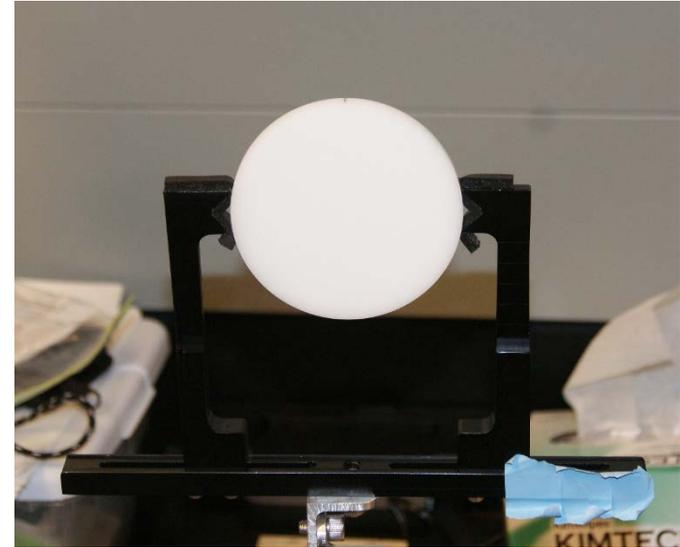


# Measurements of the hemispherical reflectance and the optical properties ( $m_a ; m_s'$ ) of a quartz diffuser

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# Sample

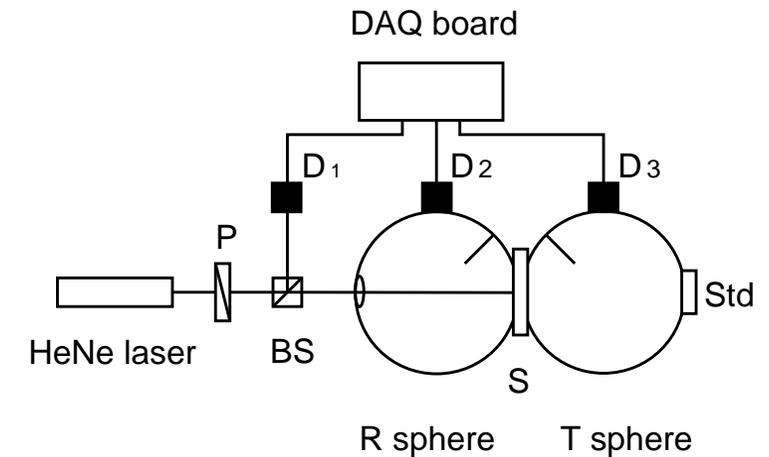
- Measurements of a HOD 500 sample from Heraeus <sup>1</sup>
  - Volume quartz diffuser
  - Homogeneous material
  - Specular and non specular faces
  - Diameter 76.2 mm, larger than sample port
  - Thickness 5.27 mm



<sup>1</sup> Certain commercial materials and equipment are identified in order to adequately specify the experimental procedure. Such identification does not imply recommendation by the National Institute of Standards and Technology.

# NIST DIS setup

- Laser operated Double Integrating Spheres (DIS) System
- Originally to measure biomedical phantoms and tissues
- Setup
  - Double Integrating Spheres, substitution method
  - 2 laser lines, 543 nm and 632 nm, HeNe
  - Light power fluctuations, reference channel, polarizer + beam splitter
  - Measure diffuse R and T, not unscattered T

