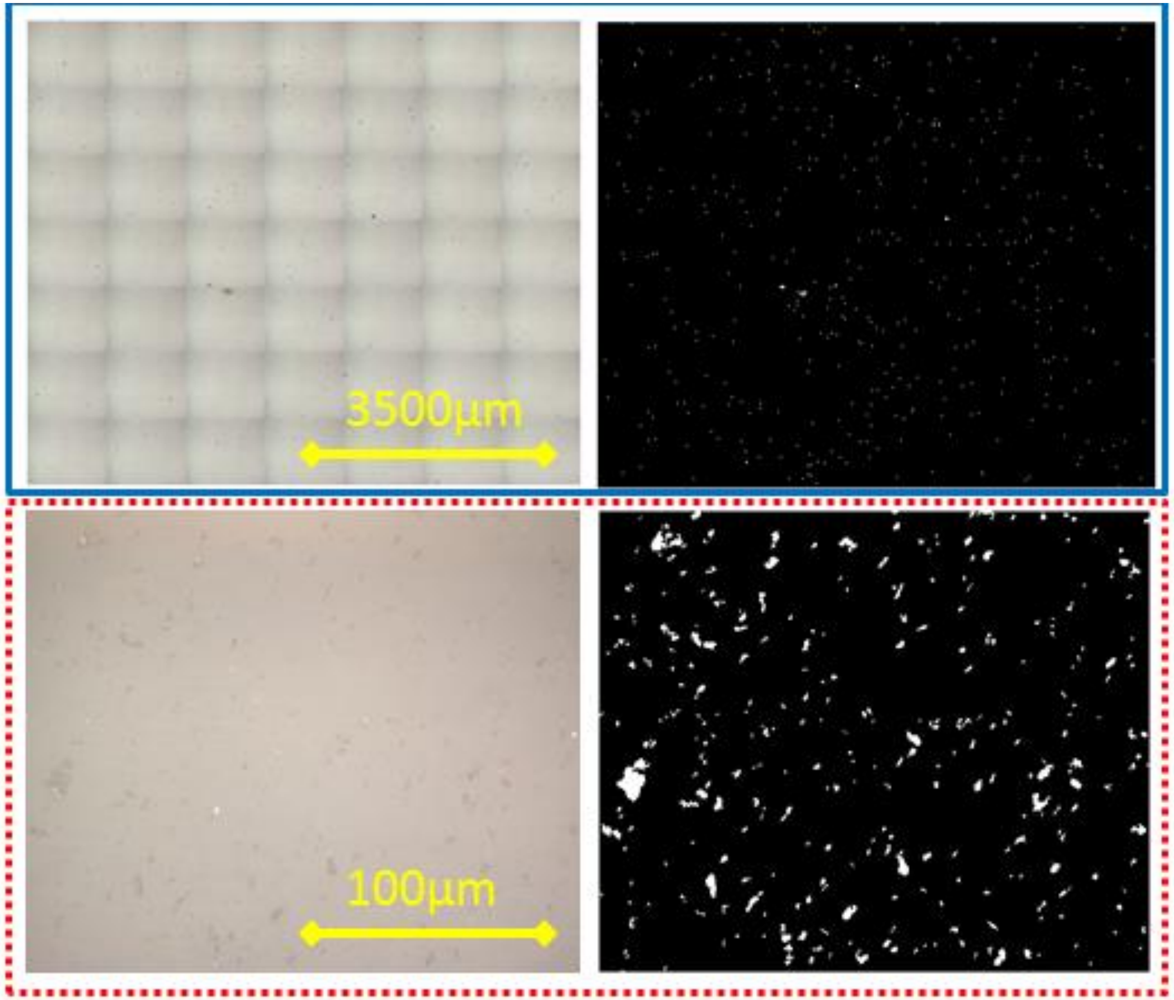
Erosion Testing – Standardization - DSDD

