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# Angle-dependent measurement of solar-shading materials

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Helen Rose Wilson, Fraunhofer ISE

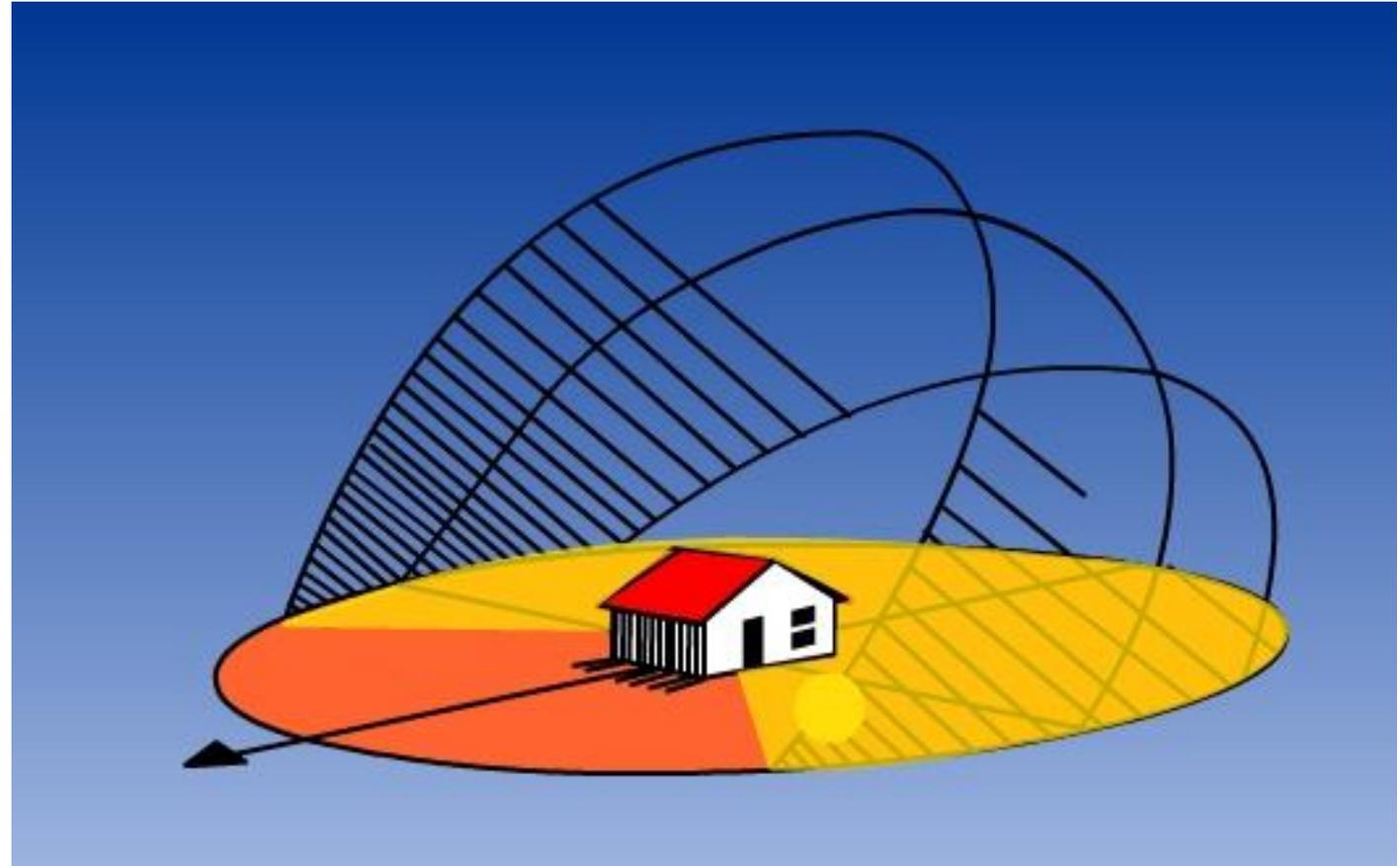
ES-SO Expert Discussion  
Online

31st May, 2022

[www.ise.fraunhofer.de](http://www.ise.fraunhofer.de)

# Motivation

- Normally incident sunlight on building envelope components is the exception – not the rule!
- Angle-dependent light and solar transmittance and reflectance is needed to calculate solar gains, daylighting levels and glare protection in buildings



Source: Ivo Opstelten, ECN

# The need for measured angle-dependent optical data

- Optical and thermal properties of solar envelope components are needed as a reliable basis for further calculations relevant to building performance
- This performance has often been based on optical properties measured at normal incidence
- Angle-selective shading and fenestration systems require optical properties measured at least at oblique incidence
  - $\tau_{n-h}$ ,  $\tau_{n-n}$ ,  $\rho_{n-h}$  are not enough !



Venetian blind system mounted in the Köln Triangle building in Cologne

# A hierarchy of spatial resolution for optical properties

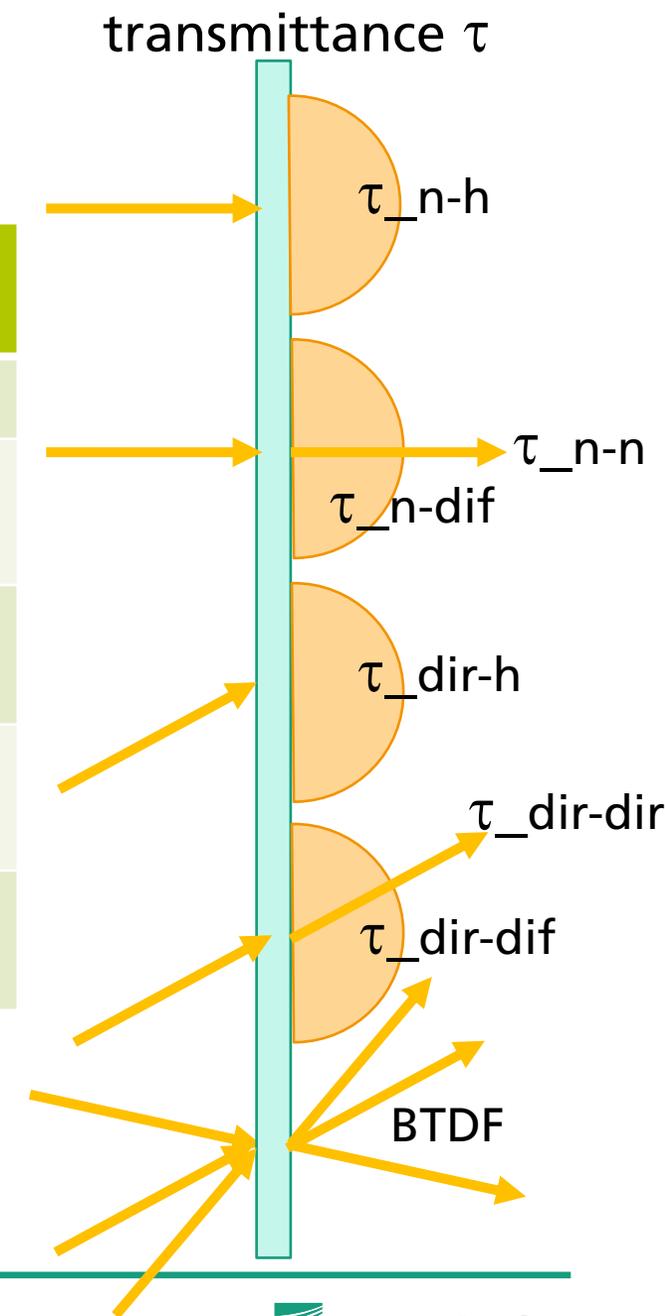
## - transmittance $\tau$ and reflectance $\rho$

Incidence direction	Exit directions	Qualifier	Symbol
Normal	Hemispherical	Normal-hemispherical	$\tau_{n-h}, \rho_{n-h}$
Normal	Normal or diffuse	Normal-normal or normal-diffuse	$\tau_{n-n}, \tau_{n-dif}$ $\rho_{n-n}, \rho_{n-dif}$
Direct (varying both $\theta$ and $\phi$ )	hemispherical	Direct-hemispherical	$\tau_{dir-h}, \rho_{dir-h}$
Direct (varying both $\theta$ and $\phi$ )	Direct or diffuse	Direct-direct or direct-diffuse	$\tau_{dir-dir}, \tau_{dir-dif}$ $\rho_{dir-dir}, \rho_{dir-dif}$
Direct (varying both $\theta$ and $\phi$ )	Direct (varying both $\theta$ and $\phi$ )	Bidirectional	BSDF, BTDF, BRDF*

\*Bidirectional scattering distribution function      BSDF

Bidirectional transmittance distribution function      BTDF

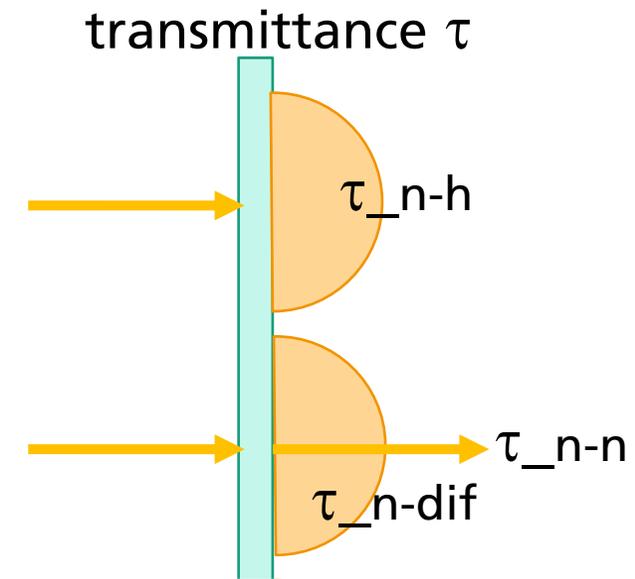
Bidirectional reflectance distribution function      BRDF



