What does "normal-normal transmittance" mean for light-scattering materials?

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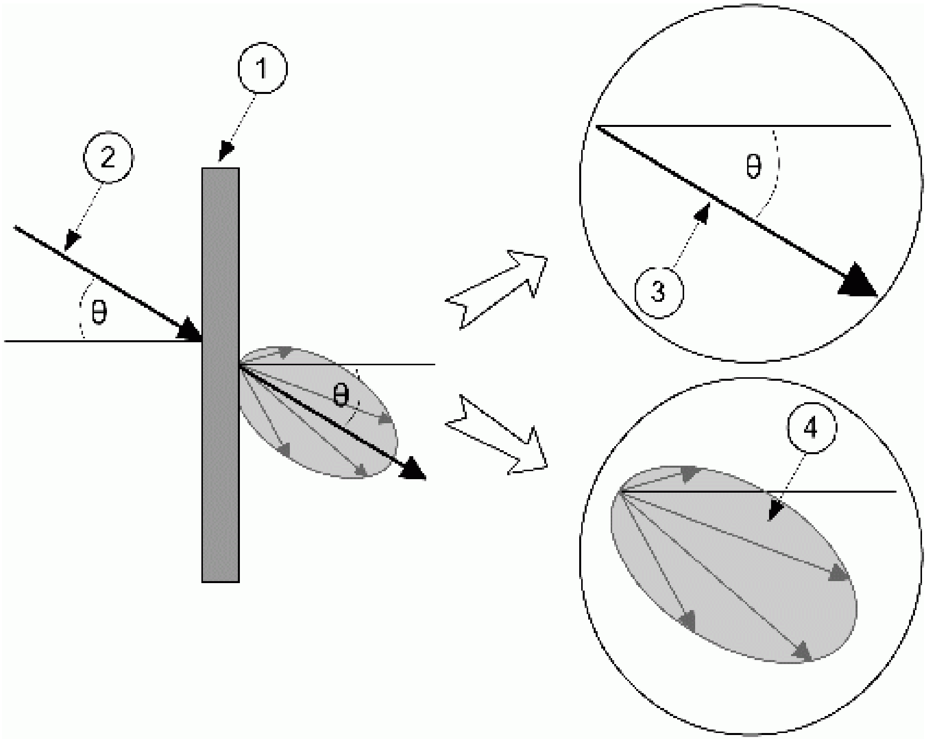
- Motivation
- Definitions
- Determining $\tau_{v,n-n}$ by measurement, concentrating on integrating spheres
- Characteristics of investigated solar-shading textiles
- Results for “critical” textile samples with regard to $\tau_{v,n-n}$
- Pullback method for improved agreement in $\tau_{v,n-n}$
- Outlook – further applications

Motivation

- Question: What does "normal-normal transmittance" mean for light-scattering materials?
- Answer (from EN 14500:2008):
  Fraction of normally incident radiation flux that is transmitted in accordance with the laws of geometrical optics, without diffusion or redirection

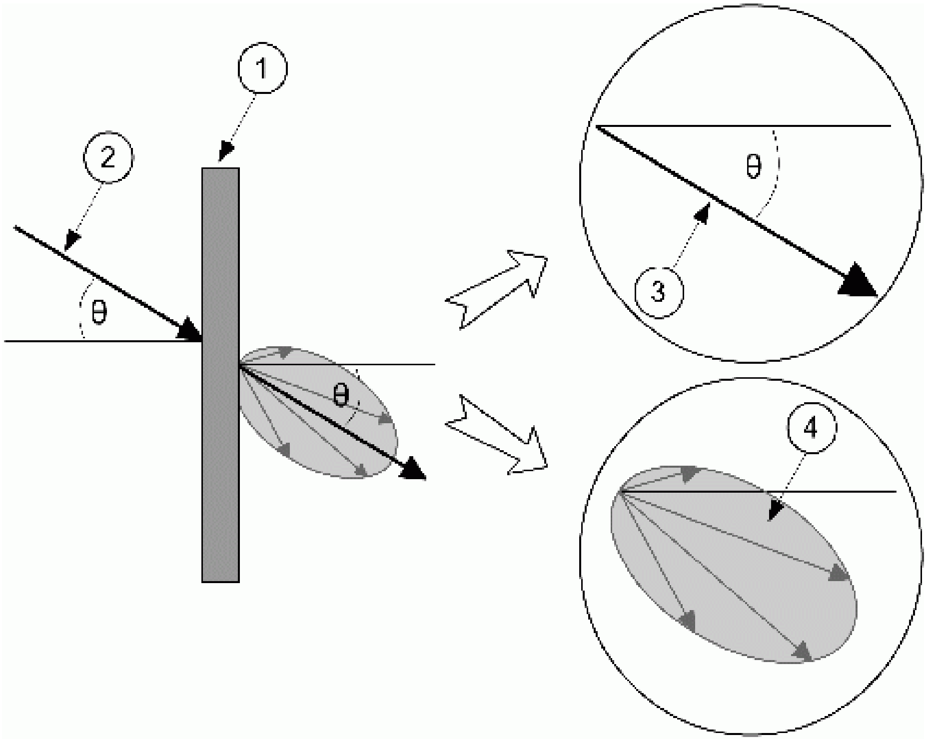
- Normal-normal transmittance is an input for performance metrics characterising solar-shading materials and glazing with respect to
  - Glare control
  - Protection against direct solar radiation
  - Night privacy
  - Visual contact with the outdoor environment

Nomenclature referring to transmittance from EN 14500



1. Solar-shading material
2. Incident directional radiation
3. Transmitted direct component radiation
4. Transmitted diffuse component radiation

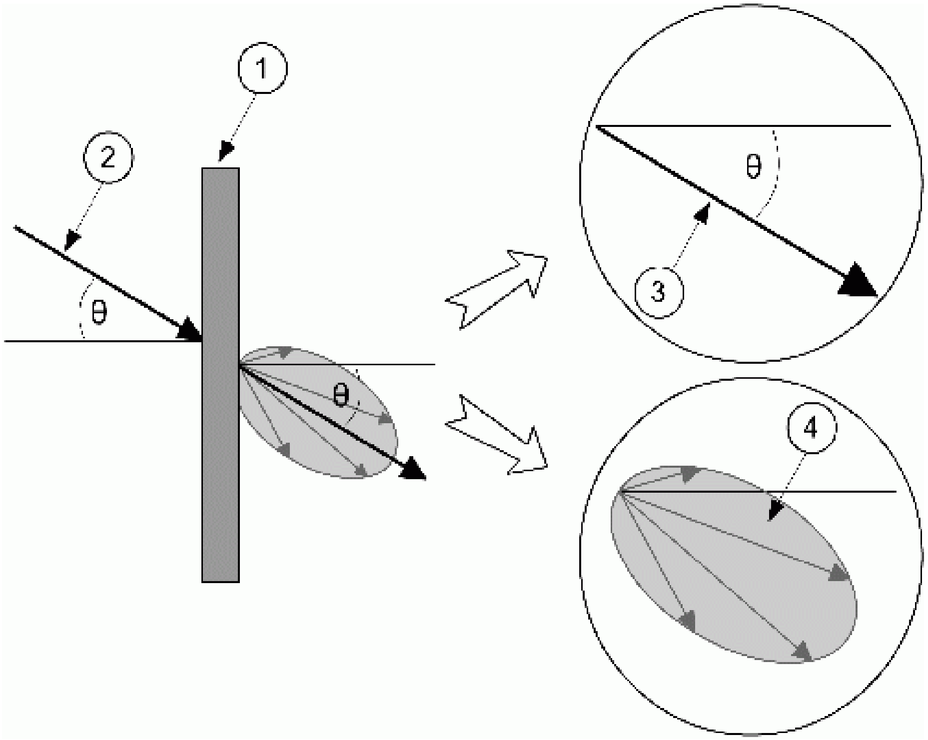
Nomenclature referring to transmittance from EN 14500



- « τ » transmittance
- « $_e$ » solar (energy)
- « $_v$ » visible (light)
- **« $_n$ » for normal $\theta = 0°$**
- « $_h$ » for hemispherical (collected in the hemisphere behind the sample plane),
- « $_{dif}$ » for diffuse radiation

$$\tau_{v,\ n\text{-}n} = \tau_{v,\ n\text{-}h} - \tau_{v,\ n\text{-}dif}$$

Measurement methods to determine $\tau_{v,\ n\text{-}n}$



- « τ » transmittance
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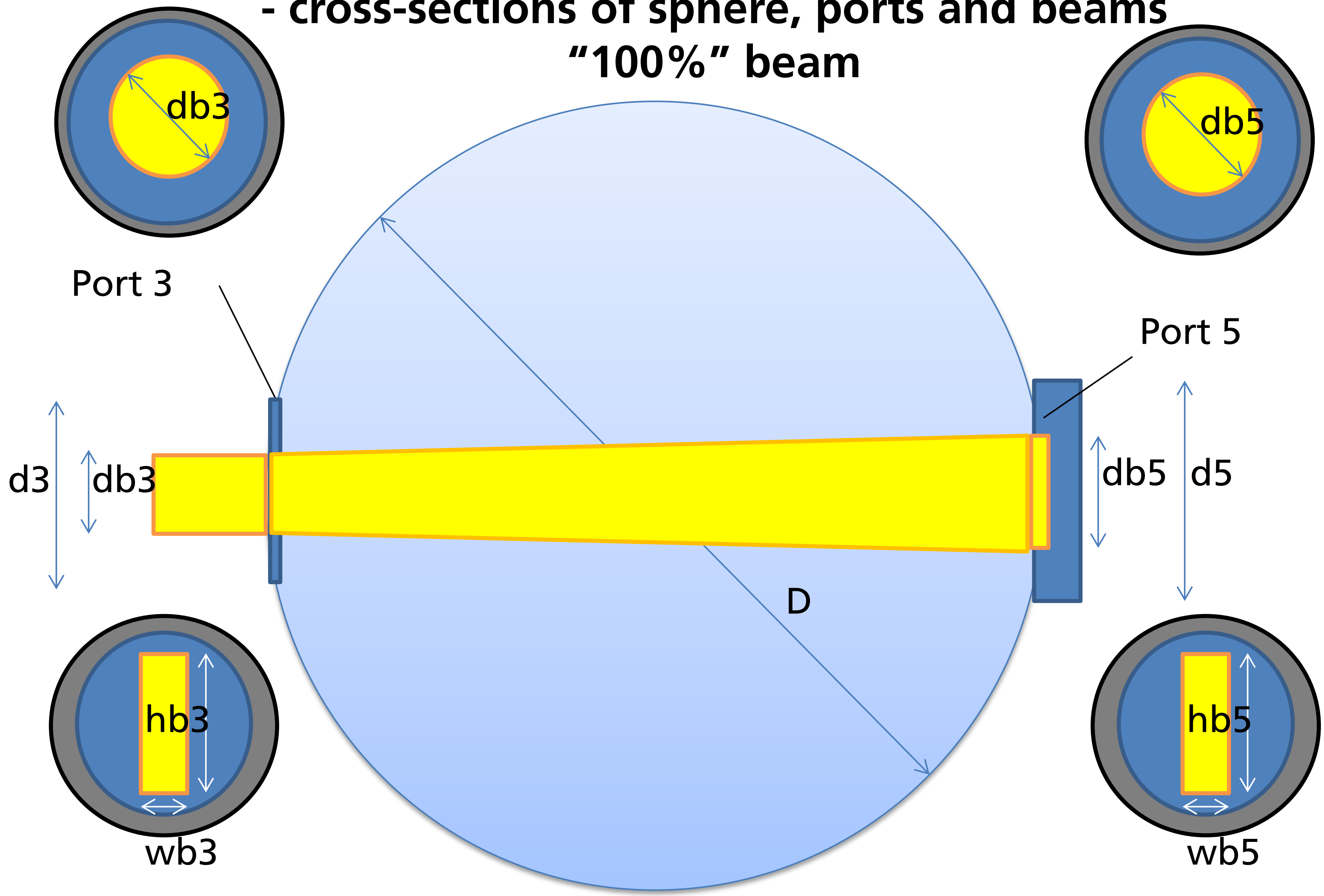
- « $_{dif}$ » for diffuse radiation