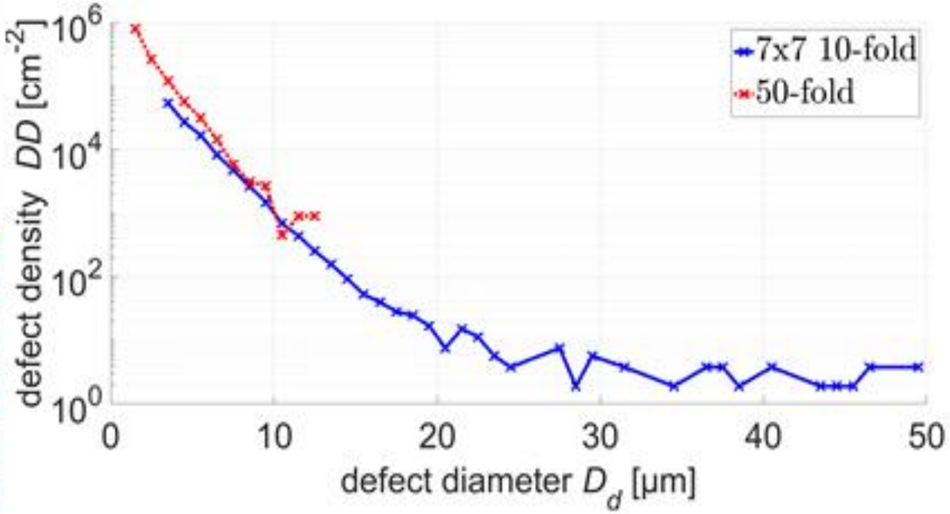
Similar image analysis technique as for optical sand particle size determination.



Erosion Testing – Standardization - DSDD

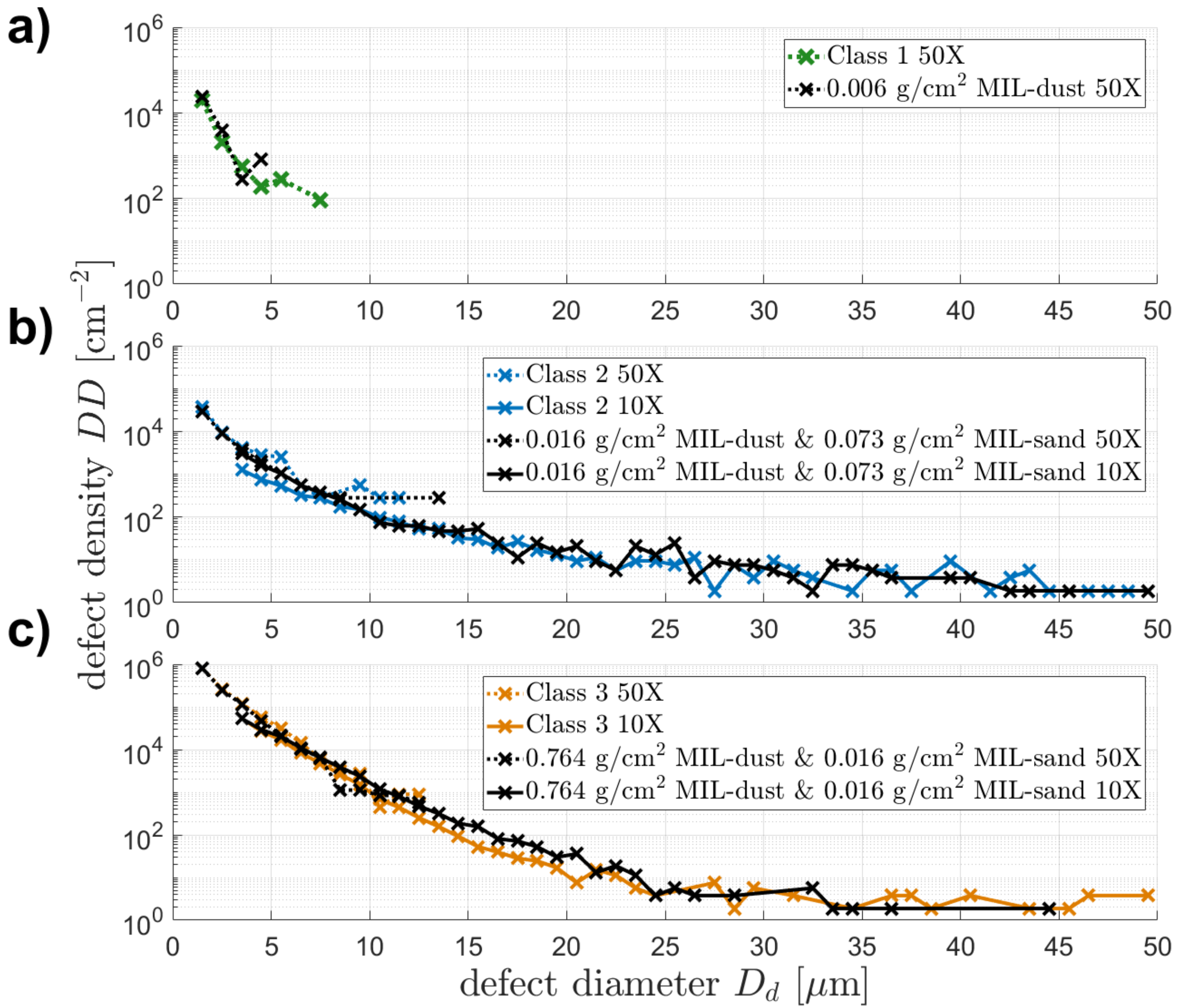
Use two different magnifications of microscope and combine them to account for whole range of defect sizes. Best (100 x 100 with high magnification but kills RAM)



