Comparison of goniospectrophotometers

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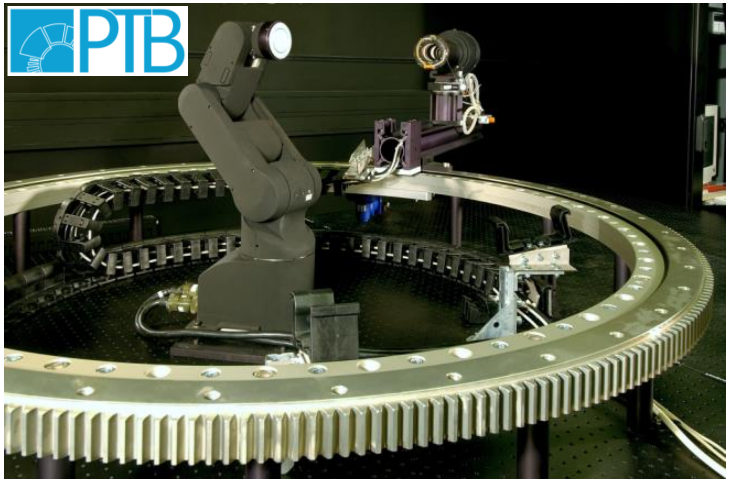
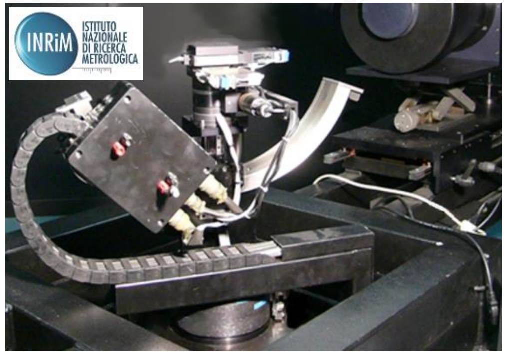
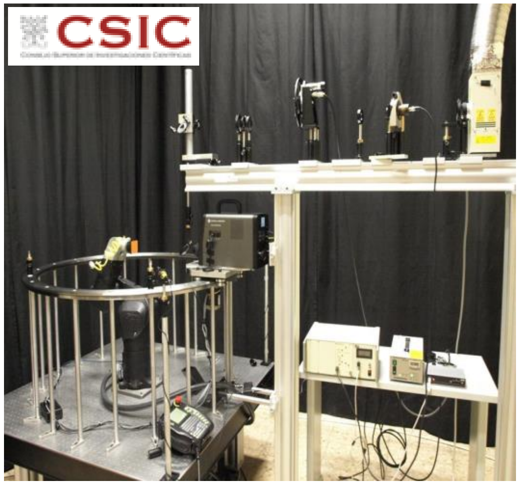
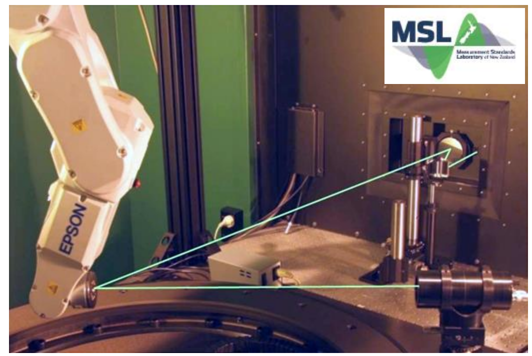