1. Integrating Sphere: $\tau_{v,\ n\text{-}n} = \tau_{v,\ n\text{-}h} - \tau_{v,\ n\text{-}dif}$
2. Direct measurement of $\tau_{v,\ n\text{-}n}$: (see EN 14500:2018)

Definition of geometrical parameters for integrating spheres - cross-sections of sphere, ports and beams "100%" beam

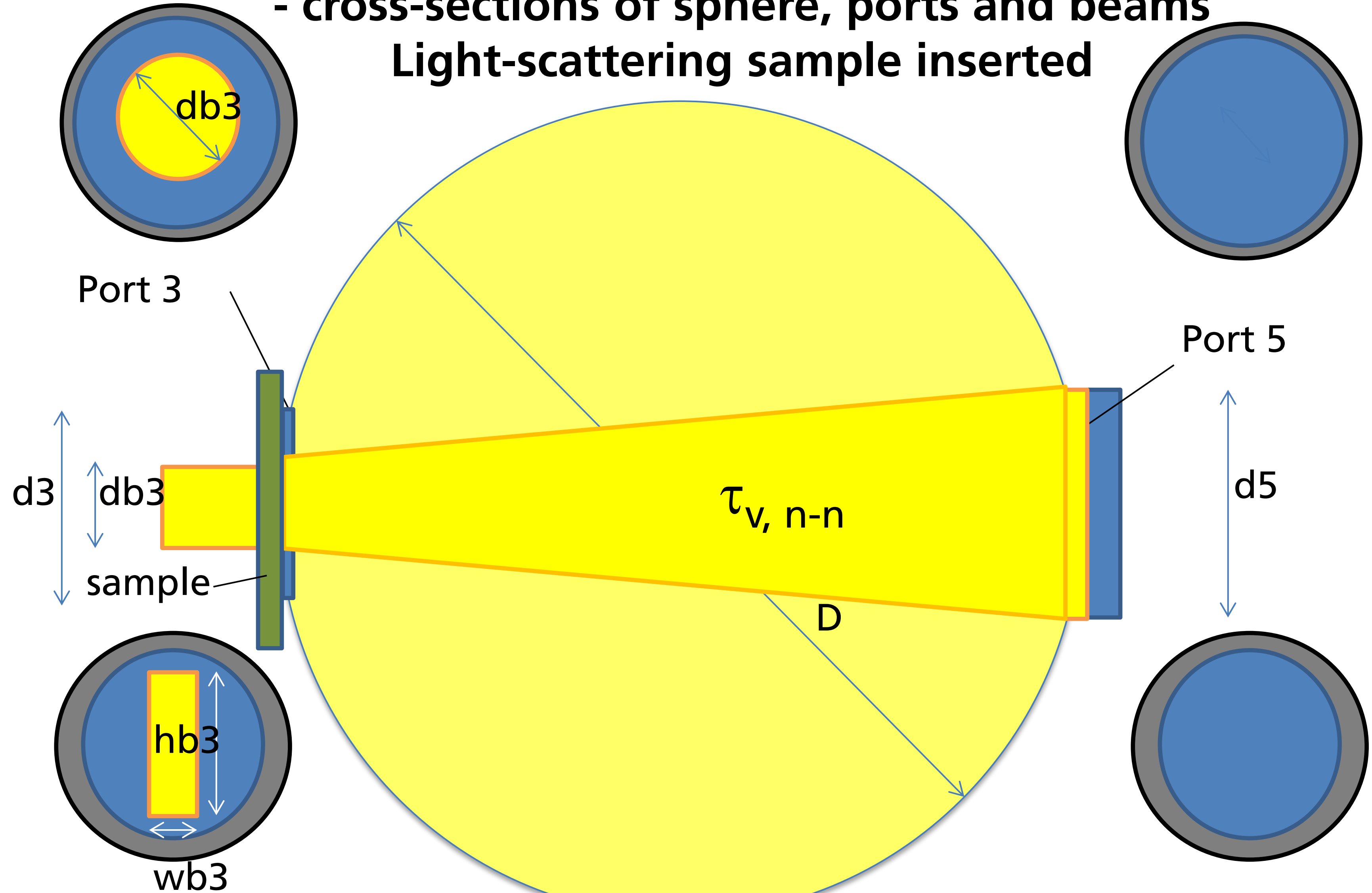


area of Port 3: a3
transmittance sample port

internal sphere area: A

area of Port 5: a5
normal-normal transmittance exit port

Definition of geometrical parameters for integrating spheres
- cross-sections of sphere, ports and beams
Light-scattering sample inserted



area of Port 3: a3
transmittance sample port

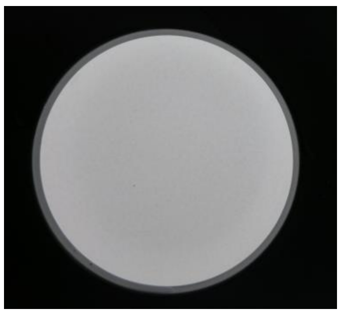
internal sphere area: A

area of Port 5: a5
normal-normal transmittance exit port

Investigated solar-shading textiles
- Transmitted images of light source

Light source

No1



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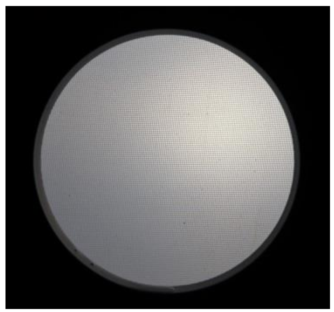

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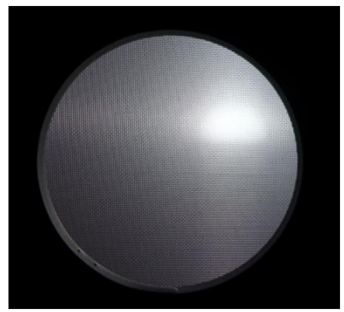

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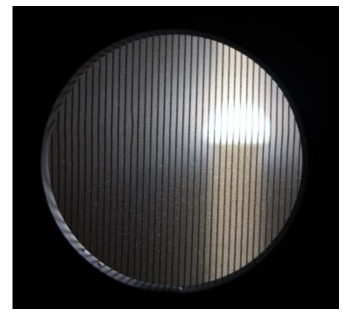

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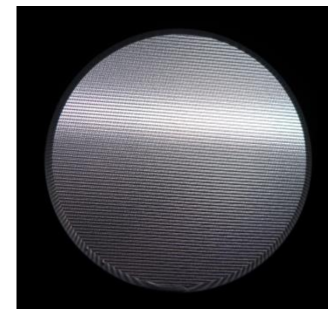
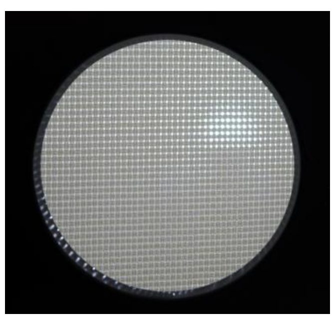
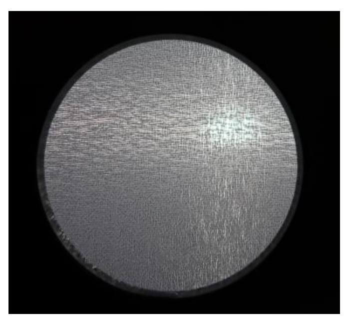


No11

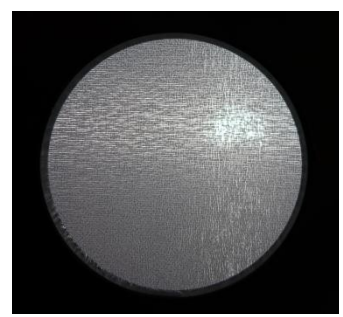
No12



No13-1

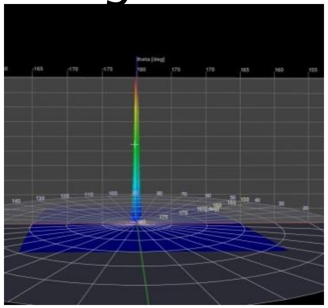


No13-2 (metallic)



Investigated solar-shading textiles
- Photogoniometric transmittance images (BTDF)

Light source



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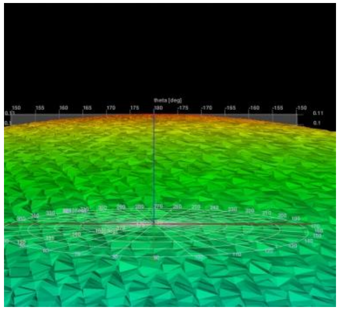

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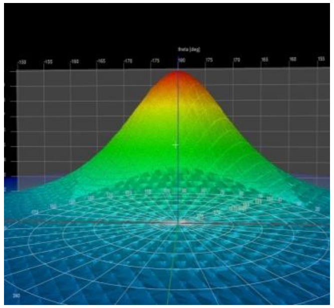

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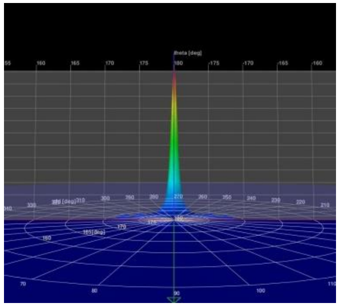

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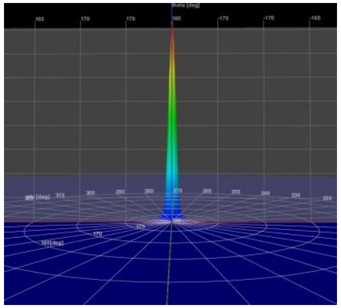

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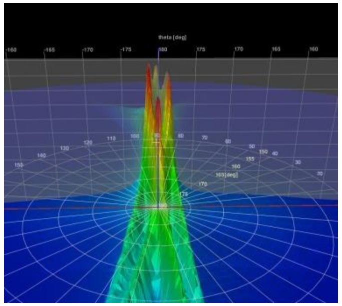

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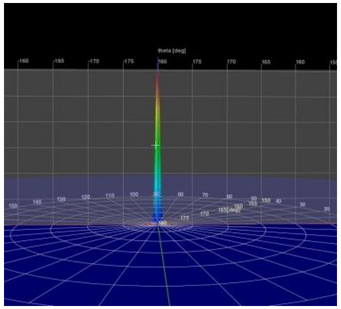

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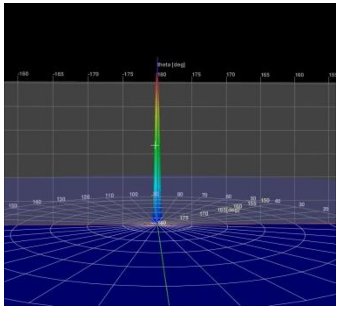
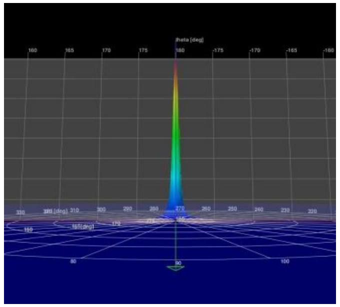
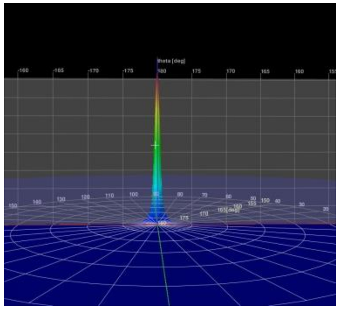