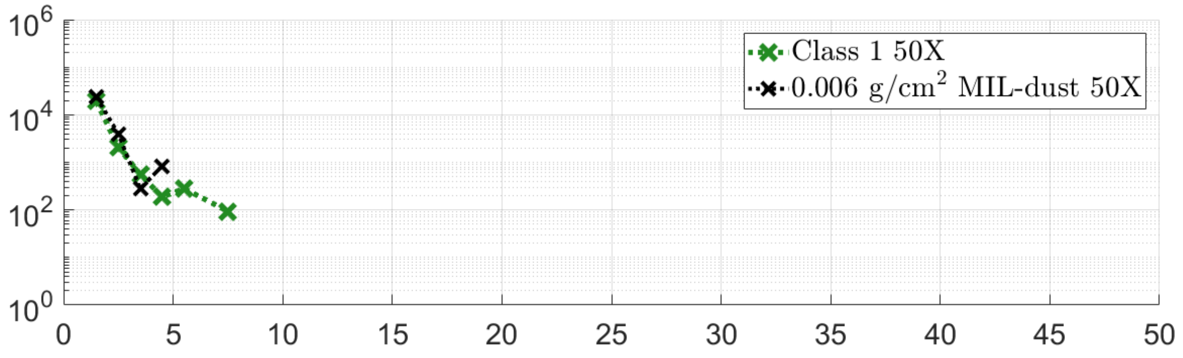


Erosion Testing – Standardization - DSDD

- Rank outdoor sites regarding the observed DSDD in three different erosion classes.
- Find adequate parameters in the Sandstorm chamber to simulate the same DSDD.



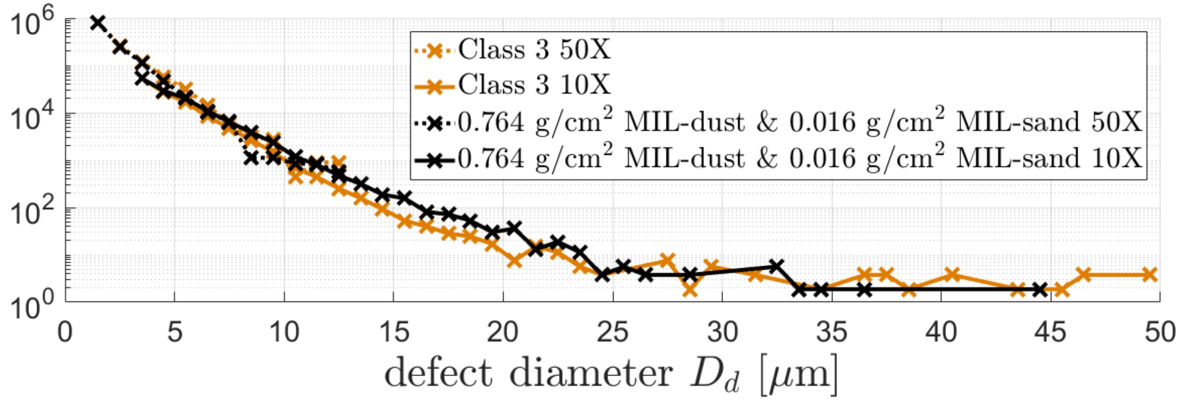
Erosion Testing – Standardization - DSDD