# A hierarchy of spatial resolution for optical properties

## - transmittance $\tau$ and reflectance $\rho$ with normal incidence

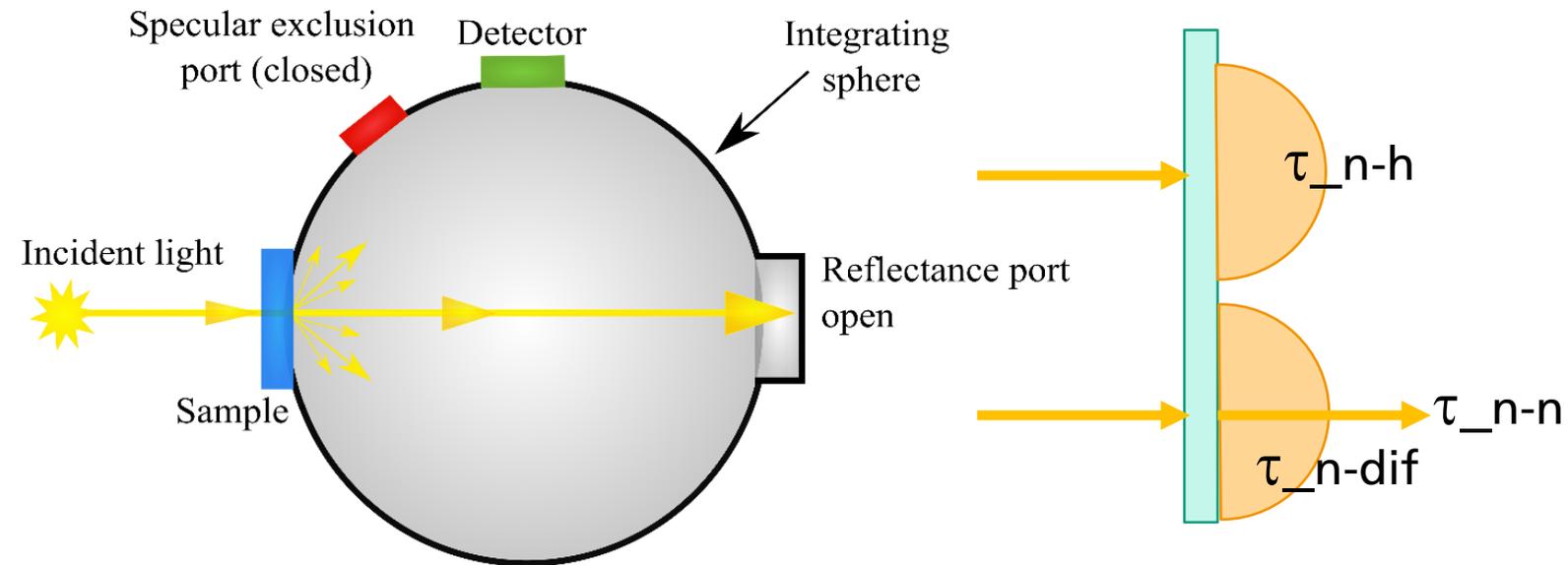
Incidence direction	Exit directions	Qualifier	Symbol
Normal	Hemispherical	Normal-hemispherical	$\tau_{n-h}$ , $\rho_{n-h}$
Normal	Normal or diffuse	Normal-normal or normal-diffuse	$\tau_{n-n}$ , $\tau_{n-dif}$ $\rho_{n-n}$ , $\rho_{n-dif}$



- Even the separation of  $\tau_{n-h}$  into  $\tau_{n-n}$  and  $\tau_{n-dif}$  implies an angular dependence – on the half-angle of the exiting light cone used to define  $\tau_{n-n}$

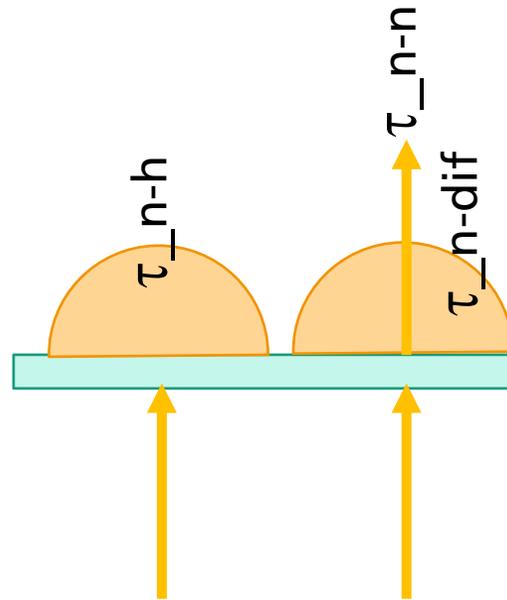
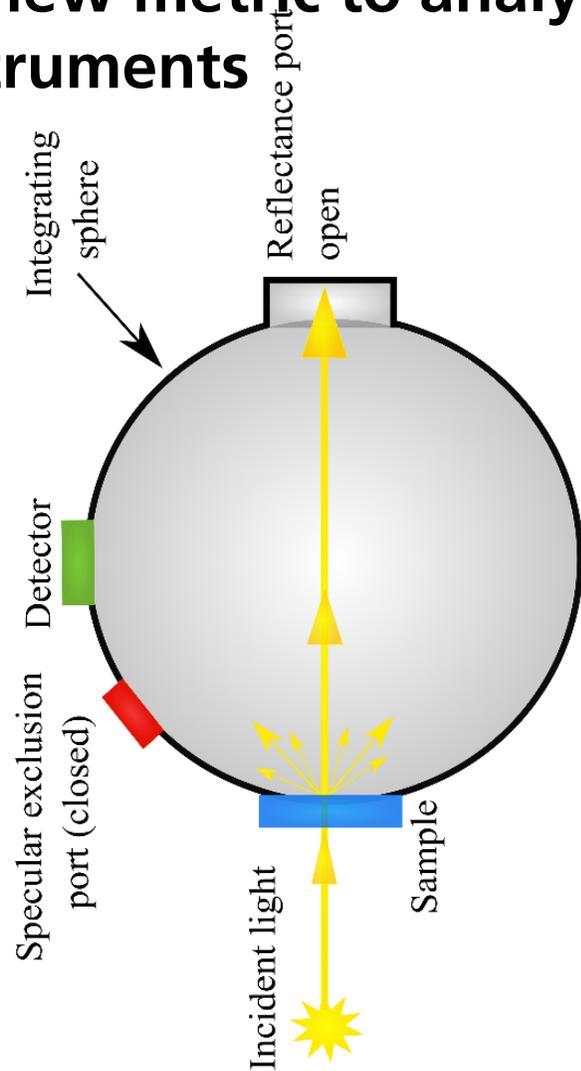
# Normal-conical transmittance $\tau_{n-con}$

- a new metric to analyse the interaction between samples and measuring instruments



# Normal-conical transmittance $\tau_{n-con}$

- a new metric to analyse the interaction between samples and measuring instruments

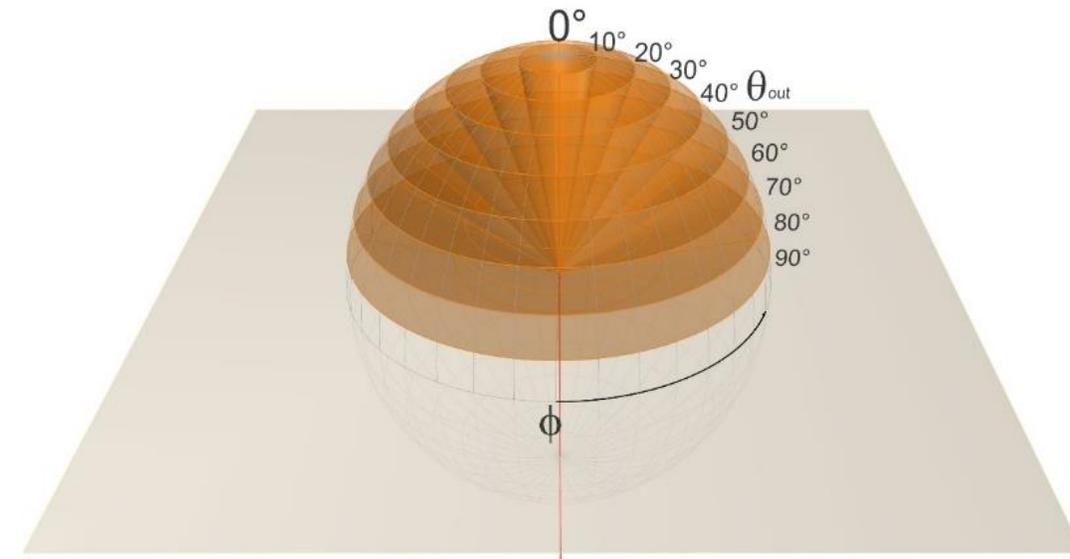


$$\tau_{n-n} = \tau_{n-con}(0^\circ) \text{ (ideal)}$$

$$\tau_{n-n} = \tau_{n-con}(\theta_{out}): 3.3^\circ < \theta_{out} < 4.8^\circ \text{ (real)}$$

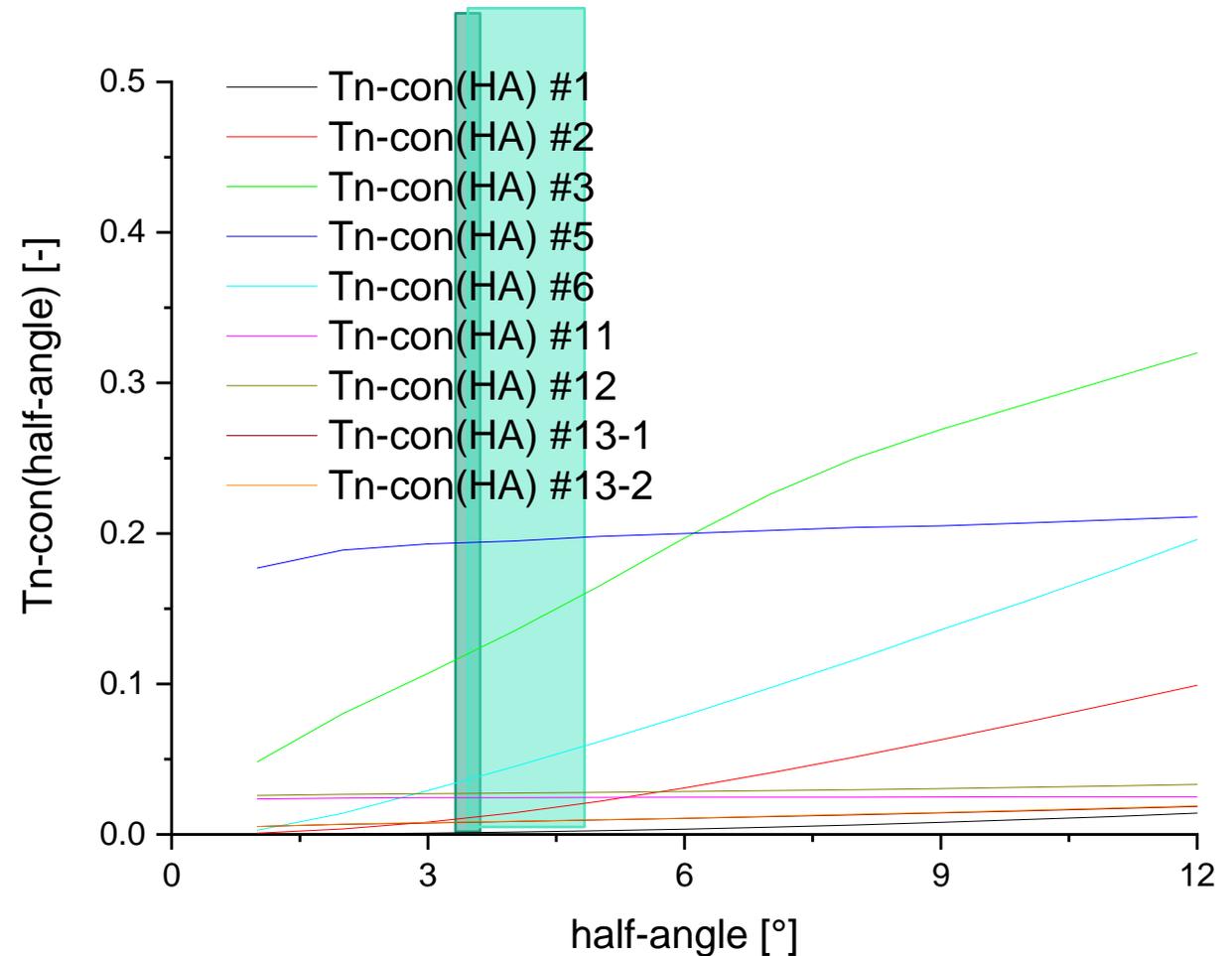
$$\tau_{n-con} = \tau_{n-con}(\theta_{out})$$