No13-1



No13-2 (metallic)



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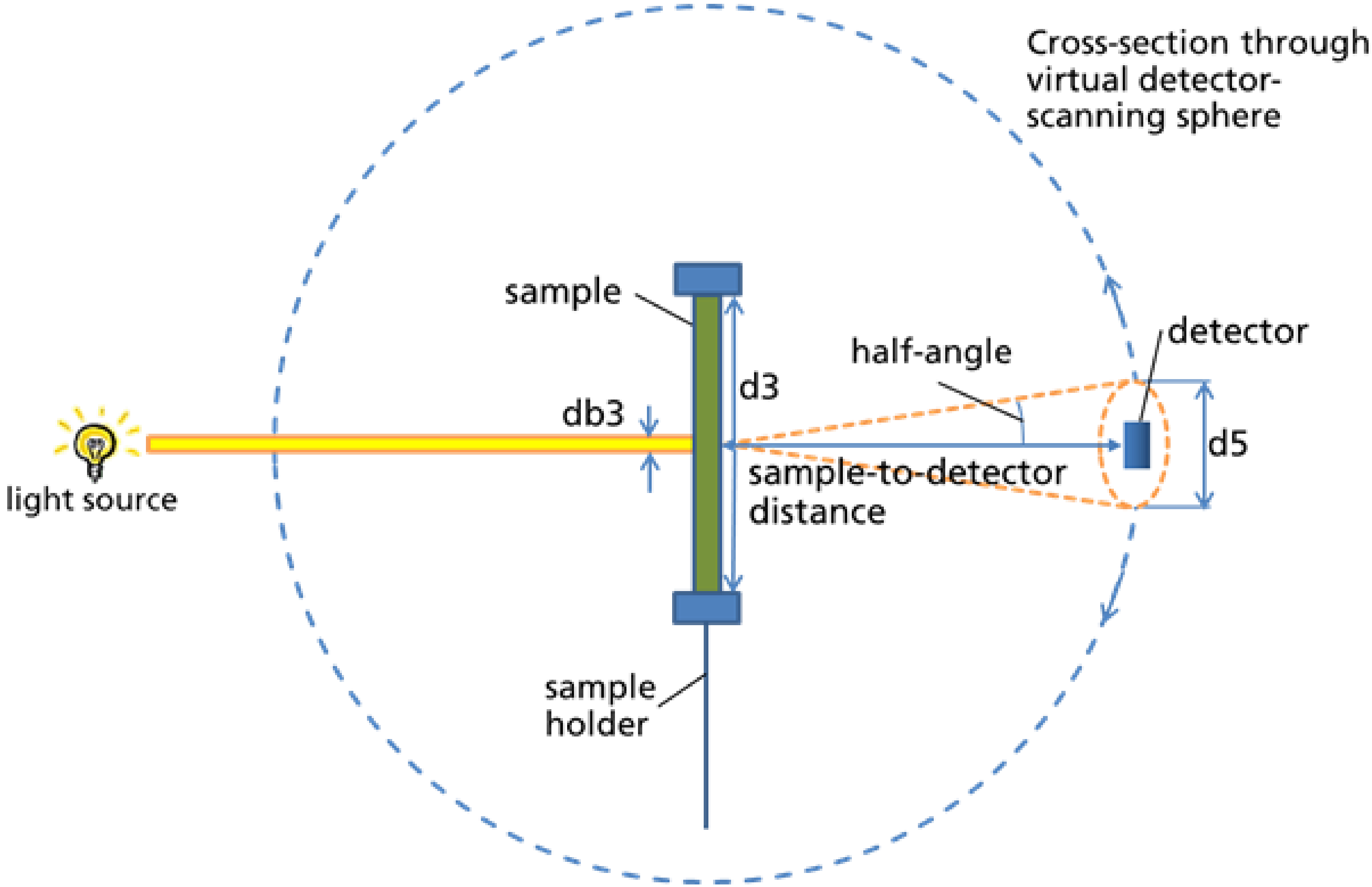
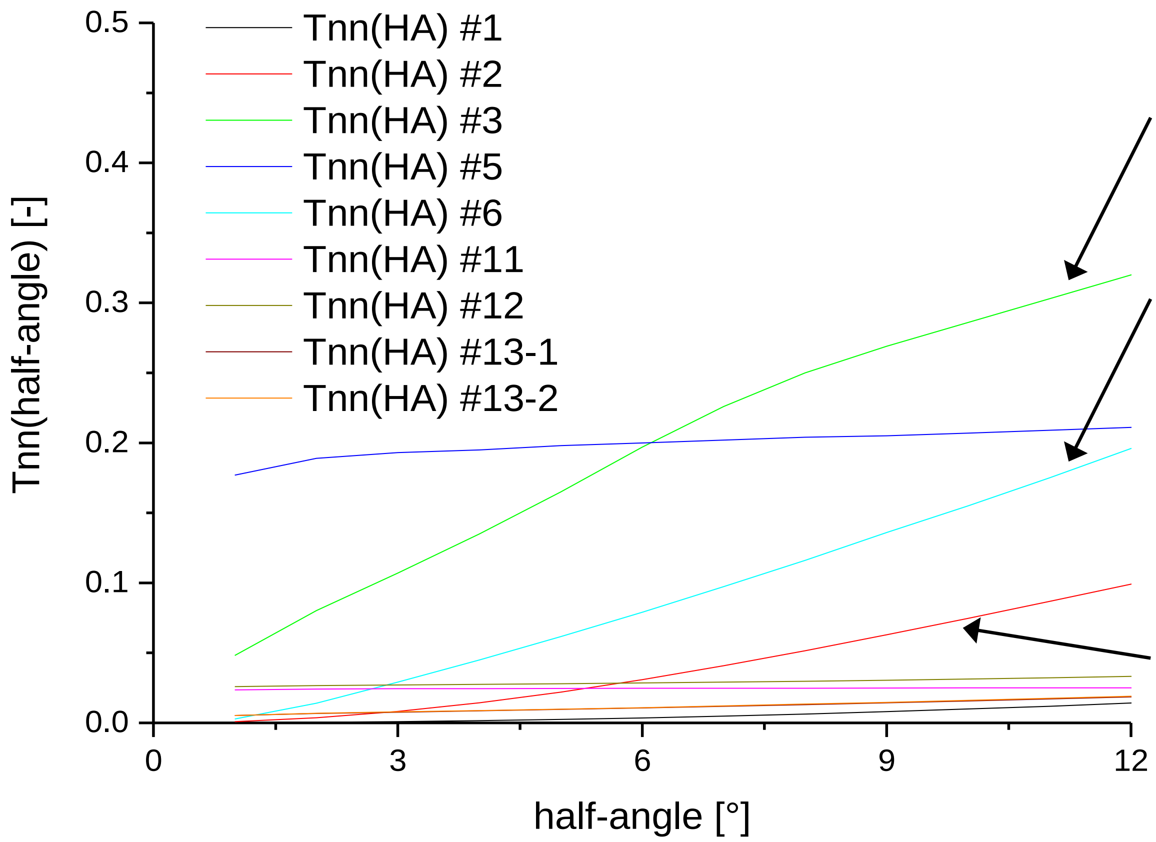
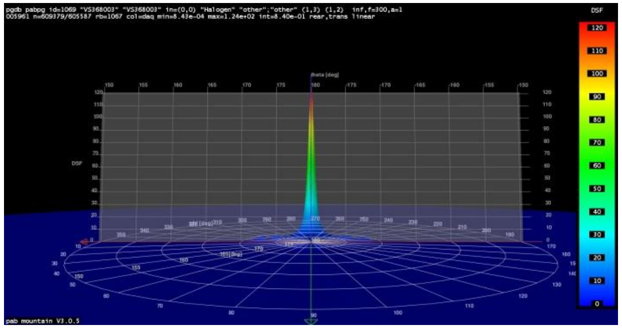
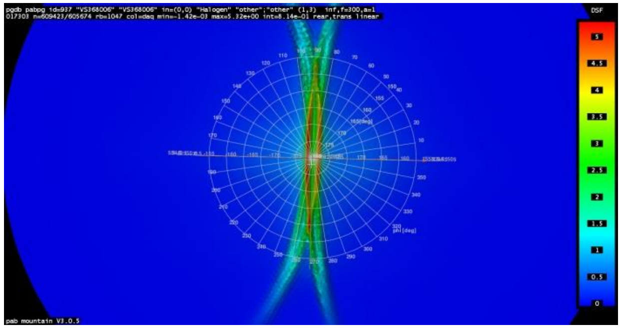
Important parameters for the photogoniometer used for the analysis of the transmitted light

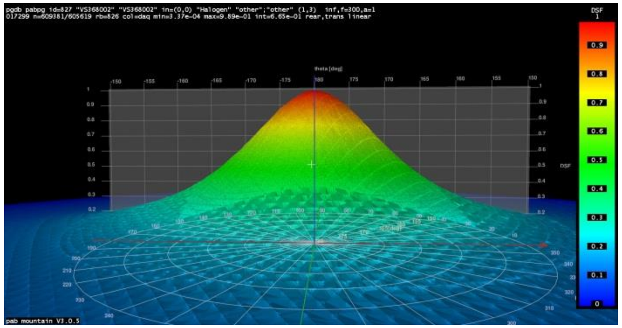


Normal-normal transmittance obtained by integrating photogoniometric data over cap of given half-angle

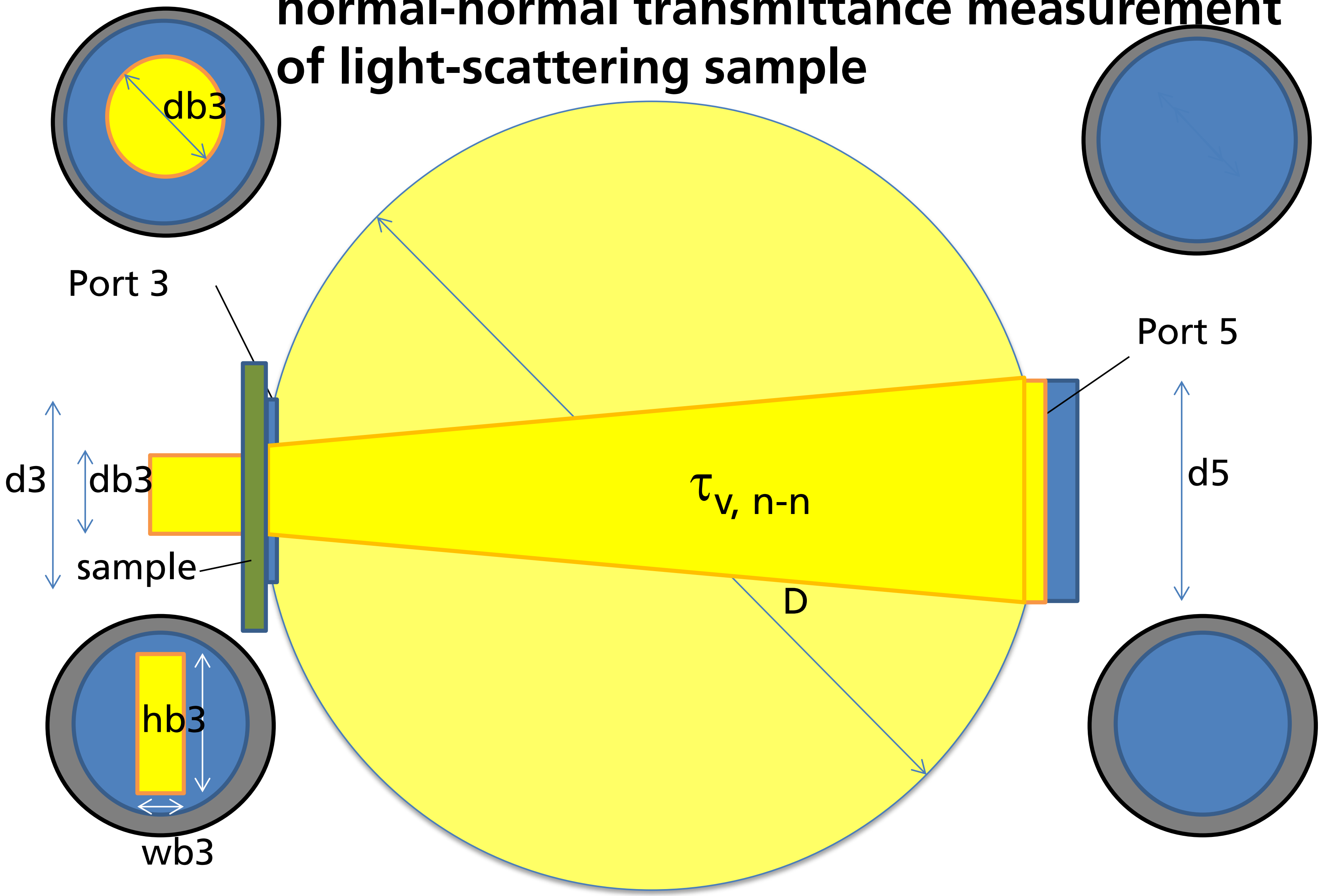








Integrating sphere configuration for normal-normal transmittance measurement of light-scattering sample