Lifetime assessment:

- Outdoor exposure for X years
- Determine DSDD and find necessary particle mass in artificial aging test to simulate X years.
- Multiply the determined particle mass in order to achieve simulation for e.g. 10 years.
- Class 1 for 10 years, use 0.06g/cm² → Δρ around 2.5% (1 year Δρ ca. 0.25%) linear behavior.

Erosion Testing – Standardization - DSDD



Lifetime assessment:

- Class 3 for 10 years Δρ around 38% (1 year Δρ ca. 5%) NON-LINEAR behavior.

Thank you for your attention

Contact: Florian.Wiesinger@dlr.de

References

[1] A techno-economic feasibility study on the use of distributed concentrating solar power generation in Johannesburg - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Parabolic-Trough-CSP-Plant-in-the-Mojave-Desert-Sitenet-2008_fig2_265231140 [accessed 31 Aug, 2022]

[2] Hanrieder, Natalie, Bernhard Mayer, and Robert Pitz-Paal. *Determination of atmospheric extinction for solar tower plants*. No. RWTH-2016-06390. Lehrstuhl für Solartechnik (DLR), 2016.

[3] Wiesinger, Florian, et al. "Sand erosion on solar reflectors: Accelerated simulation and comparison with field data." *Solar Energy Materials and Solar Cells* 145 (2016): 303-313.

[4] Reichenspurner, Sebastian. *Particle erosion on solar mirrors: Construction and first experimental stage of an open loop wind tunnel*. Diss. Hochschule Kempten, 2016.

[5] Darmenova, Kremena, et al. "Development of a physically based dust emission module within the Weather Research and Forecasting (WRF) model: Assessment of dust emission parameterizations and input parameters for source regions in Central and East Asia." *Journal of Geophysical Research: Atmospheres* 114.D14 (2009).

[6] Wiesinger, Florian, et al. "Assessment of the erosion risk of sandstorms on solar energy technology at two sites in Morocco." *Solar Energy* 162 (2018): 217-228.

[7] Wiesinger, Florian, et al. "Sandstorm erosion on solar reflectors: Highly realistic modeling of artificial aging tests based on advanced site assessment." *Applied energy* 268 (2020): 114925.

[8] Wiesinger, F., et al. "Sandstorm erosion on solar reflectors: A field study on height and orientation dependence." *Energy* 217 (2021): 119351.

[9] DIN 52348, Prüfung von Glas und Kunststoff, in: Verschleißprüfung-Sandrieselverfahren, DIN, 1985.

[10] Wiesinger, Florian, et al. "Sandstorm erosion testing of anti-reflective glass coatings for solar energy applications." *Solar Energy Materials and Solar Cells* 179 (2018): 10-16.

[11] Arabnejad, Hadi & Mansouri, Amir & Shirazi, Siamack & McLaury, Brenton. (2015). Evaluation of Solid Particle Erosion Equations and Models for Oil and Gas Industry Applications. 10.2118/174987-MS.

[12] Wiesinger, Florian Werner, Robert Pitz-Paal, and Martin Schmücker. *Erosion of solar reflectors in desert environments*. No. RWTH-2019-00903. Lehrstuhl für Solartechnik (DLR), 2019.