$$\tau_{n-hem} = \tau_{n-con}(90^\circ)$$



# Normal-conical transmittance $\tau_{n-con}$ for different shade fabrics

- Strongly light-scattering fabrics 2, 3, 6
  - strong variation of  $\tau_{n-con}$  with half-angle (HA)
  - >  $\tau_{n-n}$  result very sensitive to instrument geometry
- Other shade fabrics
  - little variation of  $\tau_{n-con}$  with half-angle (HA)
  - >  $\tau_{n-n}$  result insensitive to instrument geometry



# Applications of transmittance measured at normal incidence

- $\tau_{n-h}$ ,  $\tau_{n-n}$  and  $\tau_{n-dif}$  form the basis for product classification in EN 14501:2021 for

- Glare control
- Night privacy
- Visual contact
- Daylight utilisation

- Dependence on exit half-angle is restricted in EN 14500:2020 by limitations on exit aperture size in integrating sphere

# A hierarchy of spatial resolution for optical properties

## - transmittance $\tau$ and reflectance $\rho$ with oblique incidence

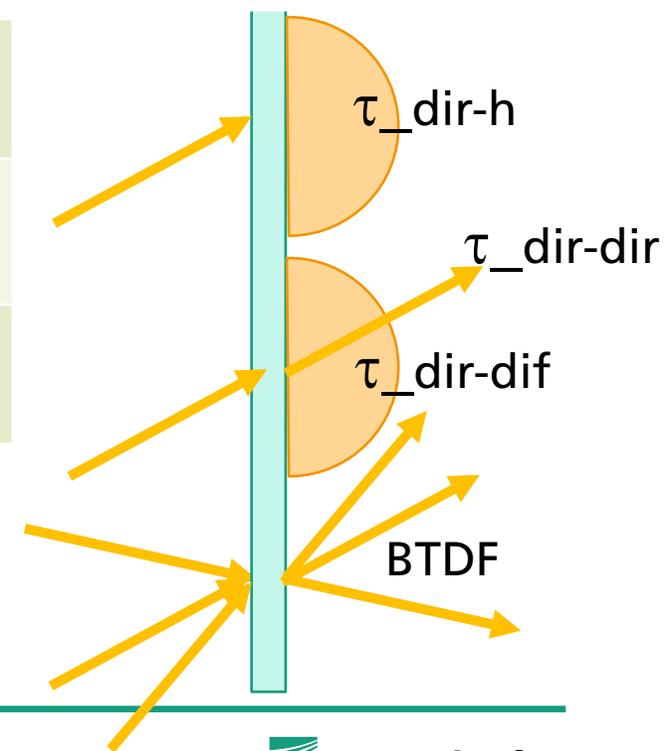
Incidence direction	Exit directions	Qualifier	Symbol
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Direct (varying both $\theta$ and $\phi$ )	hemispherical	Direct-hemispherical	$\tau_{\text{dir-h}}$ , $\rho_{\text{dir-h}}$
Direct (varying both $\theta$ and $\phi$ )	Direct or diffuse	Direct-direct or direct-diffuse	$\tau_{\text{dir-dir}}$ , $\tau_{\text{dir-dif}}$ $\rho_{\text{dir-dir}}$ , $\rho_{\text{dir-dif}}$
Direct (varying both $\theta$ and $\phi$ )	Direct (varying both $\theta$ and $\phi$ )	Bidirectional	BSDF, BTDF, BRDF*

\*Bidirectional scattering distribution function      BSDF

Bidirectional transmittance distribution function      BTDF

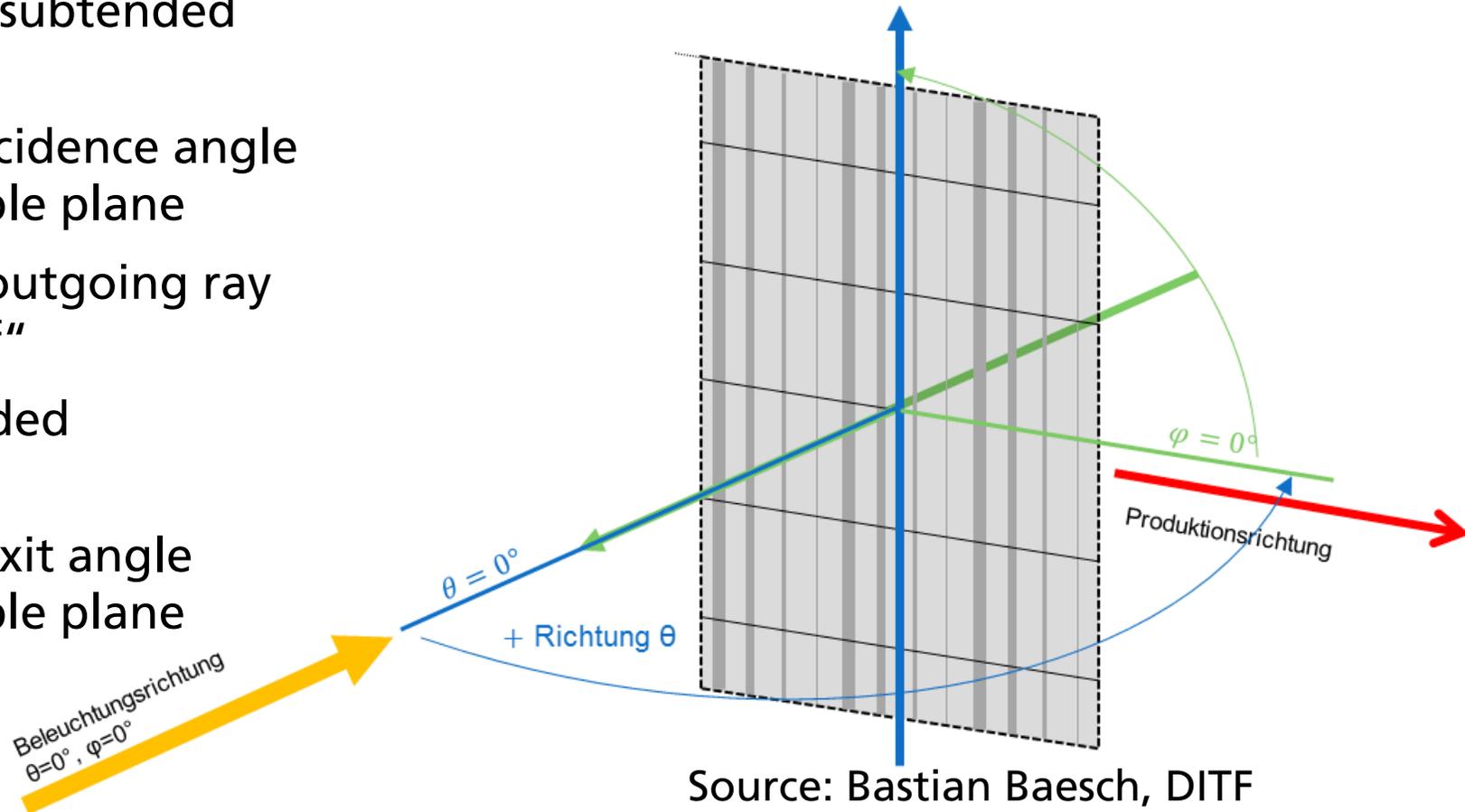
Bidirectional reflectance distribution function      BRDF



# Transmittance $\tau$ and reflectance $\rho$ with oblique incidence

- more angles become relevant, particularly for solar-shading textiles

- $\theta_{in}$ : "classic" angle of incidence subtended to sample normal
- $\varphi_{in}$ : azimuthal component of incidence angle - equivalent to rotation in sample plane
- Half-angle of cone centred on outgoing ray for separation of „dir“ and „dif“
- $\theta_{out}$ : "classic" exit angle subtended to sample normal
- $\varphi_{out}$ : azimuthal component of exit angle - equivalent to rotation in sample plane
- (s and p polarisation angles)



# Characterization of solar shading with oblique incidence

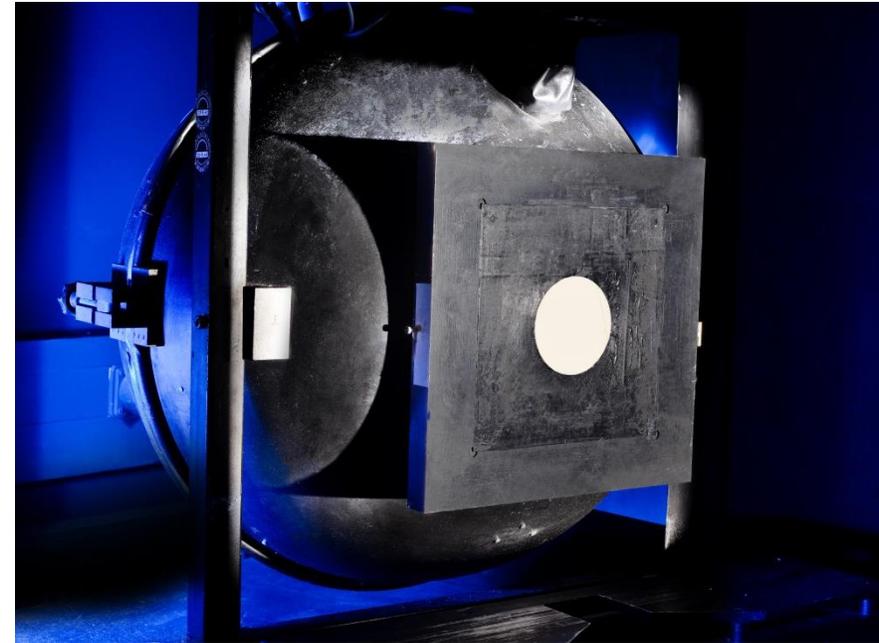
## Measurement of directional-hemispherical transmittance $\tau_{dir-h}$