area of Port 3: a3
transmittance sample port

internal sphere area: A

area of Port 5: a5
normal-normal transmittance exit port

Determining normal-normal transmittance with an integrating sphere

$T_{nn}(\lambda) = T_{nh}(\lambda) - T_{ndif}(\lambda)$,

where $T_{nh}(\lambda)$ is measured with Port 5 closed with a white plug and $T_{ndif}(\lambda)$ is measured with Port 5 open.

Two hypotheses:

- If the sample at Port 3 is not moved between the $T_{nh}(\lambda)$ and $T_{ndif}(\lambda)$ measurements, **$T_{nn}(\lambda)$ can be determined from the equation above** even when the $T_{nh}(\lambda)$ and $T_{ndif}(\lambda)$ values themselves are incorrect (errors are identical for both measurements)
- The determined value of $T_{nn}(\lambda)$ depends on a5/A - how much depends on the sample scattering distribution

First hypothesis:
$T_{nn}(\lambda)$ can be determined from $T_{nn}(\lambda) = T_{nh}(\lambda) - T_{ndif}(\lambda)$

- if sample at Port 3 is not moved between $T_{nh}(\lambda)$ and $T_{ndif}(\lambda)$ measurements
- despite incorrrect $T_{nh}(\lambda)$ and $T_{ndif}(\lambda)$ values (errors are practically identical for both measurements)

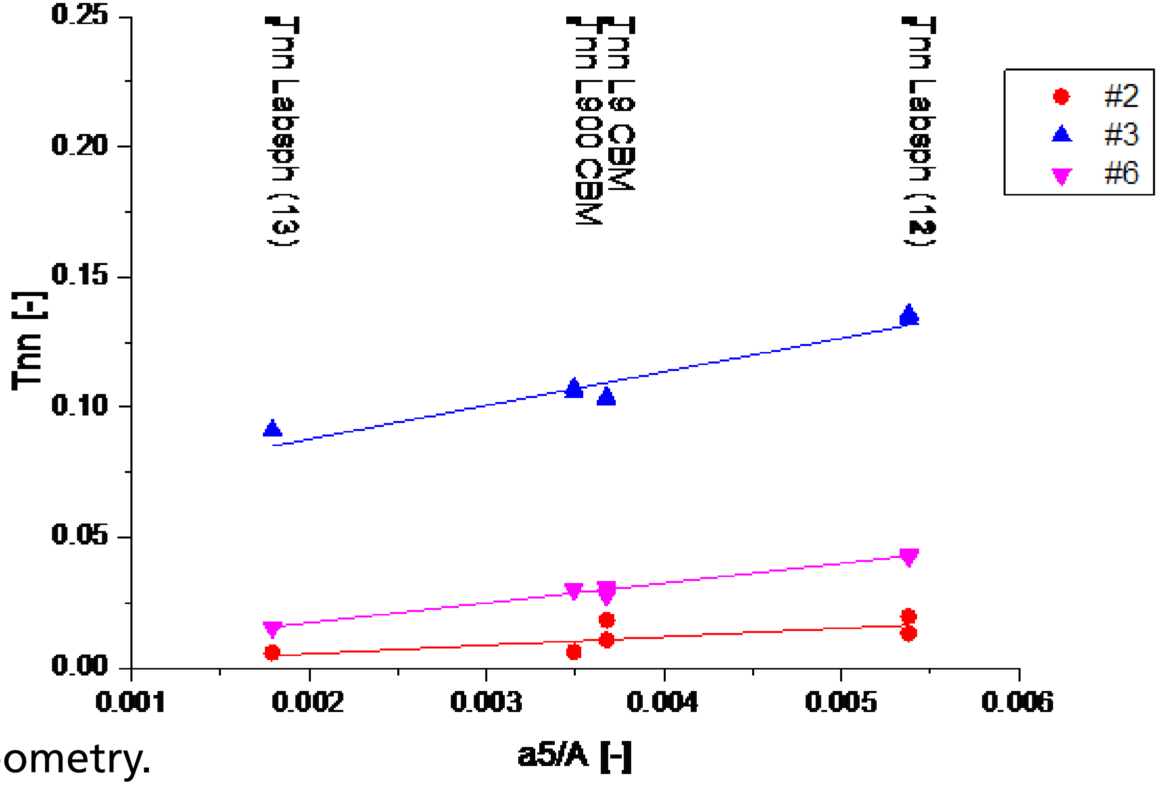
Typical causes of errors in $T_{nh}(\lambda)$ and $T_{ndif}(\lambda)$ determination:

- Losses due to lateral light shift within sample
- Inhomogeneous reflectance of sphere wall (including Port 5 plug)
- Departure from ideal spherical geometry (ports, detectors, baffles
- Detector field of view (assuming this does not include Port 5)

Second hypothesis: T_{nn} (= $T_{nh} - T_{ndif}$) depends on a5/A

$T_{v,nn}$ versus a5/A for three „critical" textile samples (#2, #3, #5):

"Critical" refers to variation of $T_{v,nn}$ value with a5/A



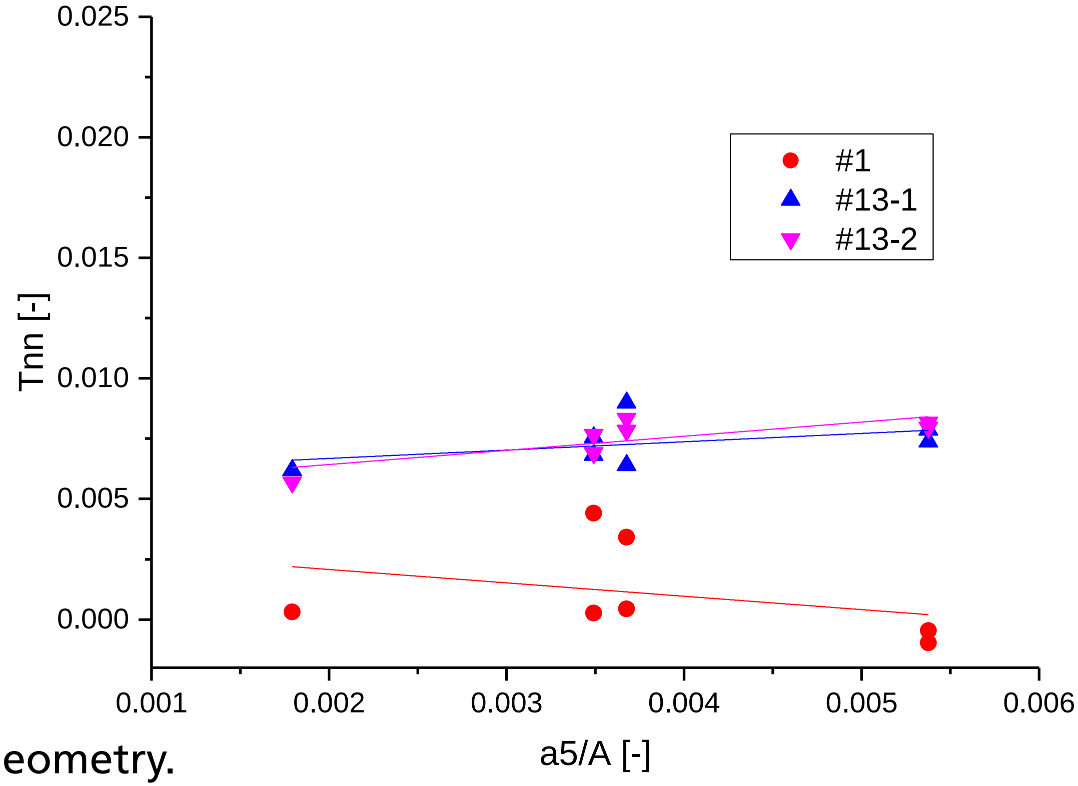
a5/A varied by sphere geometry.
Labsph 11, 12, 13, L9, L900 refer to integrating spheres with different dimensions.

Second hypothesis: T_{nn} (= $T_{nh} - T_{ndif}$) depends on a5/A

- but is significant only for "critical" samples

$T_{v,nn}$ versus a5/A for three „non-critical" textile samples (#1, #13-1, #13-2):

"Critical" refers to variation of $T_{v,nn}$ value with a5/A



a5/A varied by sphere geometry.

Note reduction in y-axis scaling compared to previous slide!

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Problem

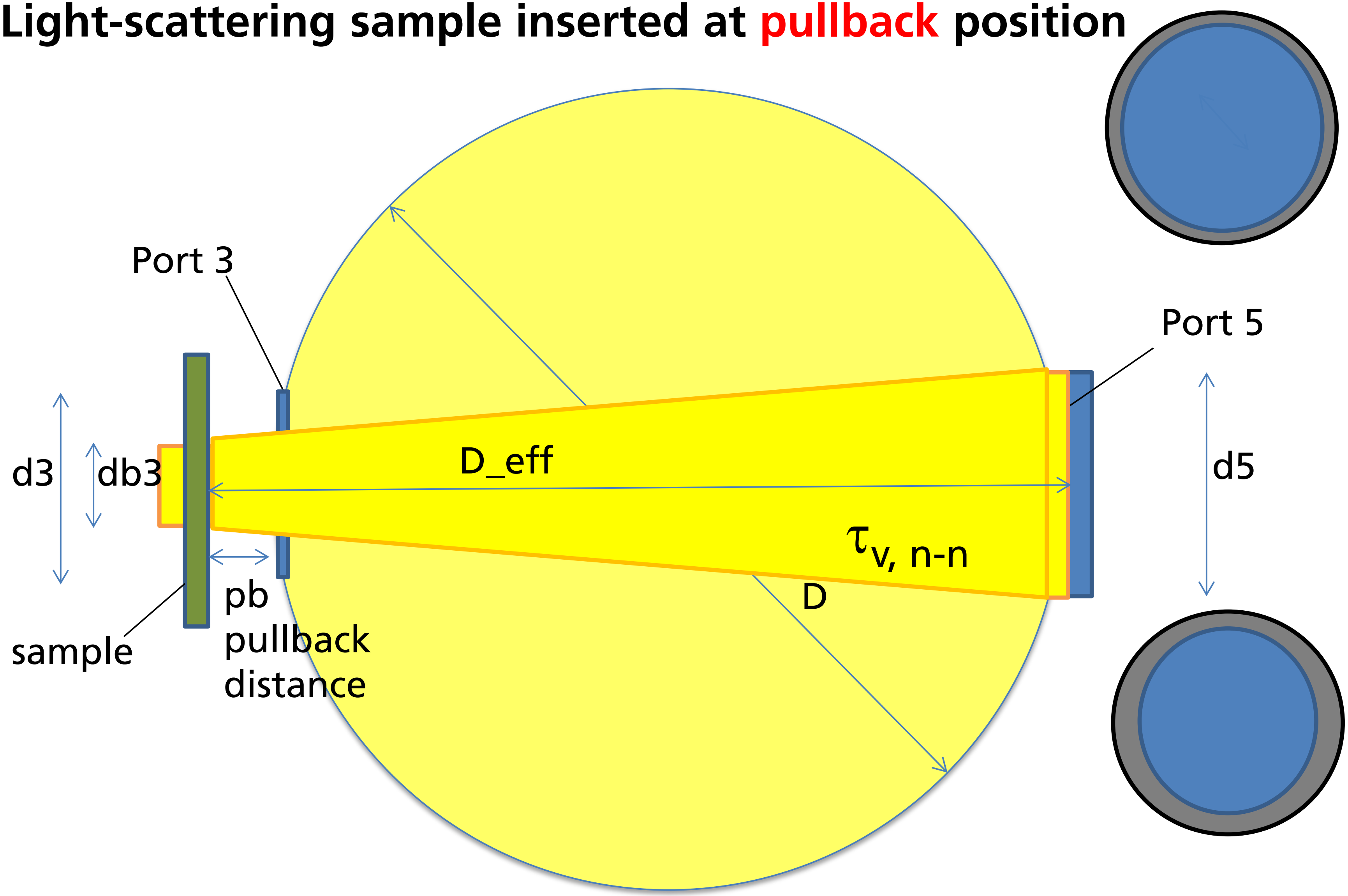
As $T_{nn}(\lambda)$ (= $T_{nh}(\lambda)$ - $T_{ndif}(\lambda)$) depends on a5/A,