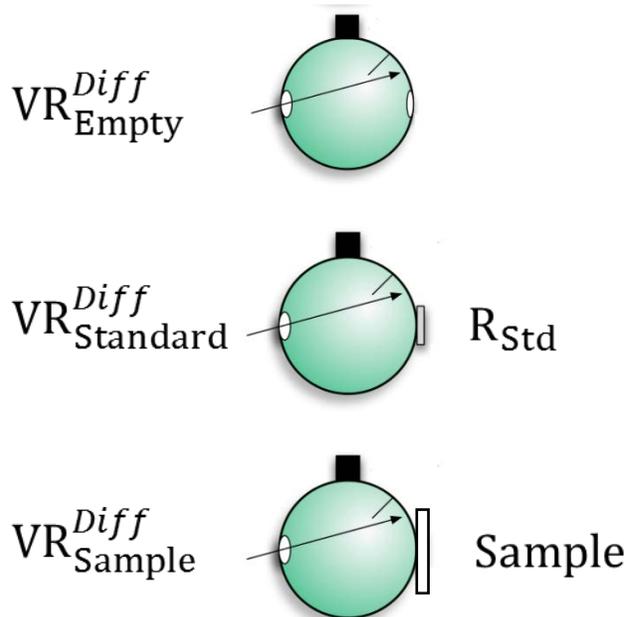


# Hemispherical reflectances of HOD 500

- Measurements with one sphere, simpler formulas
- Hemispherical R under diffuse illumination
- Hemispherical R under normal illumination
- Uncertainties by Gaussian propagation

# Hemispherical reflectances of HOD 500

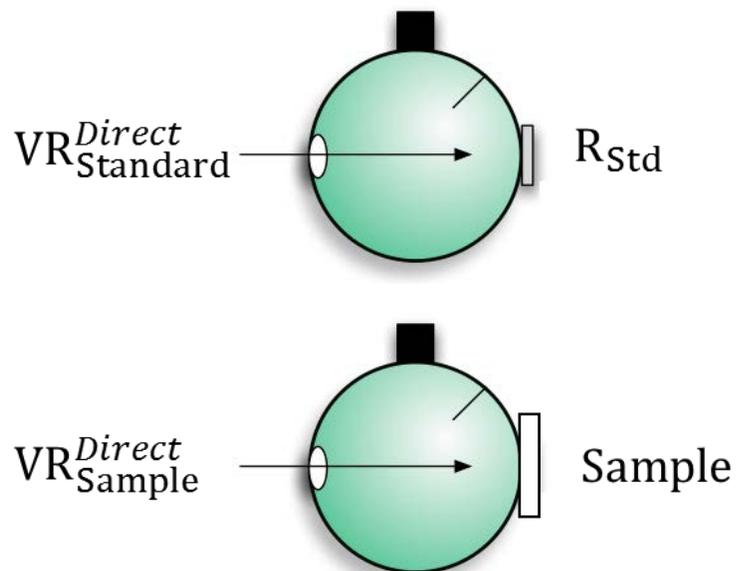
- Hemispherical R under diffuse illumination
- Needed to measure the reflectance under normal illumination



$$R_{Sample}^{Diff} = R_{Std} \frac{VR_{Standard}^{Diff}}{VR_{Sample}^{Diff}} \frac{(VR_{Empty}^{Diff} - VR_{Sample}^{Diff})}{(VR_{Empty}^{Diff} - VR_{Standard}^{Diff})}$$

# Hemispherical reflectances of HOD 500

- Hemispherical R under normal illumination



$$R_{Sample}^{Direct} = R_{Std} \frac{VR_{Standard}^{Diff}}{VR_{Sample}^{Diff}} \frac{VR_{Sample}^{Direct}}{VR_{Standard}^{Direct}}$$

# Hemispherical reflectances of HOD 500

- Hemispherical R under diffuse illumination

	Face	Value	Absolute uncertainty (k =2)	Relative uncertainty
$\lambda = 543.5 \text{ nm}$				
	<i>Specular</i>	0.725	0.0066	0.91%
	<i>Non specular</i>	0.723	0.0068	0.94%
$\lambda = 632.8 \text{ nm}$				
	<i>Specular</i>	0.728	0.0070	0.96 %
	<i>Non specular</i>	0.726	0.0070	0.96 %