- Rotatable integrating sphere
- Spectral transmittance measurements at different angles of incidence
- Spectral weighting with  $v(\lambda)$  curve to obtain direct-hemispherical visible transmittance

$\tau_{v\_dir-h}$



Measured shading fabric sample



“TAUWIN”  
rotatable  
integrating  
sphere at  
Fraunhofer ISE

# Characterization of solar shading with oblique incidence

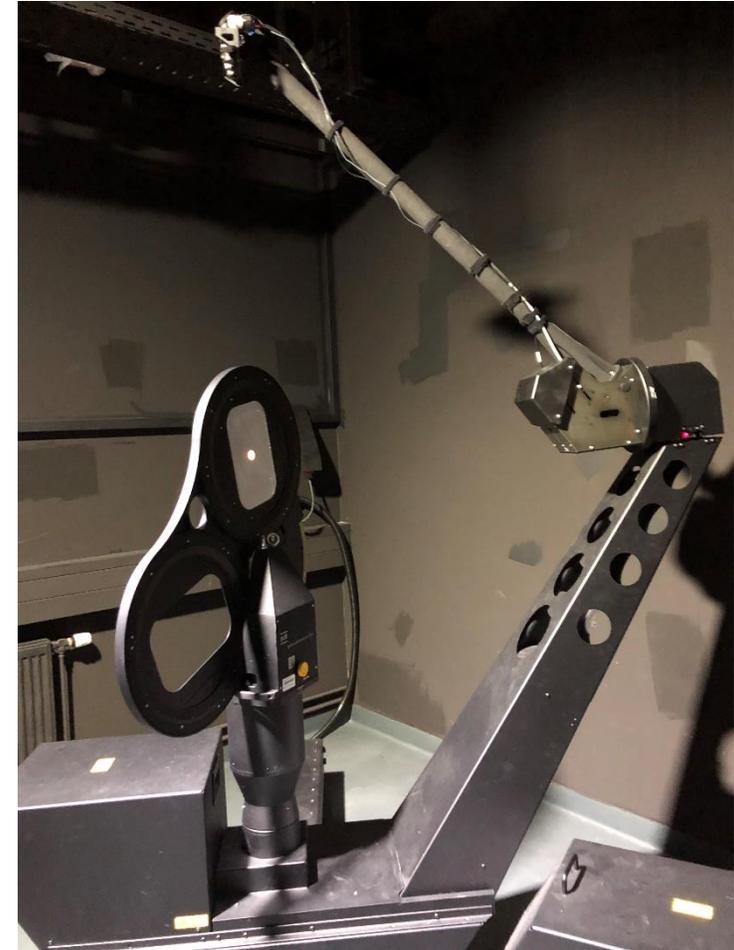
## Measurement of bi-directional transmittance distribution function BTDF

- Photogoniometer
- Visible (light) BTDF measurements (corrected for dark signal) at different angles of incidence
- Spatial integration over hemisphere to obtain direct-hemispherical visible transmittance

$\tau_{v\_dir-h}$



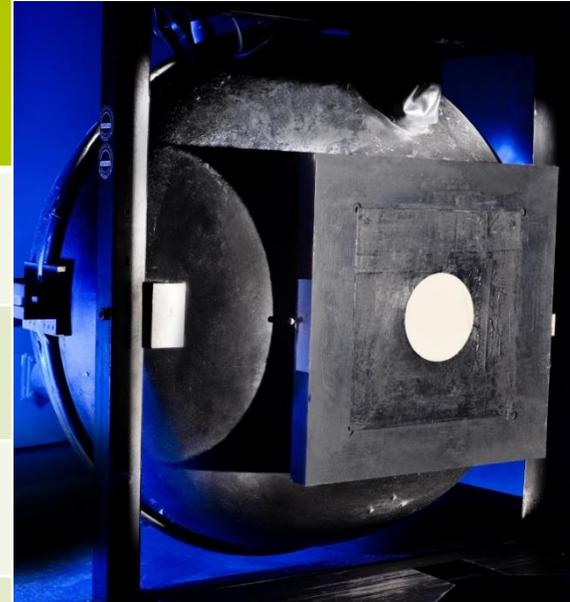
Measured shading fabric sample in photogoniometer sample holder



pgII photogoniometer with measured shading fabric

# Validation of direct-hemispherical light transmittance results by comparing integrating-sphere and photogoniometric results for $\tau_{v\_dir-h}$

Incidence angles		$\tau_{v\_dir-h}$ (Integ- rating sphere)	$\tau_{v\_dir-h}$ (Photo- gonio- meter)	Differ- ence in $\tau_{v\_dir-h}$
$\theta_{in}$	$\phi_{in}$			
0	0	0.0194	0.0196	0.0002
20	0	0.0192	0.0188	0.0004
40	0	0.0185	0.0177	0.0008
60	0	0.0155	0.0149	0.0006
80	0	0.0086	0.0059	0.0026



Agreement generally within 0.01 also for other incidence angles.

# Example of angle-dependent measurement results – fabric sample for roller blind

MechoShade EuroTwill Slate 6216,  $T_v = 3\%$  Batch 2 (IEA-T61 sample)