how can $T_{nn}(\lambda)$ be determined reproducibly
with different integrating spheres?

Solution:

- Limit the allowable range of a5/A (or a5/A_eff: see below)
- Apply the pullback method to measure within this range

Definition of geometrical parameters for integrating spheres: Light-scattering sample inserted at pullback position



area of Port 3: a3
transmittance sample port

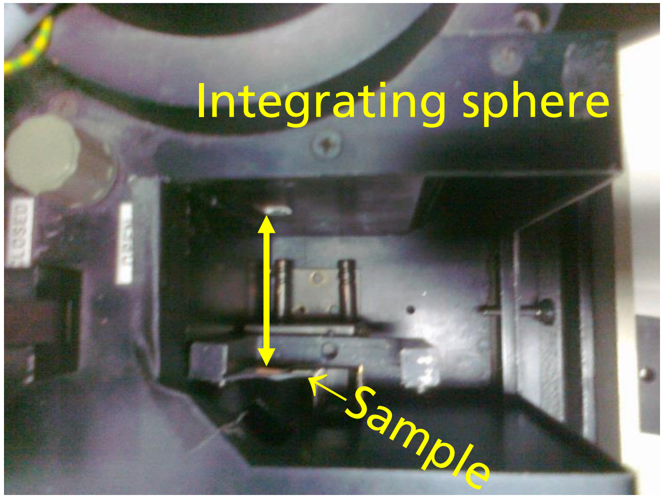
internal sphere area: A

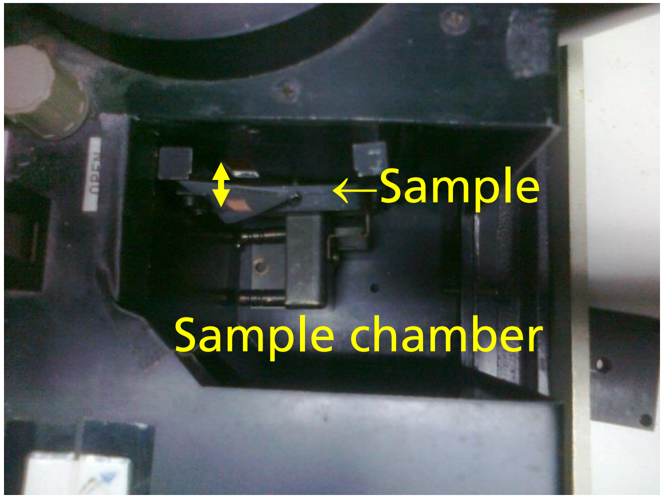
area of Port 5: a5
normal-normal transmittance exit port

Pullback of sample from transmittance port (port 3)

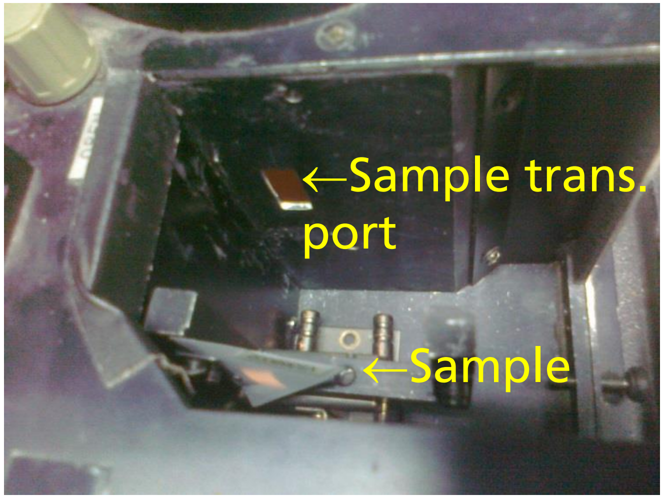
53 mm pullback | 12 mm pullback

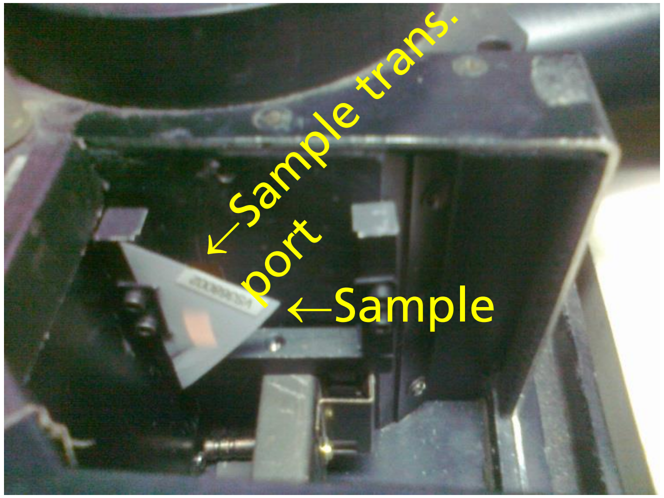
Top views





Oblique views





If pb is the pullback distance, D_eff = D + pb and A_eff = π (D_eff)^2

T_{nn} with and without pullback for Screen S2 col S065 white grey (non-critical for T_{nn})

For integrating spheres (220 mm, 150 mm) at Fraunhofer ISE

D [mm]	Pullback [mm]	a5/A or $a5/A_{eff}$	T_{nh} (pseudo) [-]	T_{ndif} (pseudo) [-]	T_{nn} [-] (550 nm or vis)
220	75	0.00194	0.0380	0.0025	0.0355
220	0	0.00349	0.0788	0.0438	0.0350
150	0	0.00368	0.0774	0.0412	0.0361

Good agreement between T_{nn} results with sample at Port 3 (pullback = 0 mm) and at pullback = 75 mm – despite low $a5/A_{eff}$ value

Fraunhofer ISE

T_{nn} with and without pullback for Screen S2 col S094 white pearl (non-critical for T_{nn})

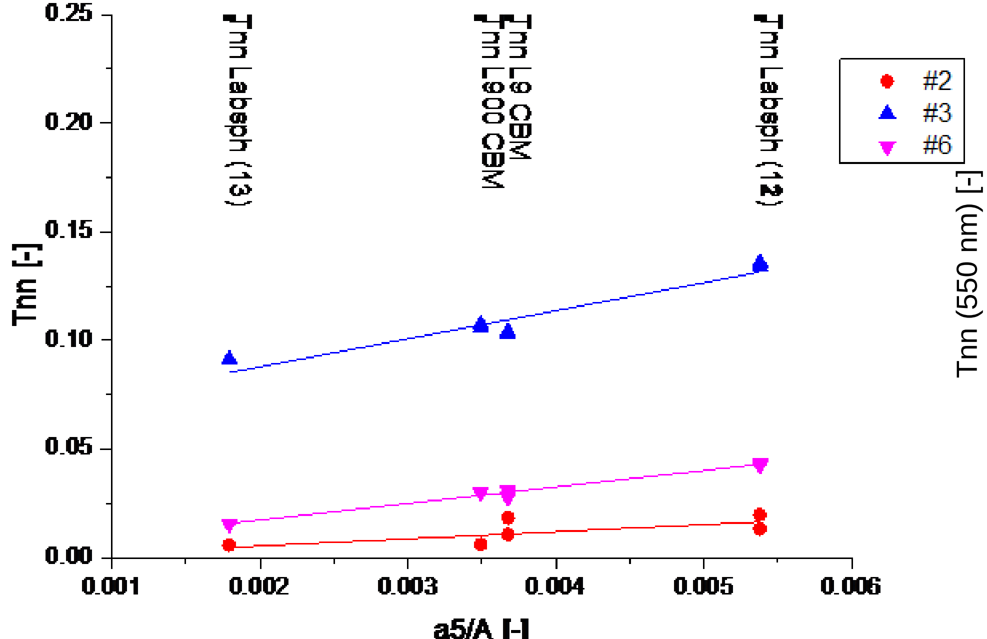
For integrating spheres (220 mm, 150 mm) at Fraunhofer ISE

D [mm]	Pullback [mm]	a5/A or a5/A_{eff}	T_{nh} (pseudo) [-]	T_{ndif} (pseudo) [-]	T_{nn} [-] (550 nm or vis)
220	75	0.00194	0.0380	0.0033	0.0347
220	0	0.00349	0.1094	0.0722	0.0371
150	0	0.00368	0.1087	0.0722	0.0365

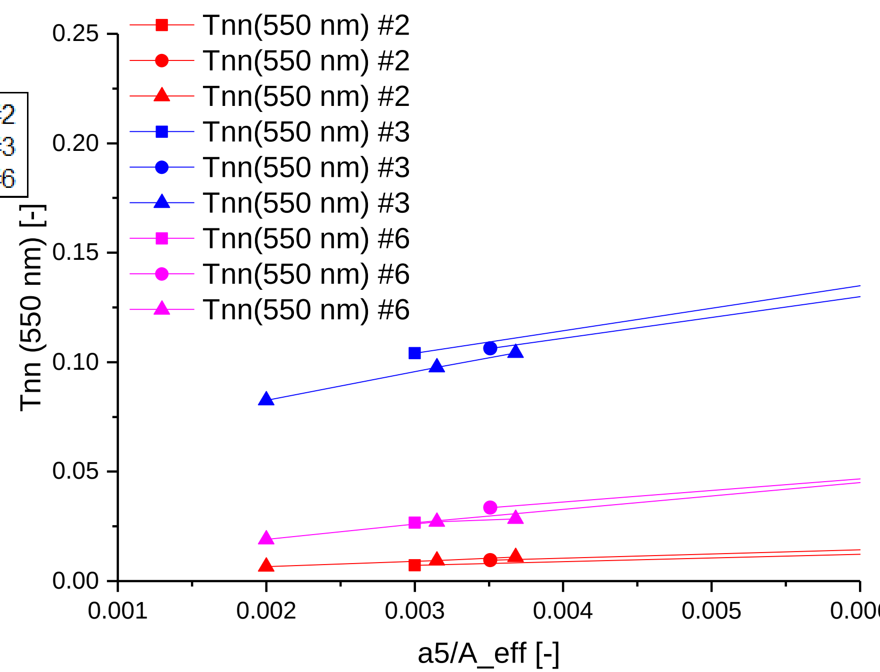
Good agreement between T_{nn} results with sample at Port 3 (pullback = 0 mm) and at pullback = 75 mm – despite low a5/A_{eff} value