# Hemispherical reflectance of HOD 500

- Hemispherical R under normal illumination

Non specular face

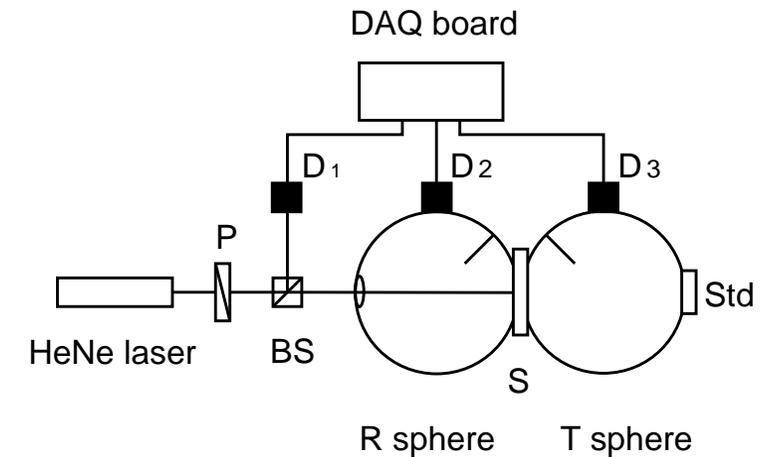
Specular face

	$R_{Sample}^{Direct}$	Absolute uncertainty (k = 2)	Relative uncertainty		$R_{Sample}^{Direct}$	Absolute uncertainty (k = 2)	Relative uncertainty
$\lambda = 543.5 \text{ nm}$	0.769	0.0040	0.52 %	$\lambda = 543.5 \text{ nm}$	0.732	0.0038	0.52 %
$\lambda = 632.8 \text{ nm}$	0.775	0.0046	0.60 %	$\lambda = 632.8 \text{ nm}$	0.742	0.0046	0.62 %

- Specular reflectance rejected out of the sphere for specular face, volume reflectance

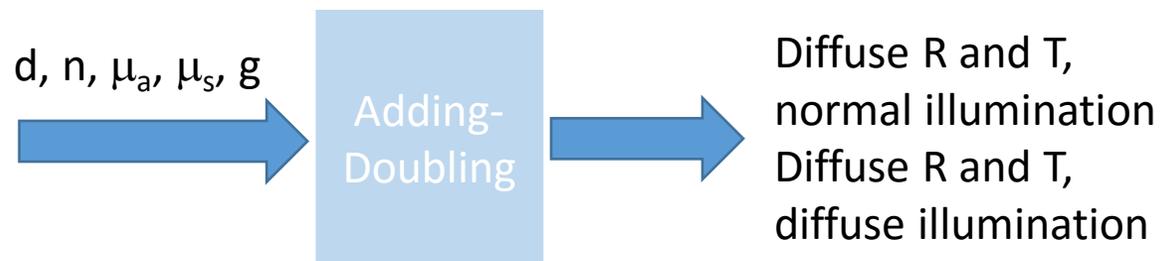
# NIST DIS setup

- Laser operated Double Integrating Spheres System + Inverse Adding Doubling
- Setup
  - Double Integrating Spheres, substitution method
  - 2 laser lines, 543 nm and 632 nm, HeNe
  - Light power fluctuations, reference channel, polarizer + beam splitter
  - Measure diffuse R and T, not unscattered T so far so  $\mu_a$  and  $\mu_s'$