Measured by ISE (ISE ID: VS415004, A20/002 ) and LBNL within ICON project



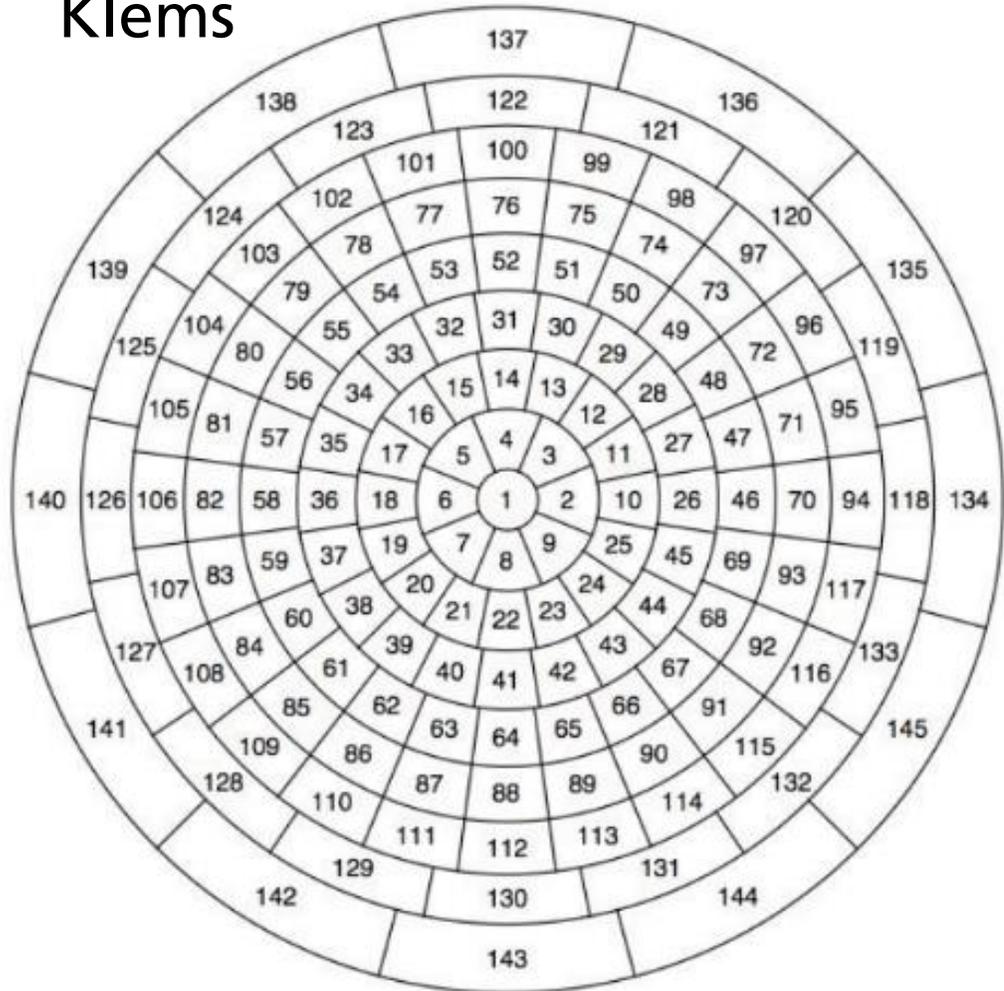
Exterior



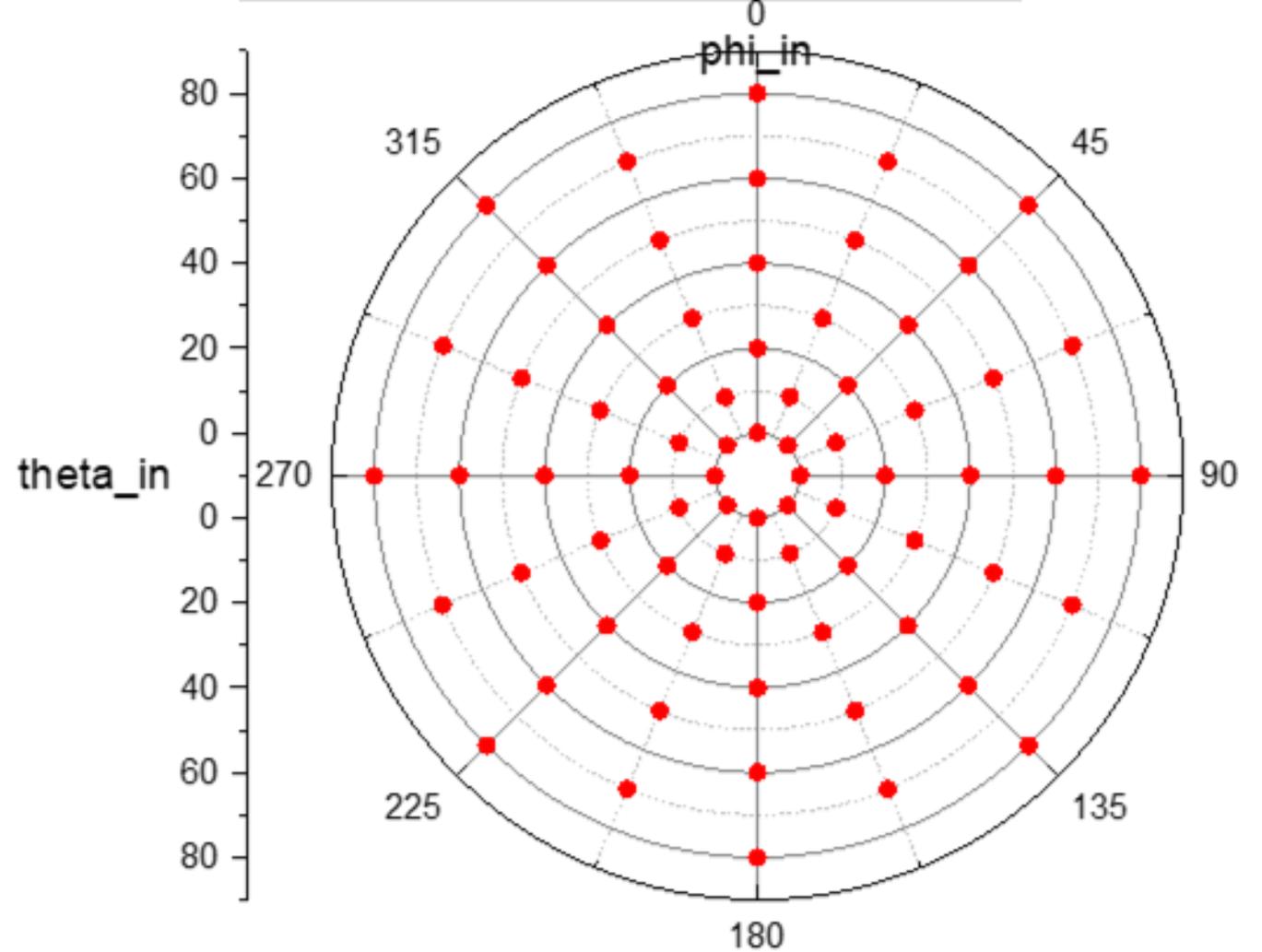
Exterior rotated by 180°

# Choice of incidence angles for these photogoniometric measurements

Klems

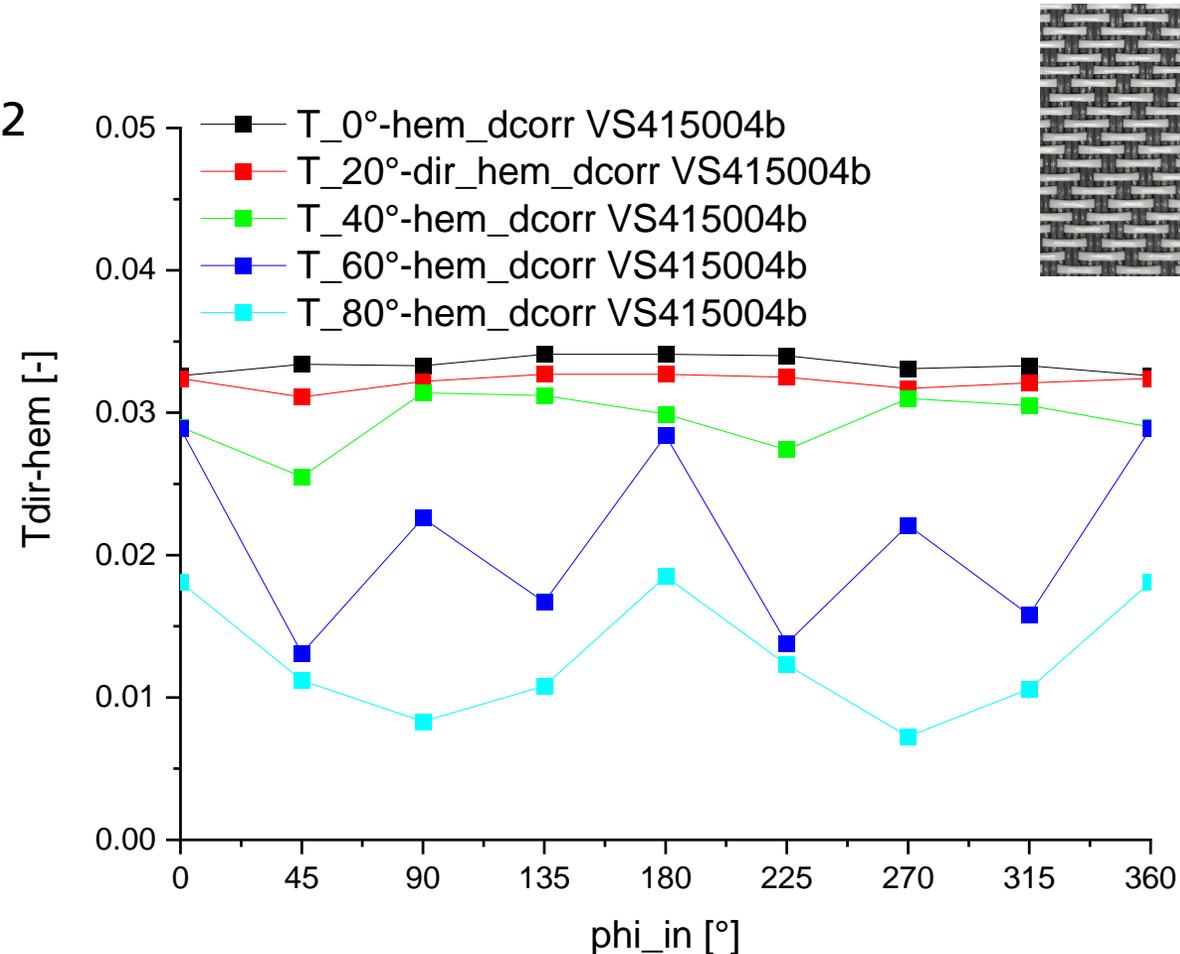


● incidence angles of measurements



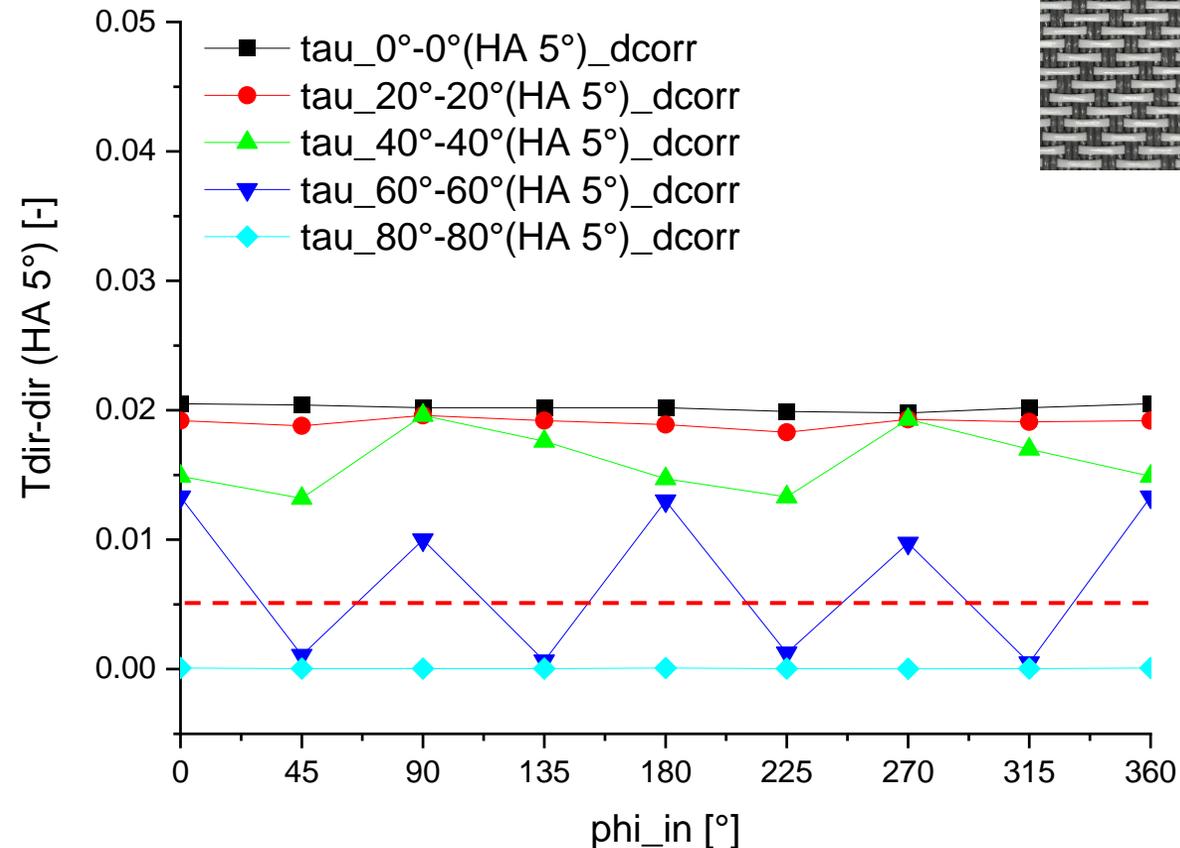
# Direct-hemispherical transmittance vs $\phi_{in}$ for different $\theta_{in}$ [ $0^\circ$ ( $20^\circ$ ) $80^\circ$ ] - light incident on exterior surface of VS415004

- **Rotational** symmetry of order 2 evident for  $\theta_{in}$  between  $40^\circ$  and  $60^\circ$
- Rotational symmetry could be used to halve the number of measurements needed
- **EN 14500**: Need to differentiate between symmetry by reflection and symmetry by rotation