Comparison for three „critical“ textile samples (2, 3, 5) -
Dependence of T_{nn} on a5/A or a5/A_eff
“Critical“ refers to variation of T_{nn} value with a5/A

$T_{v,nn}$ versus a5/A



T_{nn}(550 nm) versus a5/A_eff



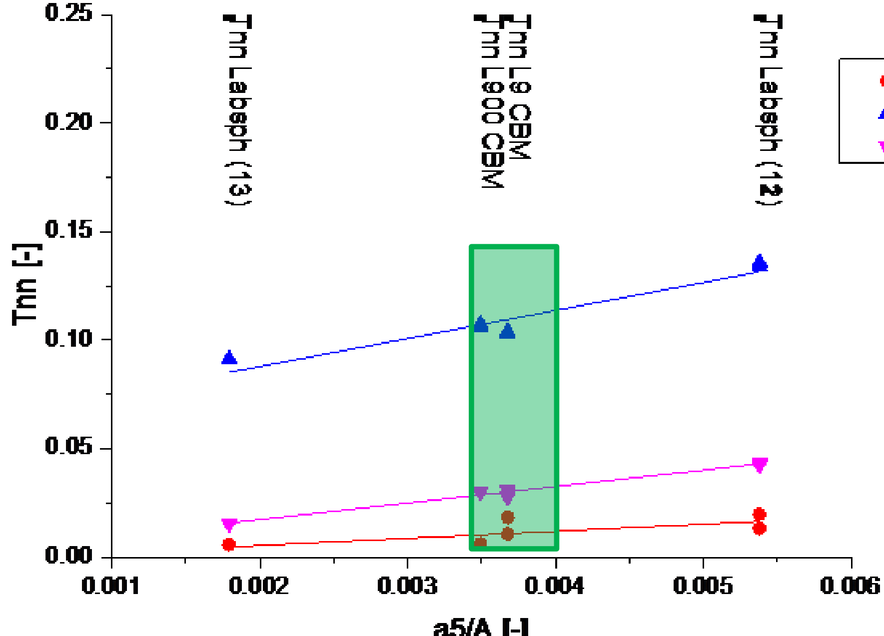
a5/A varied by sphere geom.
Labsph 11, 12, 13, L9, L900 refer to different integrating spheres

Pullback results using three different 150 mm spheres

Fraunhofer ISE

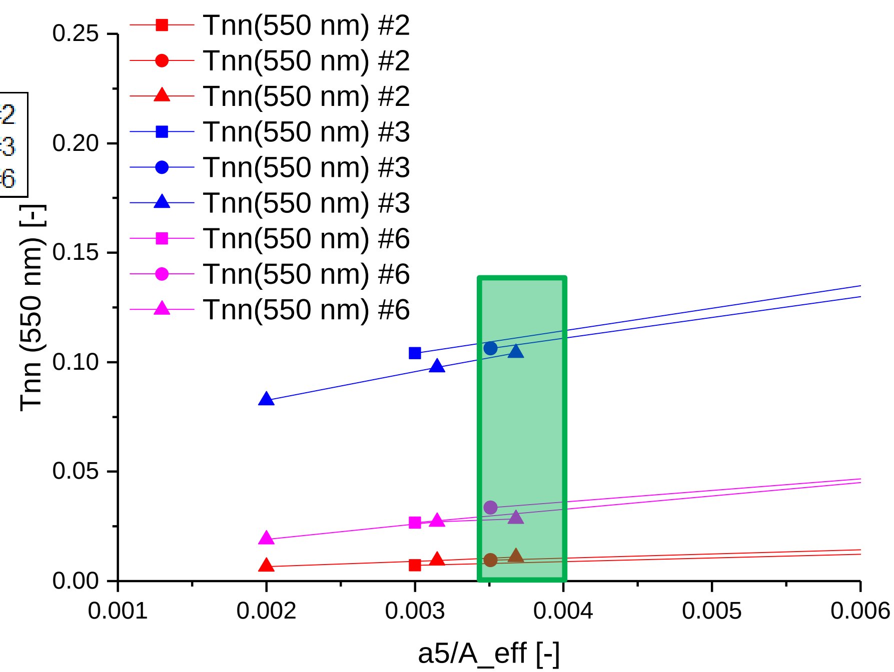
Comparison for three “critical“ textile samples (2, 3, 5) - Dependence of T_{nn} on a5/A or a5/A_eff -> limit allowable values of a5/A or a5/A_eff

$T_{v,nn}$ versus a5/A



a5/A varied by sphere geom.
Labsph 11, 12, 13, L9, L900 refer to different integrating spheres

T_{nn}(550 nm) versus a5/A_eff



Pullback results using three different spheres

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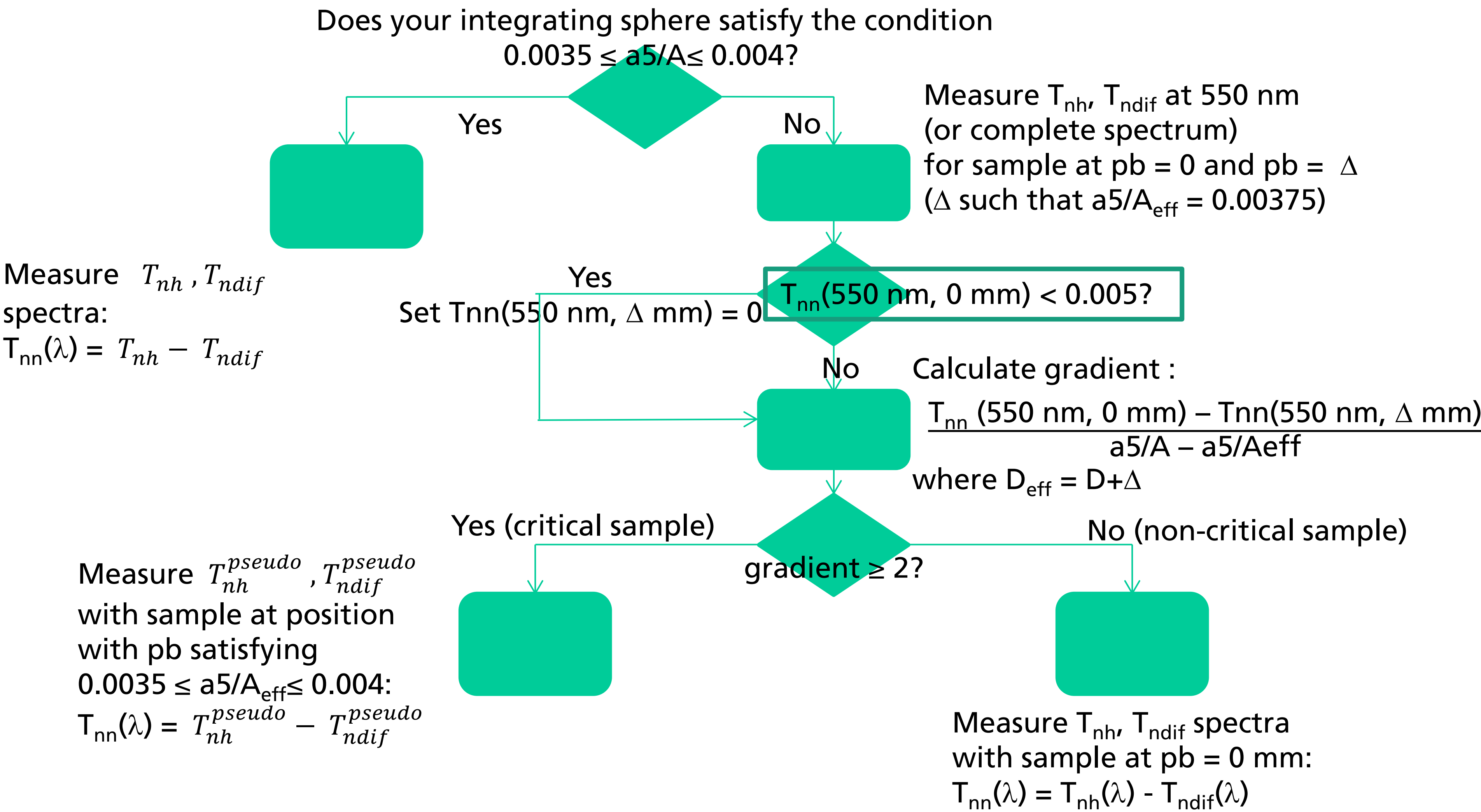
Revised decision tree for T_{nn} measurements

Def.: T_{nn} of “critical” samples varies significantly with the relative area of port 5



Caution: Special instrumentation may be needed to measure the correct values of T_{nh}, T_{ndif}

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Conclusions

What does "normal-normal transmittance" mean for light-scattering materials?

- Answer (from EN 14500:2008):
  Fraction of normally incident radiation flux that is transmitted in accordance with the laws of geometrical optics, without diffusion or redirection
- Answer (if determined using an integrating sphere):
  $T_{nn}(\lambda) = T_{nh}(\lambda) - T_{ndif}(\lambda)$
  - $T_{nn}(\lambda)$ is valid, even if $T_{nh}(\lambda)$ and $T_{ndif}(\lambda)$ are not,
    as the main errors cancel out

As $T_{nn}(\lambda)$ depends on the relative area of the exit port (a5/A or a5/A_eff),

the range of this relative area must be restricted to achieve comparability.

- The pullback method is a practicable method to achieve this.
  - $T_{nn}(\lambda) = T_{nh}^{pseudo} - T_{ndif}^{pseudo}$ in this case.

Outlook

- CEN TC33, WG3, TG5 intends to adopt the approach of restricting the range for a5/A or a5/A_eff and allowing the pullback method to determine T_{nn} in its revision of EN 14500 for solar-shading materials.

- As the approach should be valid for other light-scattering materials, the NFRC Diffuse Glazing TG is also currently considering its adoption.

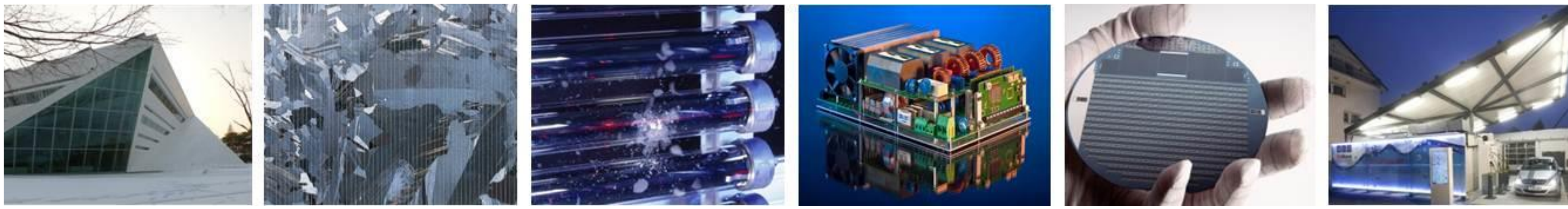
Supplementary information

For an 150 mm integrating sphere and Port 5 with a diameter of 25 mm:

$a5/A_{eff}$	pb [mm]	D_{eff}
0.003	78.2	228.2
0.0035	61.3	211.3
0.00375	54.1	204.1
0.004	47.6	197.6
0.0069	0	150

pb = pullback = distance between sample and Port 3 in mm

Thank you for your attention!