# NIST DIS setup

- Adding Doubling

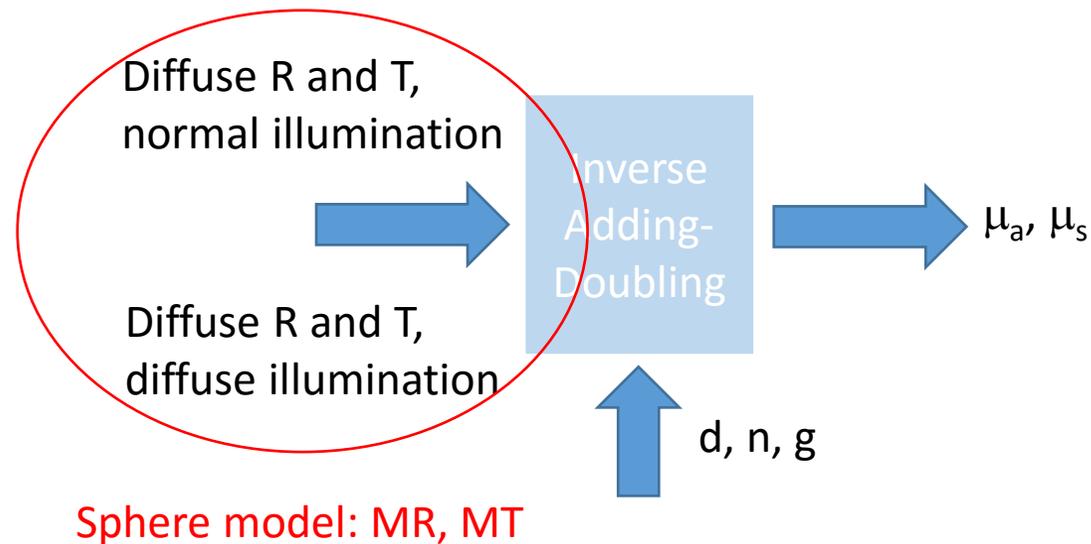


- Van de Hulst, Scott Prahl
- Infinite parallel plane slabs, homogeneous material, unpolarized light
- Solves the Radiative Transfer Equation for a thin layer (single scattering), finds the diffuse R and T
- Compound layer by adding/doubling, gives the diffuse R and T under direct and diffuse illumination

S. A. Prahl, M. J. C. van Gemert, and A. J. Welch, "Determining the optical properties of turbid media by using the adding-doubling method," *Appl. Opt.* **32**(4), 559-568 (1993).

# NIST DIS setup

- Inverse Adding Doubling



- Modified inversion code to allow for the computation of the uncertainty budget (but based on Adding-doubling code by Prahl)
- Gaussian propagation of uncertainties

# NIST DIS setup

- NIST Inverse Adding Doubling
  - Command line
  - Graphical User Interface, multiplatform (Win/Cygwin; Mac; Linux), WxWidgets open source library

The screenshot shows the 'Config File' window for 'Spheres param.'. It features two main tables: 'Reflectance Sphere' and 'Transmittance Sphere'. Each table has columns for 'Value', 'Differential', 'Uncertainty', and 'Unc.'. The 'Uncertainty' column values are highlighted with green boxes. A blue arrow points from these boxes to the text 'For numerical derivation'. Below the tables, two purple brackets are labeled 'R sphere' and 'T sphere'. A green arrow points from the text 'Type B uncertainty' to the 'Uncertainty' column.

Parameter	Value	Differential	Uncertainty	Unc.
Sphere Diameter	198.372	1e-07	0.577	✓
Sample Port Diameter	38.1	1e-07	0.0577	✓
Entrance Port Diameter	25.1	1e-07	0.0577	✓
Detector Port Diameter	12.7	1e-07	0.0577	✓
Rstd (Cal.)	0.99	1e-07	0.002	✓
Rstd (Meas.)	0.99	1e-07	0.02	✓
Detector Reflectance	0.05	1e-07	0.002	✓

Type B uncertainty

For numerical derivation

R sphere

T sphere

The screenshot shows the 'Config File' window for 'Sample reflectance' and 'Sample transmittance'. It features two 'Data Files' sections with 'Browse' buttons and file paths. An orange oval highlights these sections, with an arrow pointing to the text 'Data files'. Below, there are two tables for 'Sample' parameters with columns for 'Value', 'Differential', 'Uncertainty', and 'Unc.'. The 'Uncertainty' column values are highlighted with green boxes, with an arrow pointing to the text 'Type A Uncertainty From data files'. At the bottom, there are 'Compute' and 'Port Correct.' buttons, and a section for 'Musp' and 'k' values, highlighted with an orange box and an arrow pointing to the text 'Computation of the optical properties'.