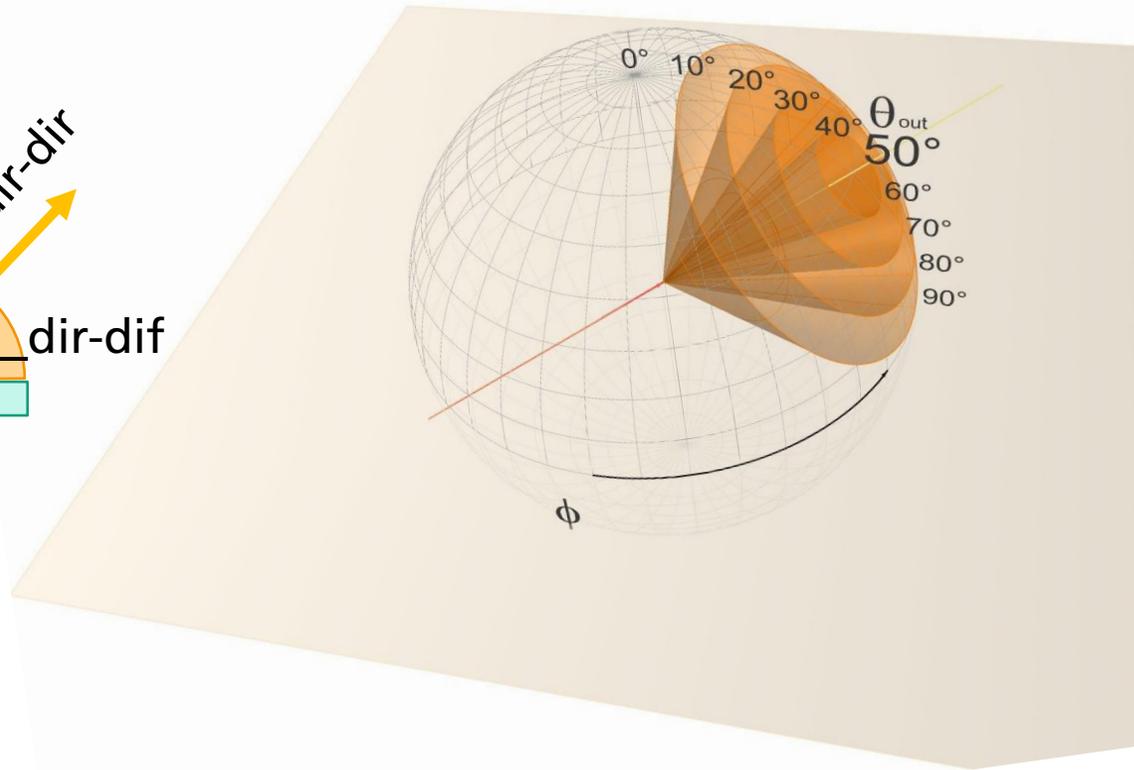
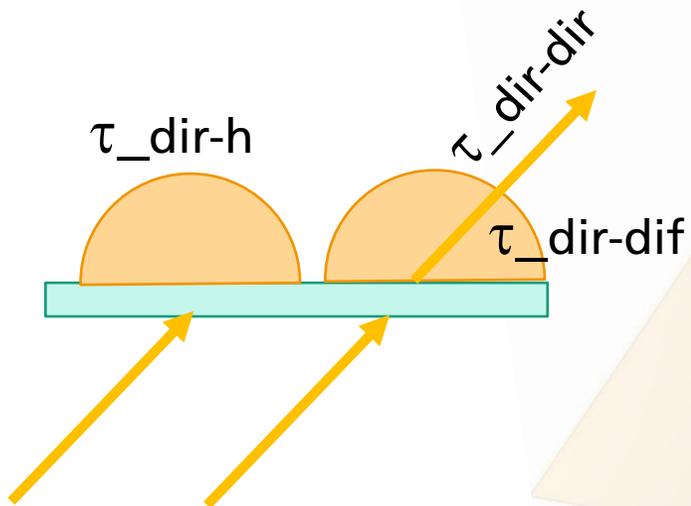
# Direct-direct transmittance (HA 5°) vs phi\_in for different theta\_in [0° (20°) 80°] - light incident on exterior surface of VS415004

- Rotational symmetry of order 2 evident for theta\_in between 40° and 60°
- For theta\_in = 60°, cut-off has been reached (T\_dir-dir < 0.005) at phi\_in = 45°, 135°, 225° and 315°
- For theta\_in = 60°, cut-off has not been reached at phi\_in = 0°, 90°, 180° and 270°
- Implications for EN 14500 / EN 14501?



# Direct-conical transmittance $\tau_{\text{dir-con}}$

- a new metric to analyse the interaction between samples and measuring instruments



$$\tau_{\text{dir-dir}} = \tau_{\text{dir-con}}(0^\circ) \text{ (ideal)}$$

$$\tau_{\text{dir-dir}} = \tau_{\text{dir-con}}(\theta_{\text{out}})$$

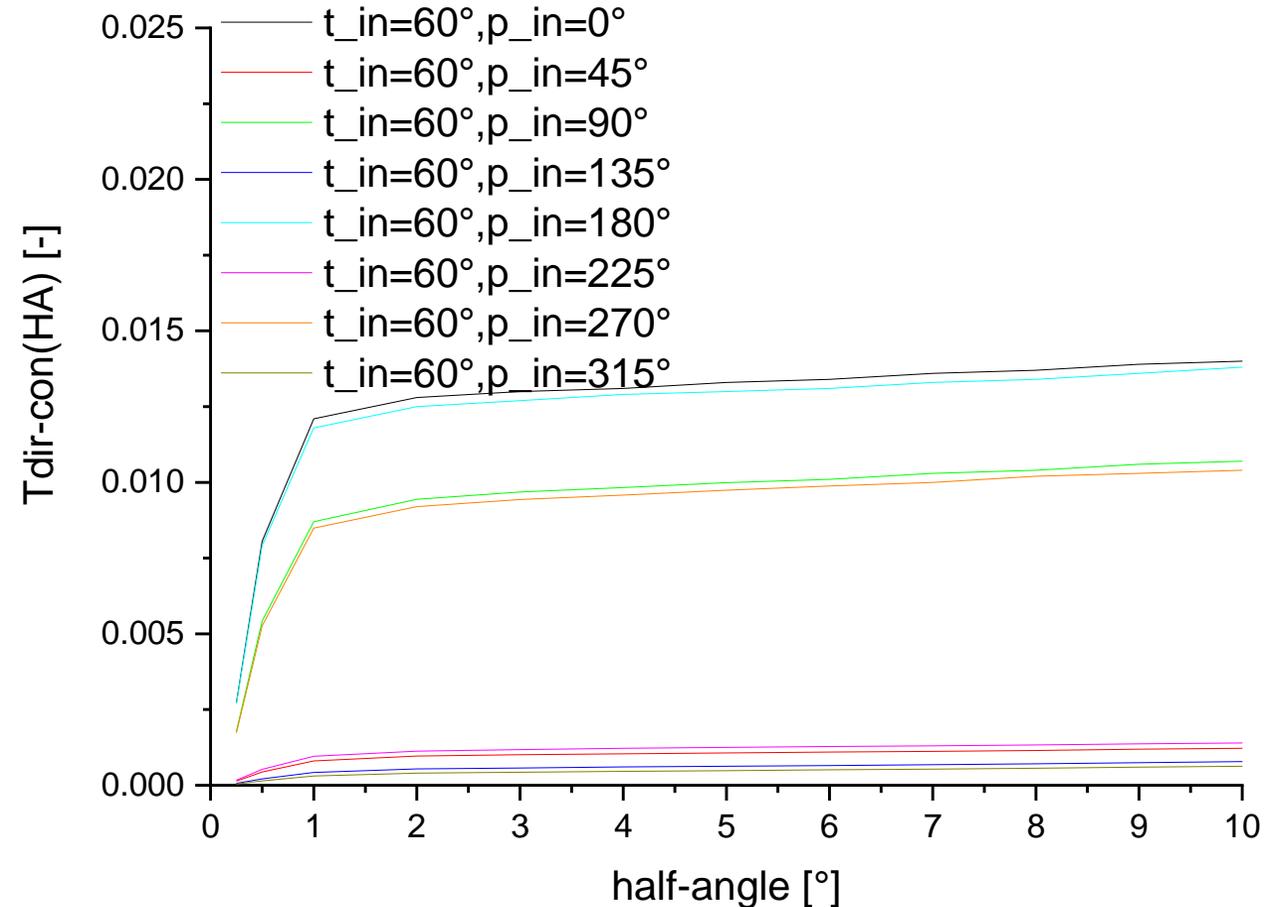
e.g.  $3^\circ < \theta_{\text{out}} < 5^\circ$  (real)

$$\tau_{\text{dir-con}} = \tau_{\text{dir-con}}(\theta_{\text{out}})$$

$$\tau_{\text{dir-hem}} \neq \tau_{\text{dir-con}}(90^\circ)$$

# Direct-conical transmittance vs half-angle for $\theta_{in} = 60^\circ$ and different $\phi_{in}$ - light incident on exterior surface of VS415004 (overview $0^\circ < HA < 10^\circ$ )

- Rotational symmetry of order 2 evident by pairing of  $T_{dir-con}$  results for  $\phi_{in}$  and  $(\phi_{in} + 180^\circ)$
- Includes measurements with  $\phi_{in}$  parallel or perpendicular to yarns



# Observations on direct-conical transmittance as a function of half-angle

- 2D graphs as representation of BTDF or BRDF for use as material signature
- Sensitivity of haze to HA can be inferred from graphs
- Allows simple visual identification of fabric symmetry by grouping of curves with different  $\phi_{in}$
- Implications for „cut-off“ angle for solar-shading fabrics – dependent on  $\phi_{in}$
- We recommend  $1^\circ < HA < 10^\circ$  as the range for direct-conical transmittance relevant for comparison of different measurement sets or analysis depending on ratio of direct-direct to direct-diffuse quantities (haze, cut-off angle, ...)

# Convergence on photogoniometric measurement procedures within IEA-SHC Task 61

- Fraunhofer ISE and LBNL collaborated with other members of task 61 to decrease the variance in our measurement results using photogoniometers
  - Dark signal correction for samples with dominating specular components
  - Beam size, shape and focus
  - Standardized conversion to Klems basis using Radiance

Reports available under:

<https://task61.iea-shc.org/publications>.