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Acknowledgement
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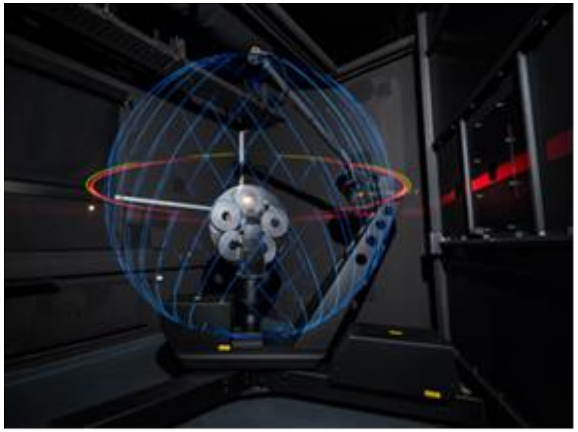
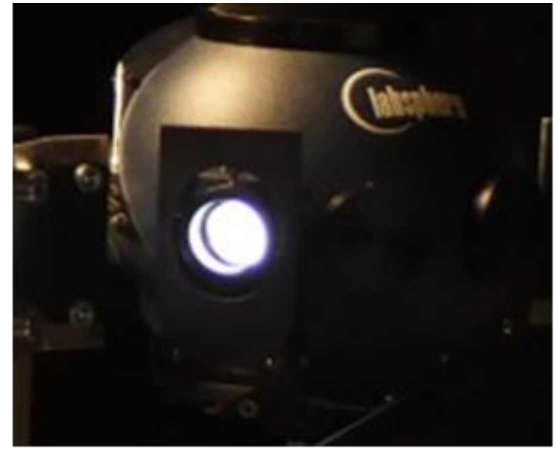
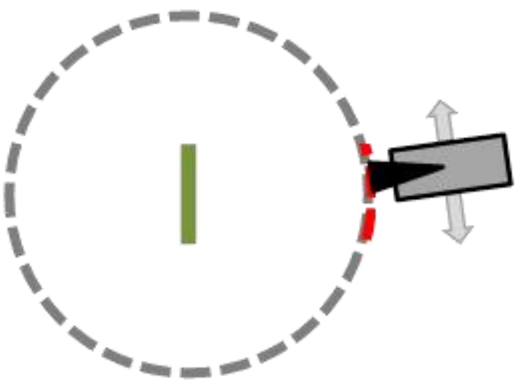
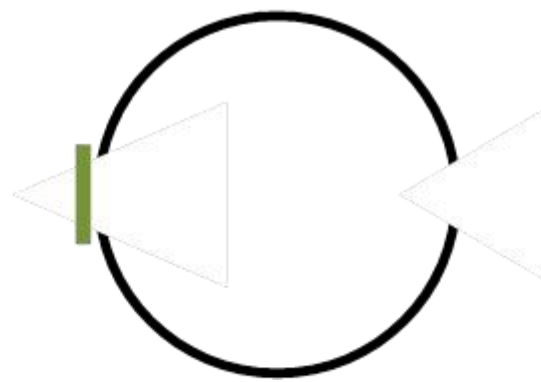
Supplementary slides