Sample	Value	Differential	Uncertainty	Unc.
VR_Sample	-2.2015	1e-05	4.93662e-05	✓
VR_Standard	-4.83149	1e-05	4.37335e-05	✓
VR_Dark	0.00119141	1e-08	2.77049e-05	✓
VR_Sample_Ref	-1.02231	1e-05	3.30813e-05	✓
VR_Standard_Ref	-1.02101	1e-05	2.1557e-05	✓
VR_Dark_Ref	0.00075439	1e-08	2.4195e-05	✓

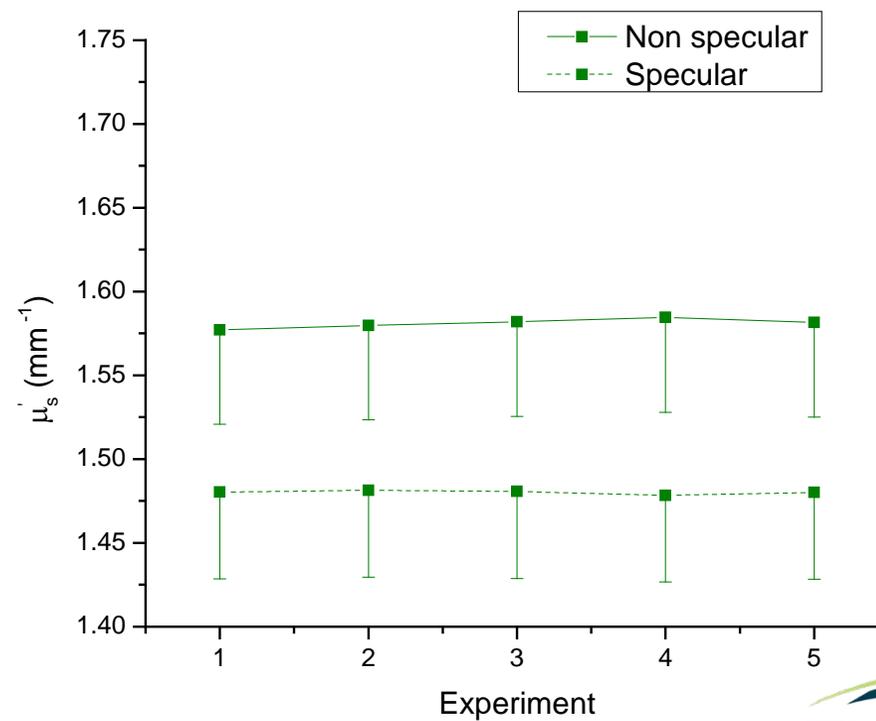
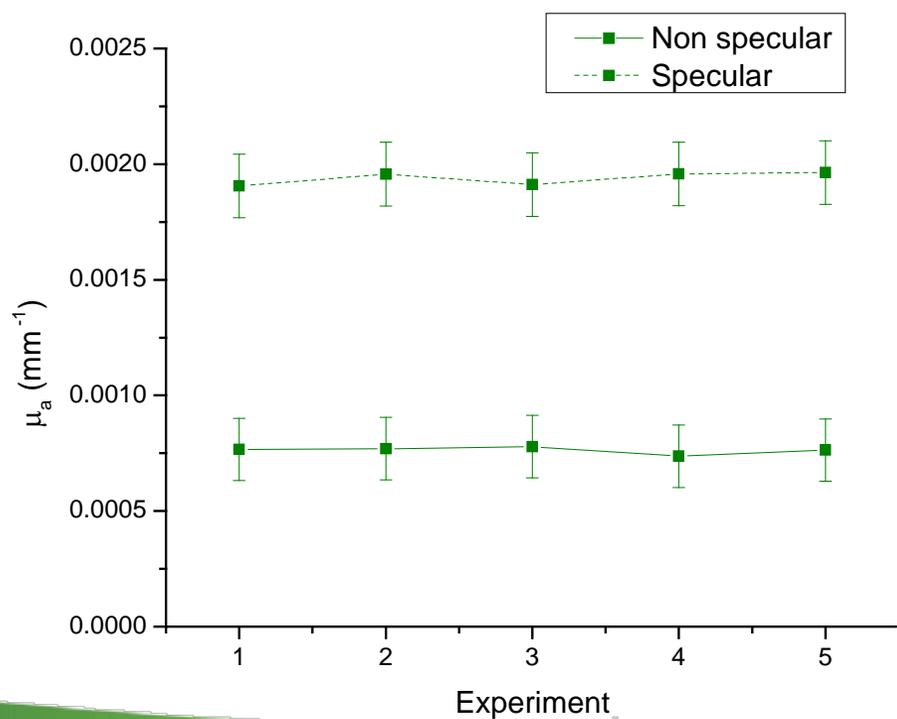
Data files