DOI: <https://doi.org/10.18777/ieashc-task61-2021-0001>

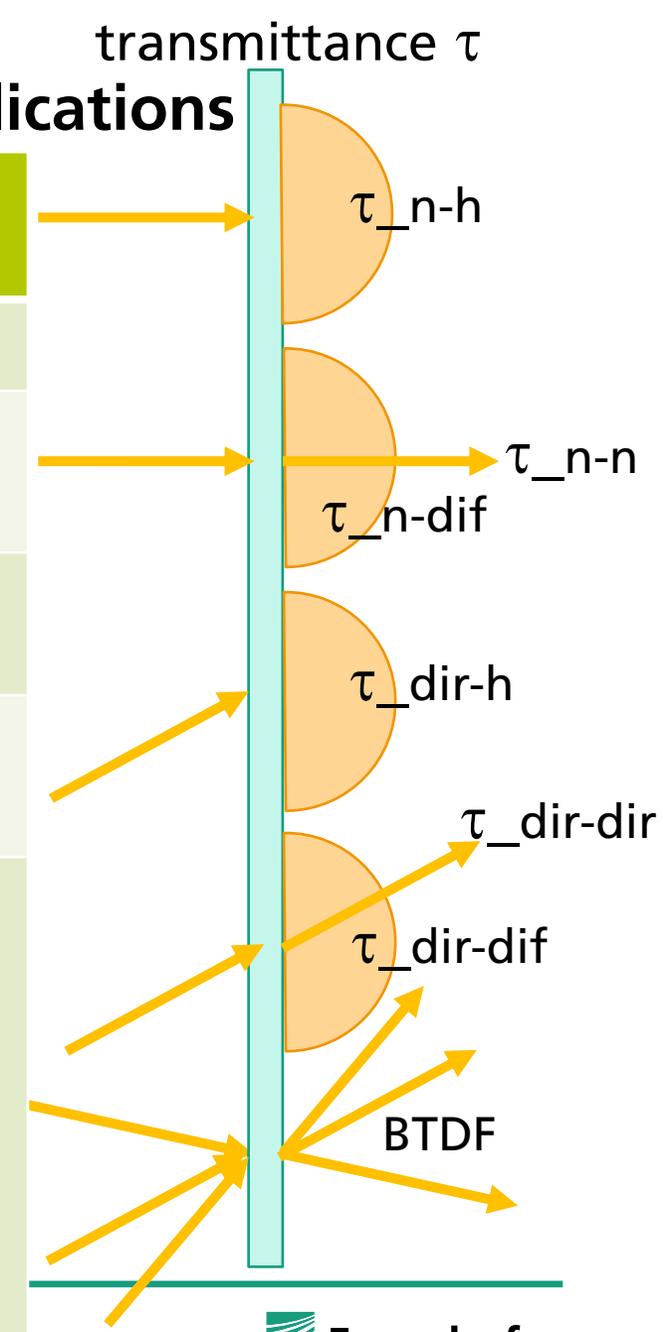
<https://task61.iea-shc.org/publications>.

DOI: <https://doi.org/10.18777/ieashc-task61-2021-0012>



# Overview of angle-dependent measurement types and applications

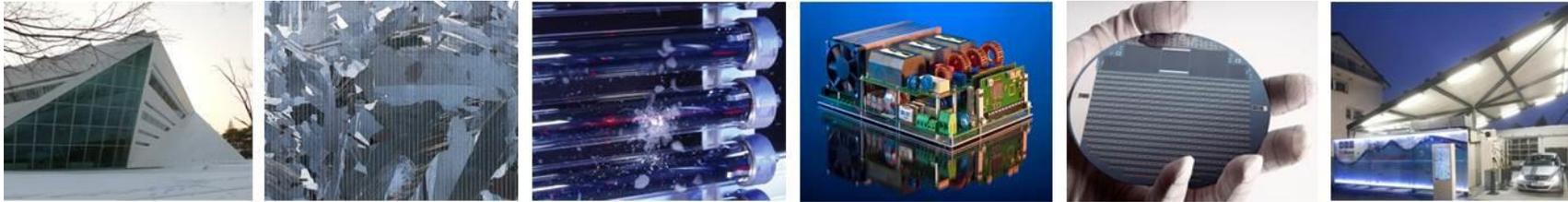
Incidence direction	Exit directions	Application
Normal	Hemispherical	Product screening
Normal	Normal or diffuse	Product classification: visual comfort, solar gain
Direct (varying both $\theta$ and $\phi$ )	hemispherical	Performance in building: solar gains
Direct (varying both $\theta$ and $\phi$ )	Direct or diffuse	Performance in building: daylighting assessment
Direct (varying both $\theta$ and $\phi$ )	Direct (varying both $\theta$ and $\phi$ )	Performance in building: Glare control  Single-layer characterisation for combination into multi-layer fenestration system  Analysis of sample-instrument match via $\tau_{dir-con}$



# Possible items for discussion

- Modifications to allocation of measurement quantities to applications in previous slides
- Comments on EN 14500: „symmetry“, cut-off angle
- Value of direct-conical transmittance as a metric

**Thank you to Jacob Jonsson, LBNL and colleagues in IEA-SHC T61 for fruitful collaboration - and to you for your attention!**



**Fraunhofer Institute for Solar Energy Systems ISE**

**Dr. Helen Rose Wilson**

[www.ise.fraunhofer.de](http://www.ise.fraunhofer.de)

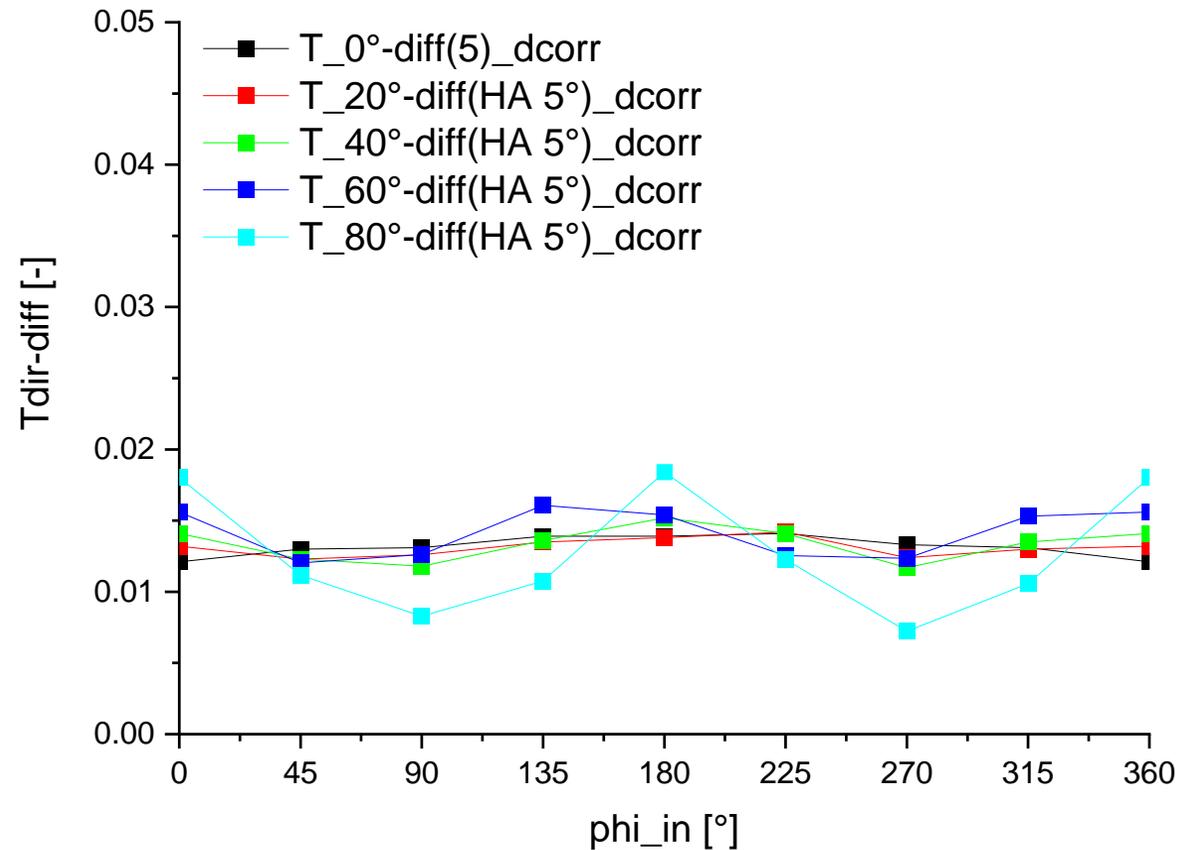
[helen.rose.wilson@ise.fraunhofer.de](mailto:helen.rose.wilson@ise.fraunhofer.de)

**Further results from the ICON project between Fraunhofer ISE and LBNL can be found under:**

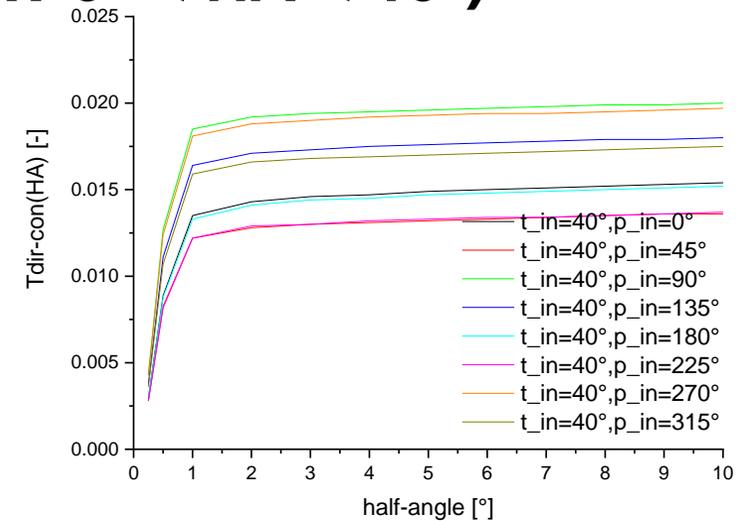
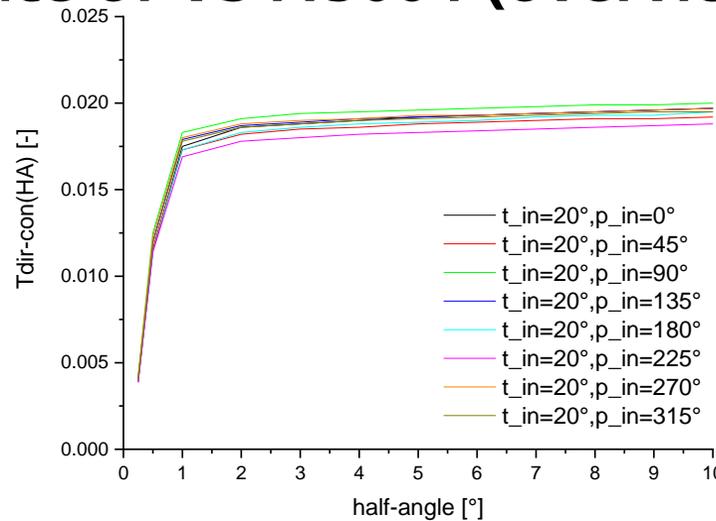
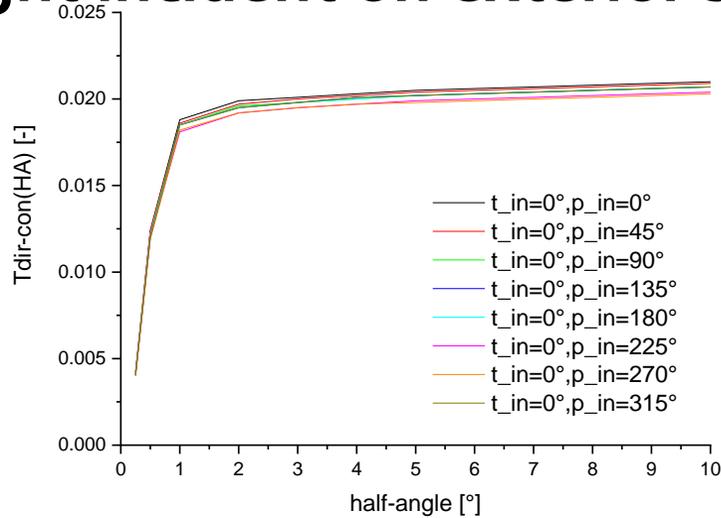
<https://www.ise.fraunhofer.de/en/research-projects/icon-lbnl-fraunhofer-ise.html>