Photogoniometer versus integrating sphere

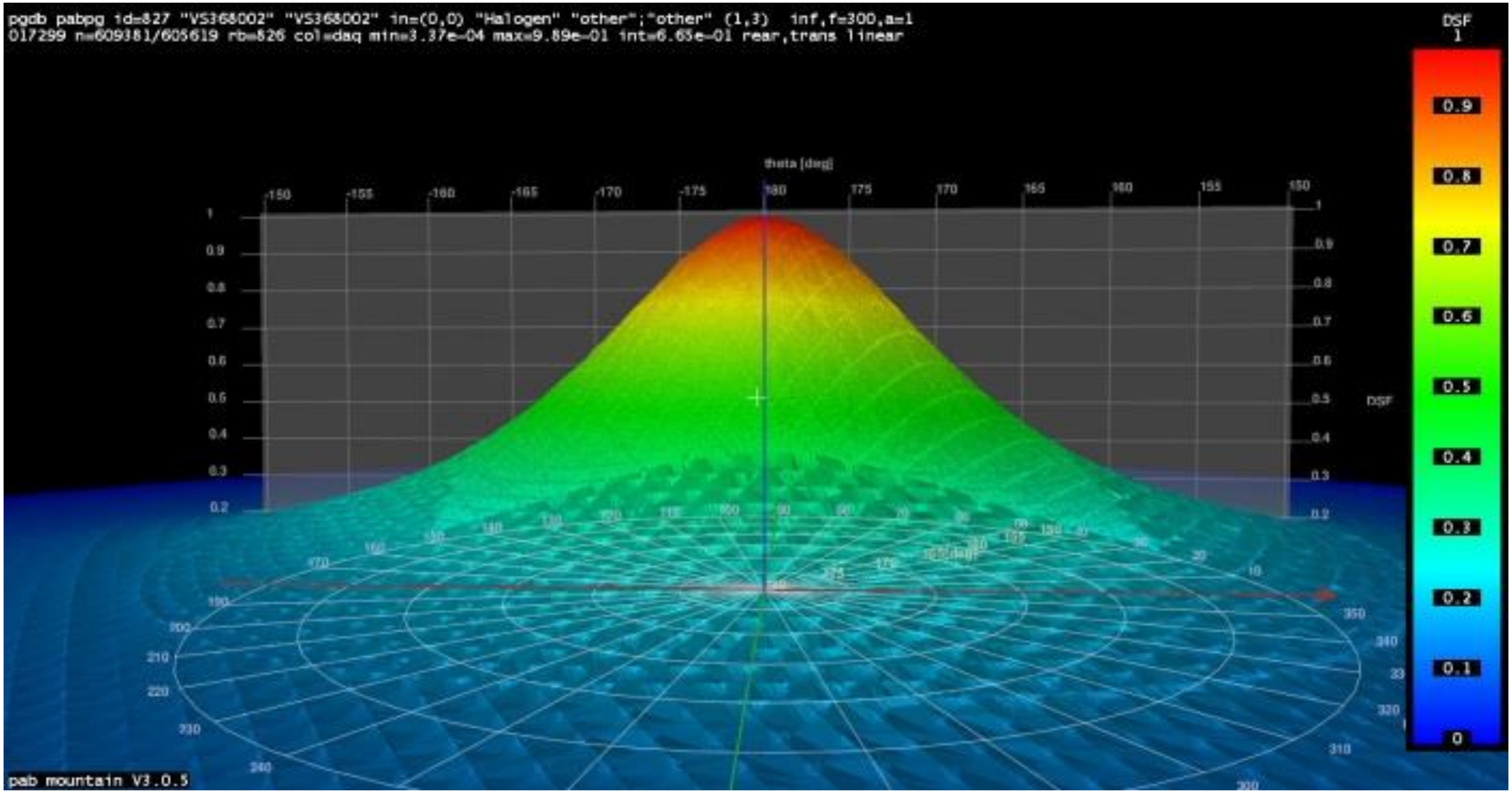






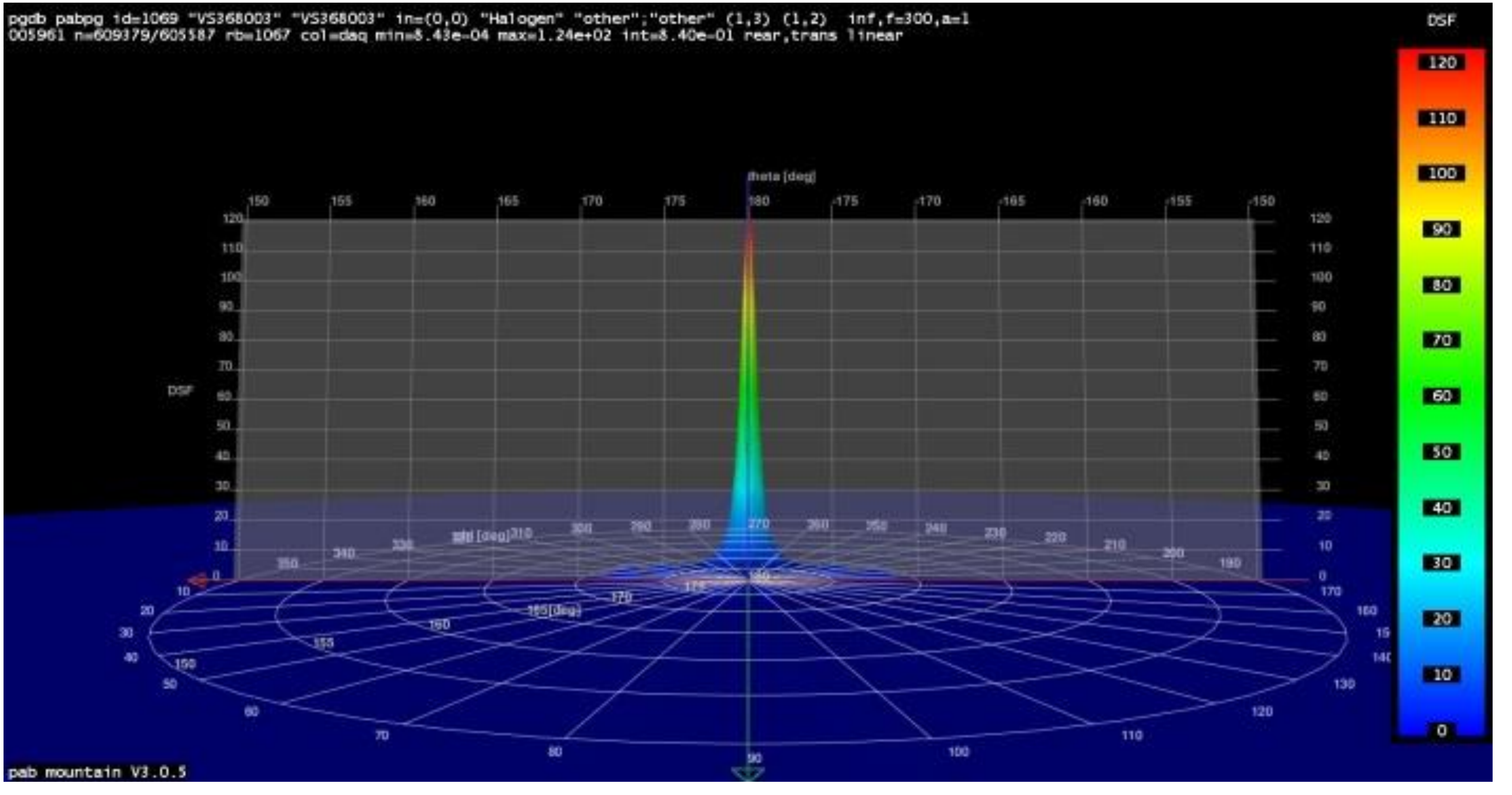


$\tau_{n\text{-}n}$: BDTF of “critical” sample #2



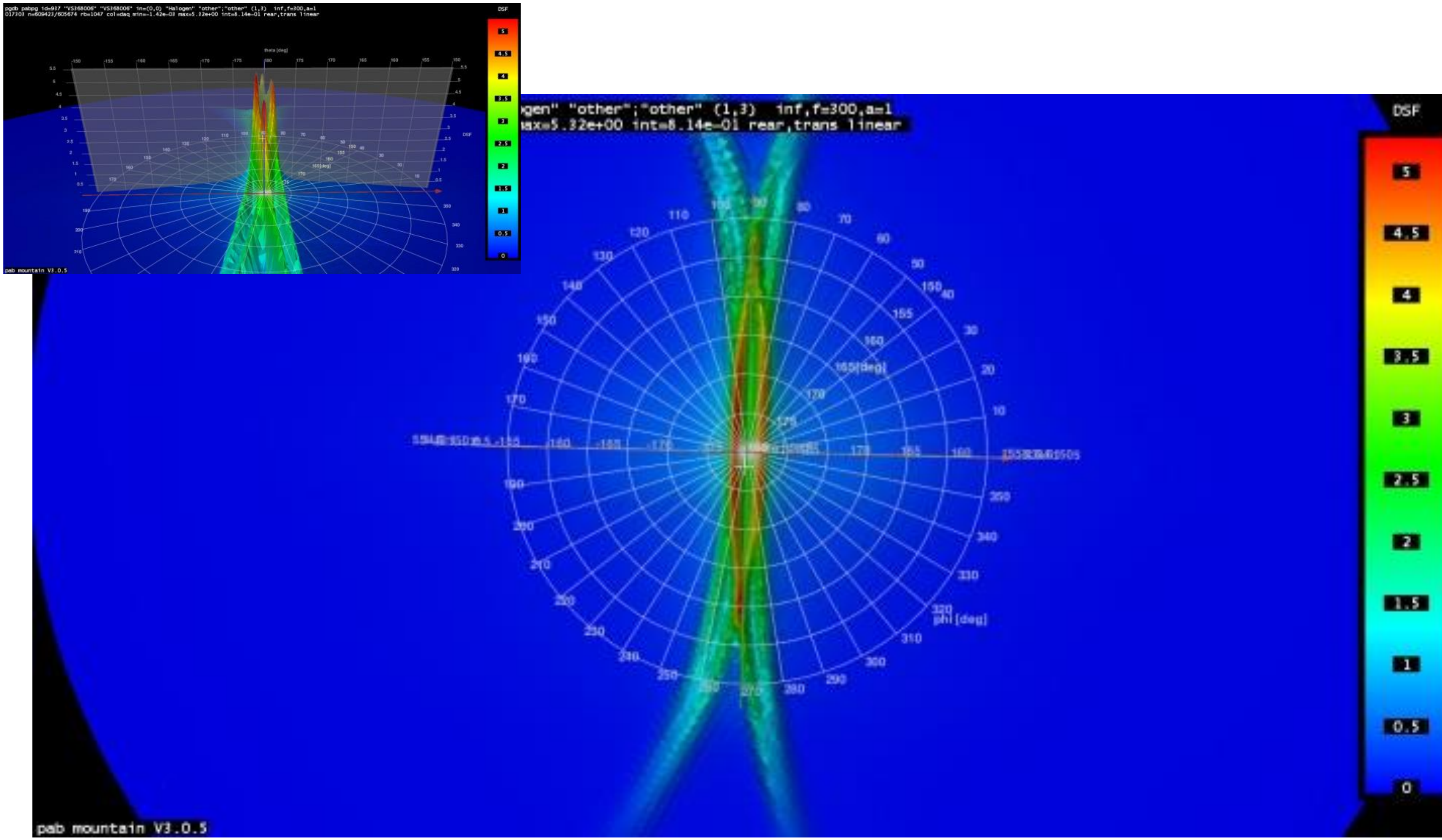
Fraunhofer ISE

τ_{n-n}: BDTF of "critical" sample #3



Fraunhofer ISE

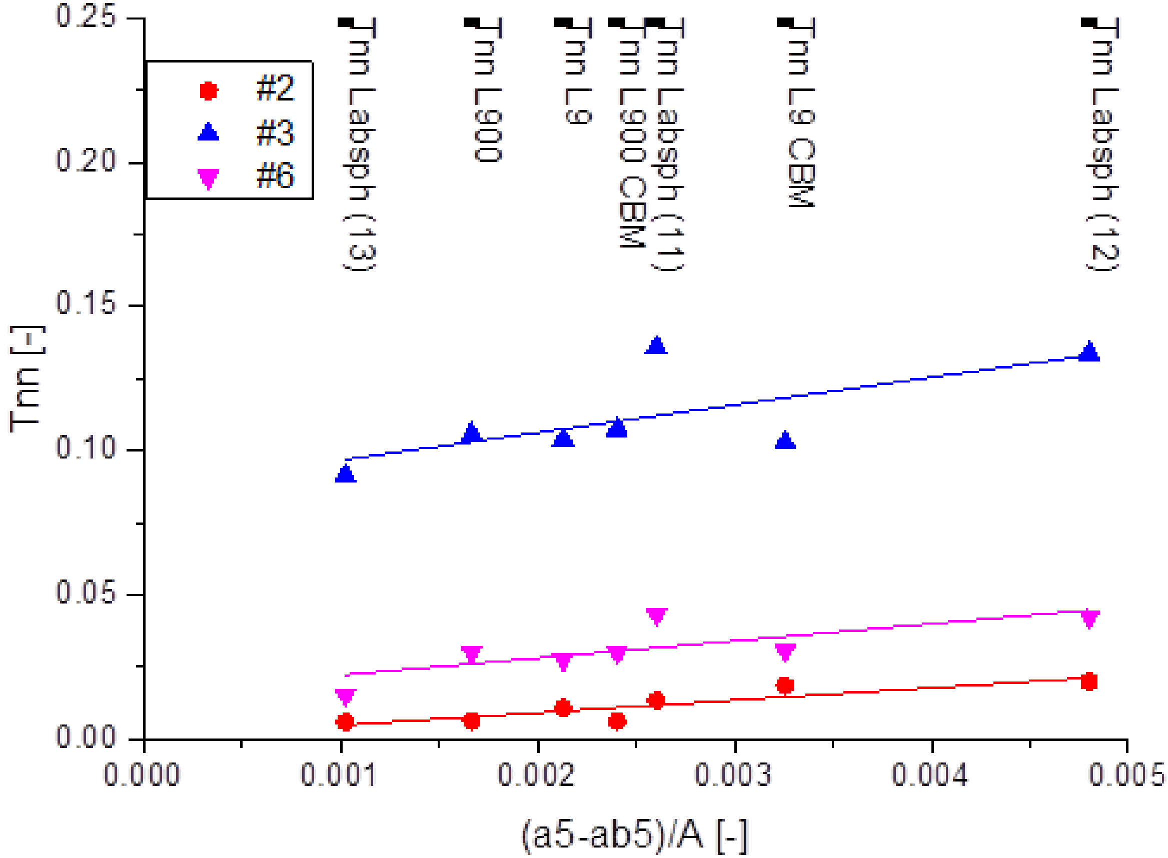
$\tau_{n\text{-}n}$: BDTF of "critical" sample #6

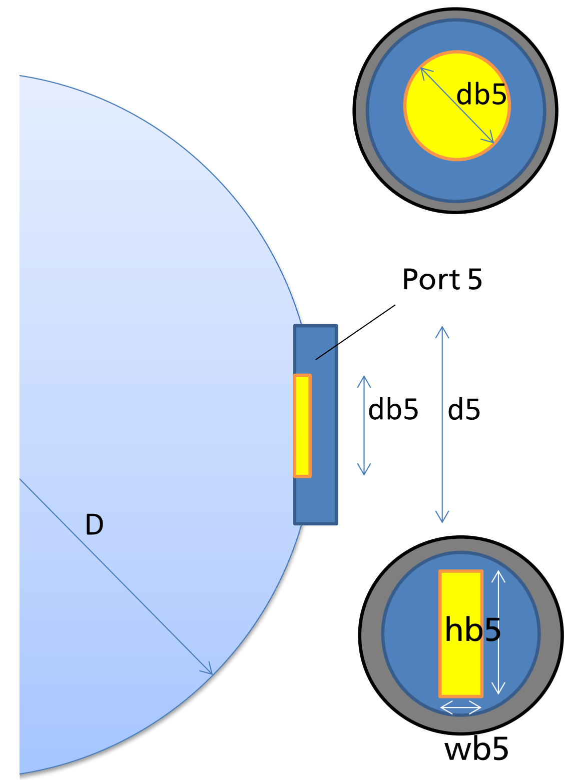


Fraunhofer ISE

$\tau_{n\text{-}n}$: Effect of relative areas of port 5 and beam at port 5

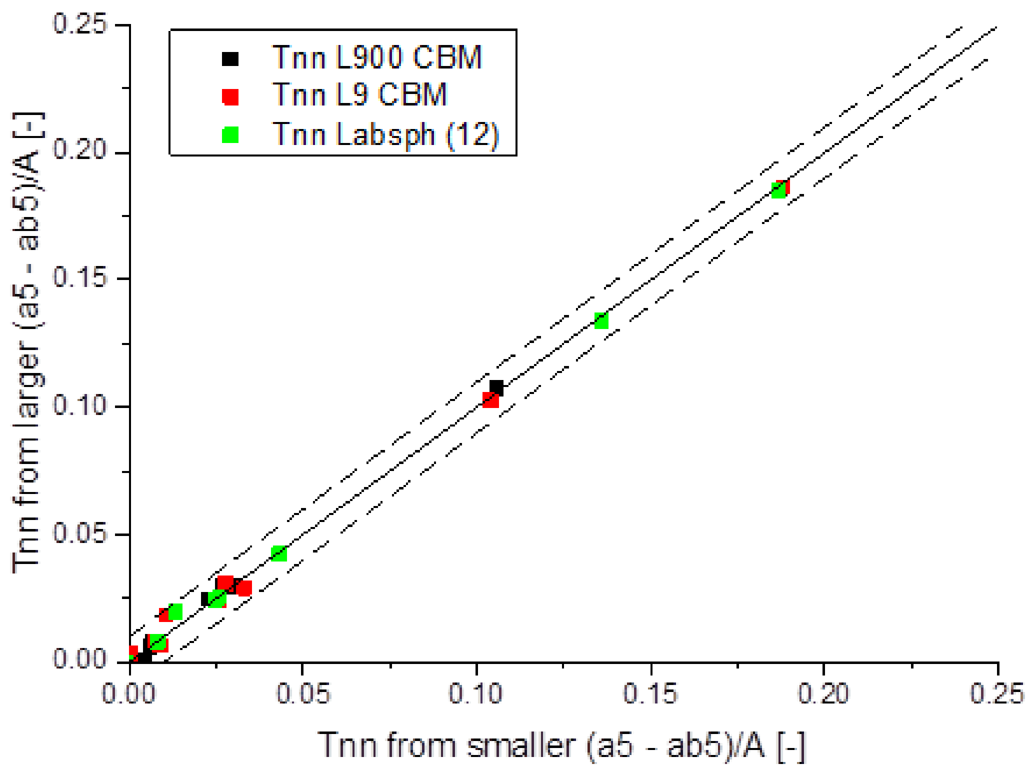
Integrating sphere measurements for critical samples 2, 3, 6

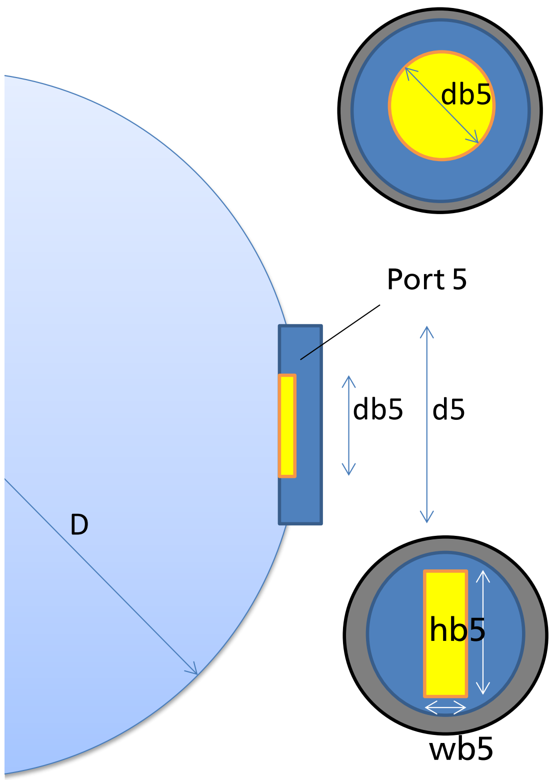




τ_{n-n}: Effect of relative areas of port 5 and beam at port 5

Tnn for all eight samples for three pairs of instruments with identical values of a5/A but different values of (a5 – ab5)/A





Fraunhofer ISE