Type A Uncertainty From data files

Computation of the optical properties

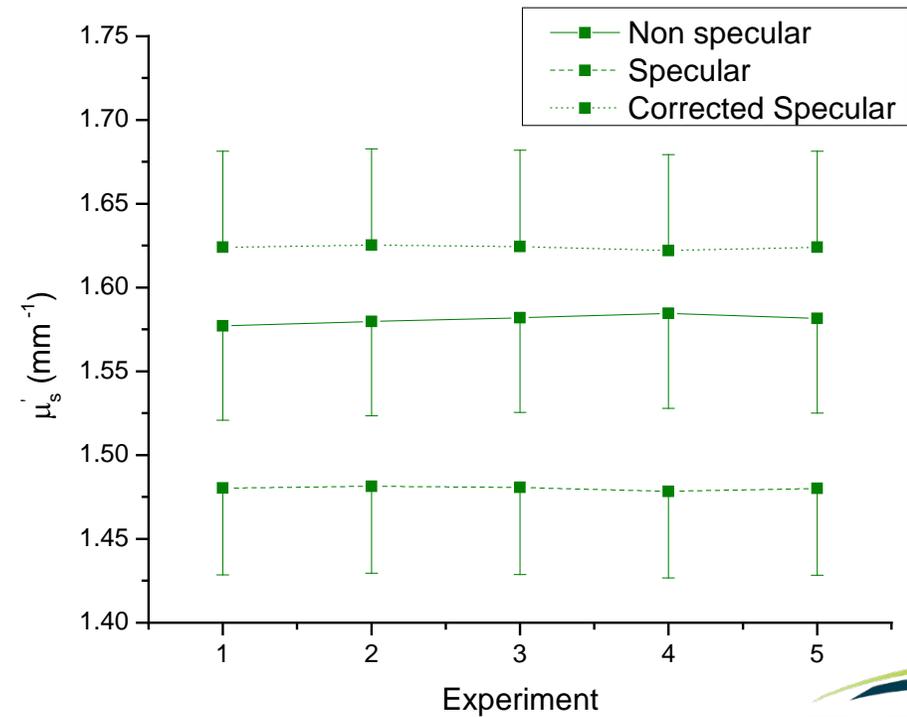
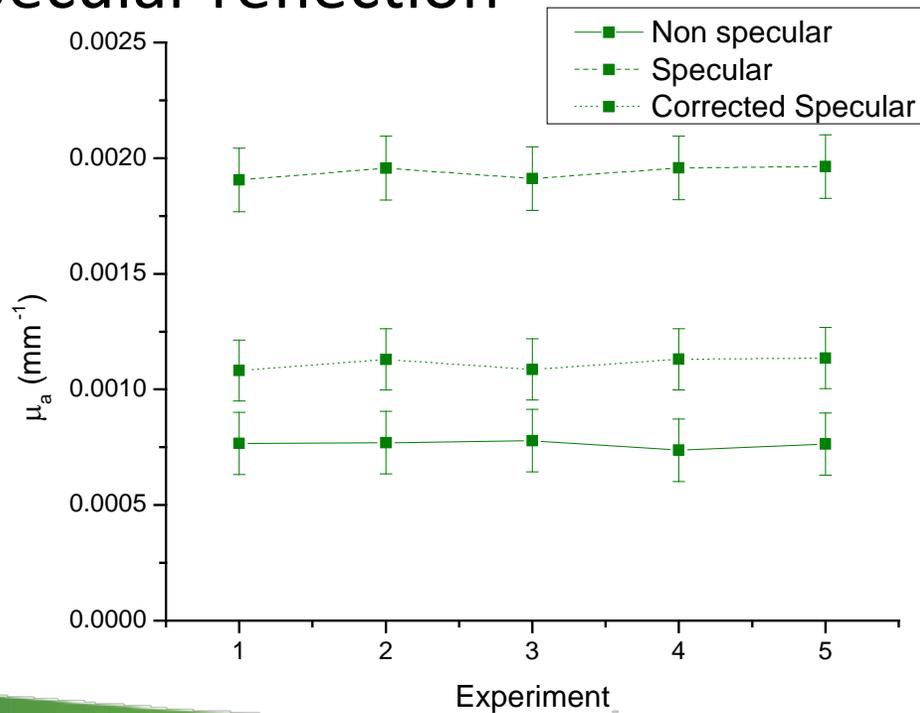
# NIST DIS setup