# Direct-diffuse transmittance (HA 5°) vs phi\_in for different theta\_in [0° (20°) 80°] - light incident on exterior surface of VS415004

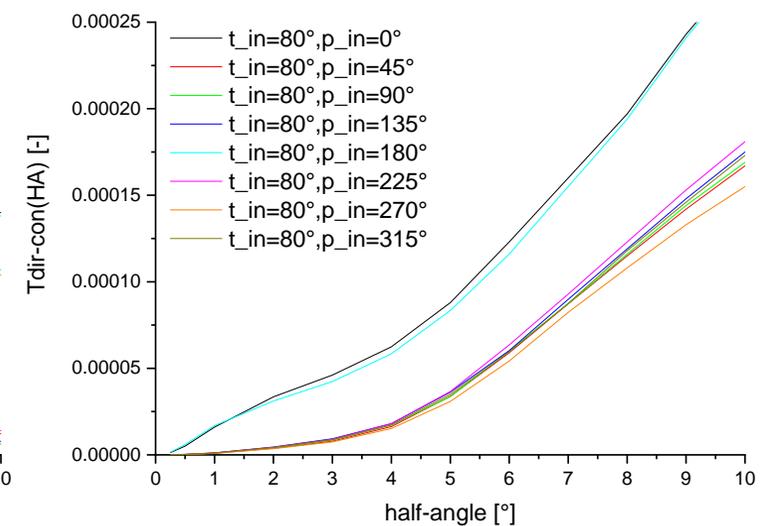
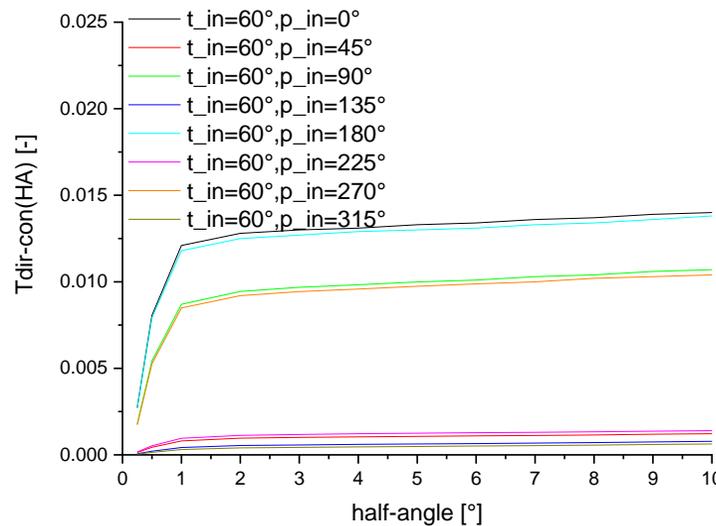
- Rotational symmetry of order 2 evident only for theta\_in = 60°
- Less variation in amplitude with phi\_in than for Tdir-hem or Tdir-dir



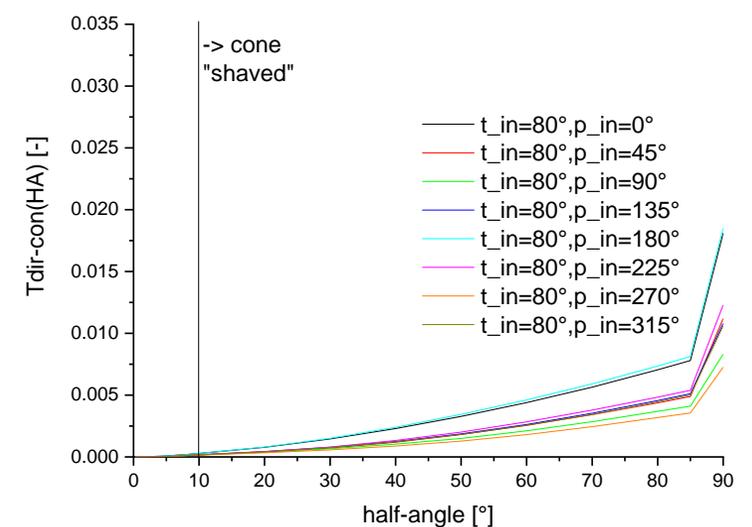
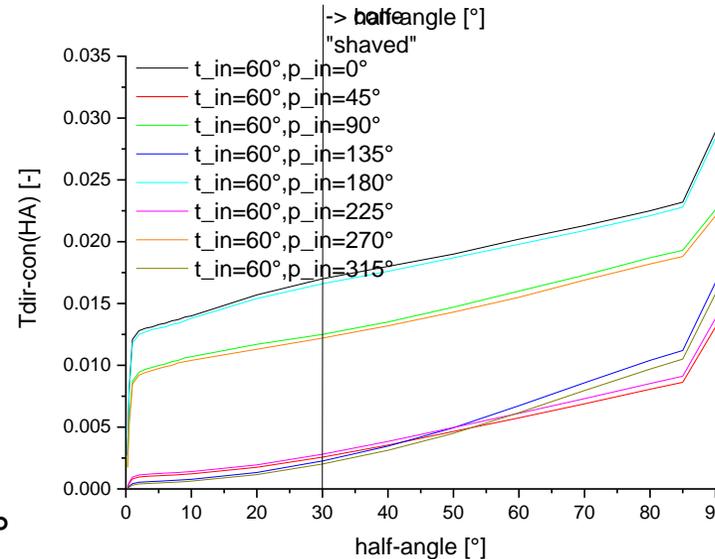
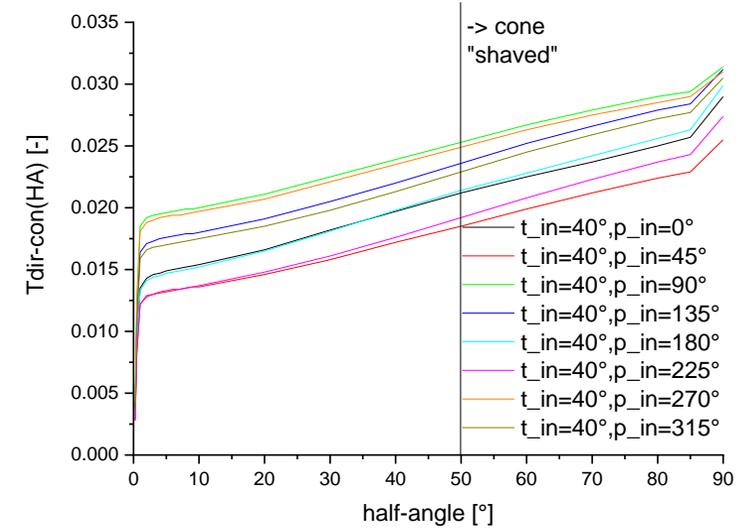
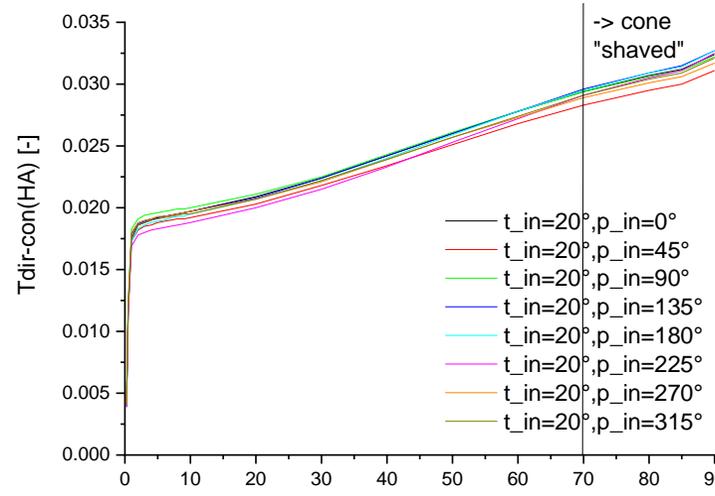
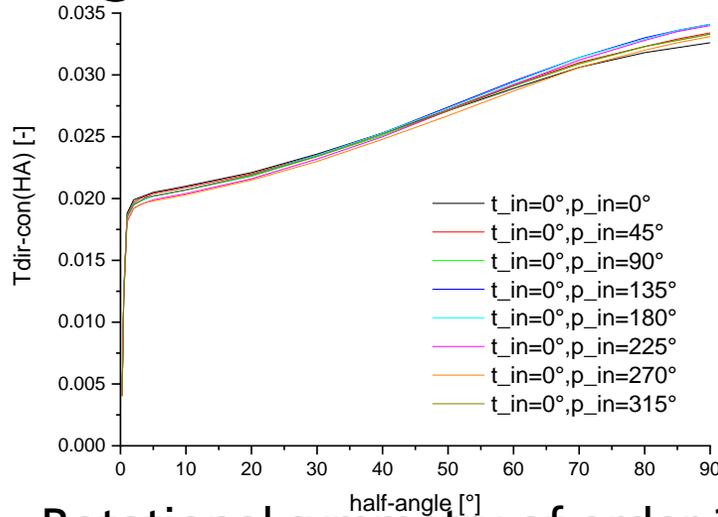
# Direct-conical transmittance vs half-angle for different $\theta_{in}$ and $\phi_{in}$ - light incident on exterior surface of VS415004 (overview $0^\circ < HA < 10^\circ$ )



- Rotational symmetry of order 2 evident for  $\theta_{in}$  between  $40^\circ$  and  $80^\circ$
- Includes measurements with  $\phi_{in}$  parallel or perpendicular to yarns



# Direct-conical transmittance vs half-angle for different $\theta_{in}$ and $\phi_{in}$ - light incident on exterior surface of VS415004 (overview $0^\circ < HA < 90^\circ$ )



- Rotational symmetry of order 2 evident for  $\theta_{in}$  between  $40^\circ$  and  $80^\circ$
- Includes measurements with  $\phi_{in}$  parallel or perpendicular to yarns
- „Cone-shaving“ for  $HA > (90^\circ - \theta_{in})$ , but true  $T_{dir-hem}$  is plotted at  $HA = 90^\circ$