- Measurements of the HOD 500 sample at 543 nm



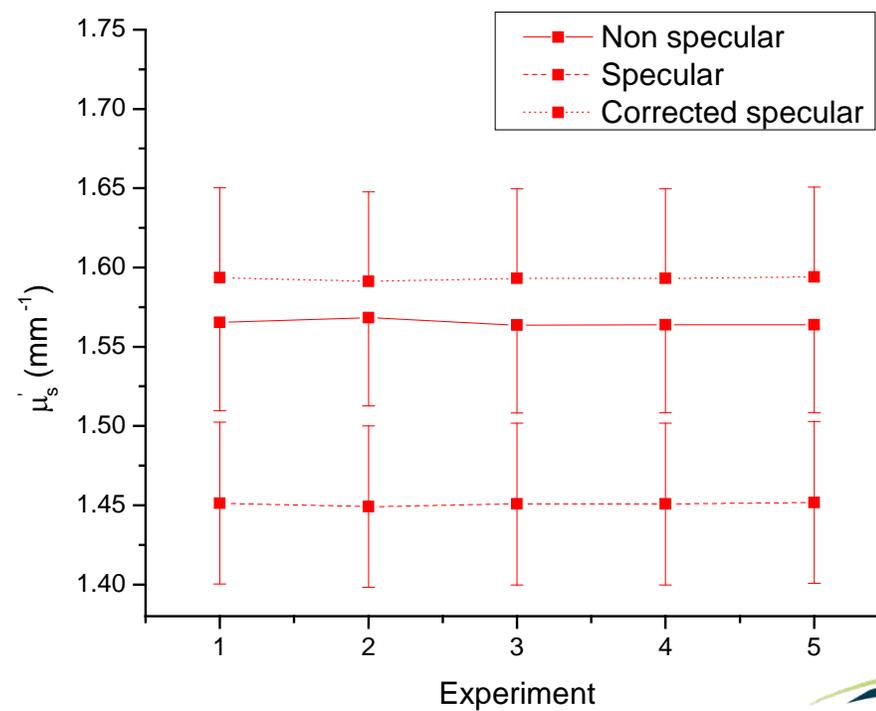
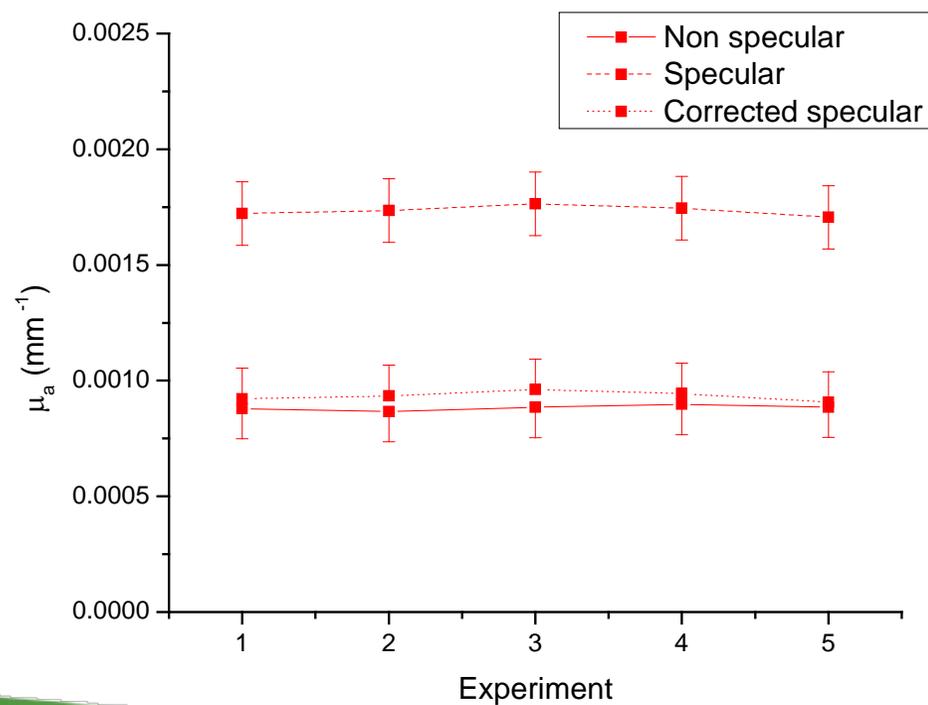
# NIST DIS setup

- Measurements of the HOD 500 sample at 543 nm
- Adjustment of Adding-Doubling to consider the rejection of the specular reflection



# NIST DIS setup

- Measurements of the HOD 500 sample at 632 nm



# NIST DIS setup

- Measurements of the HOD 500 sample

	Wavelength	Value	Absolute uncertainty (k = 2)	Relative uncertainty
<i><math>\lambda=543 \text{ nm}</math></i>				
$\mu_a$		$1.09 \cdot 10^{-3} \text{ mm}^{-1}$	$1.32 \cdot 10^{-4} \text{ mm}^{-1}$	12.1 %
$\mu_s'$		$1.62 \text{ mm}^{-1}$	$0.057 \text{ mm}^{-1}$	3.52 %
<i><math>\lambda=632.8 \text{ nm}</math></i>				
$\mu_a$		$9.61 \cdot 10^{-4} \text{ mm}^{-1}$	$1.32 \cdot 10^{-4} \text{ mm}^{-1}$	13.7 %
$\mu_s'$		$1.59 \text{ mm}^{-1}$	$0.056 \text{ mm}^{-1}$	3.52 %

# NIST DIS setup

- Double integrating sphere system
  - Measure hemispherical R with one sphere
  - Independent measurement of n and g, unscattered transmittance
  - Broad band soon
  - Process to make it a NIST certified measurement
  - Application to solid and liquid phantoms (liquid cell)
  - Application to solid reflectors

Thanks