PTB


INRiM
ISTITUTO
NAZIONALE
DI RICERCA
METROLOGICA

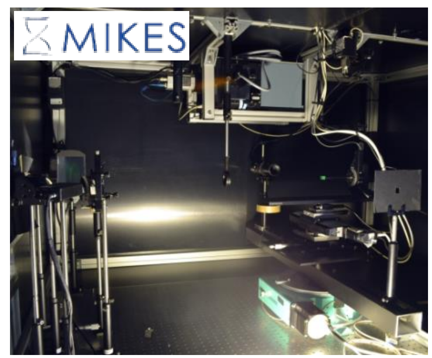

KU LEUVEN

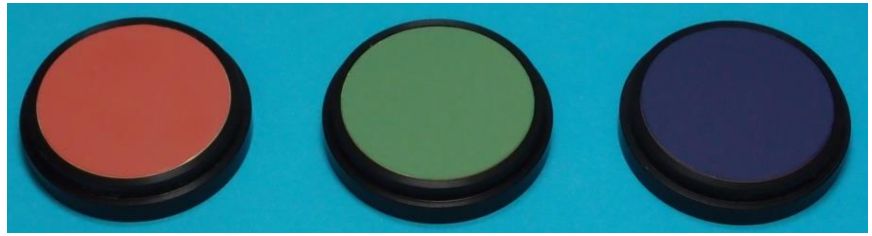

CSIC

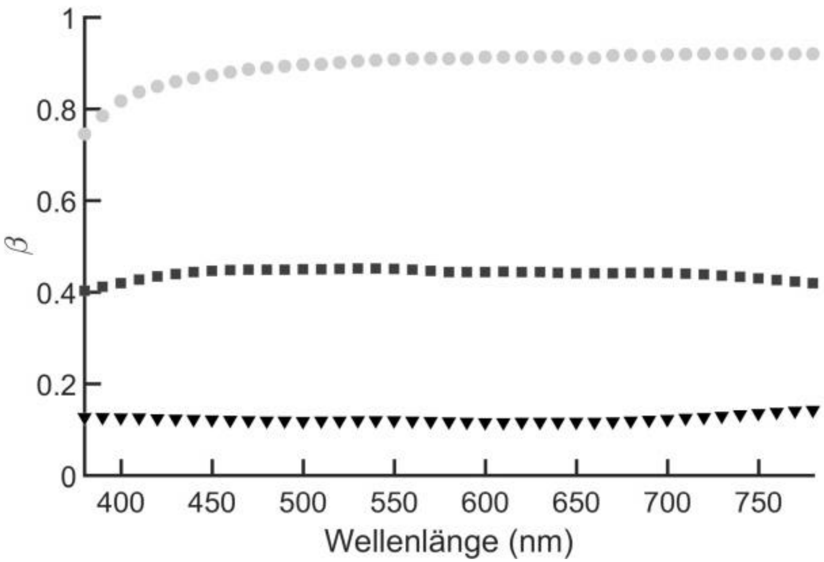

le cnam

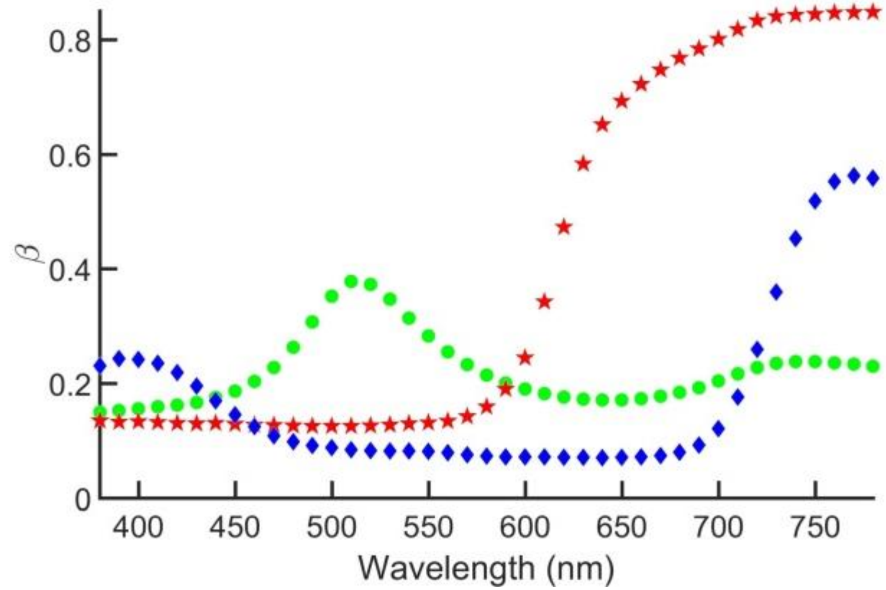

MSL
EPSON


BYK


MIKES





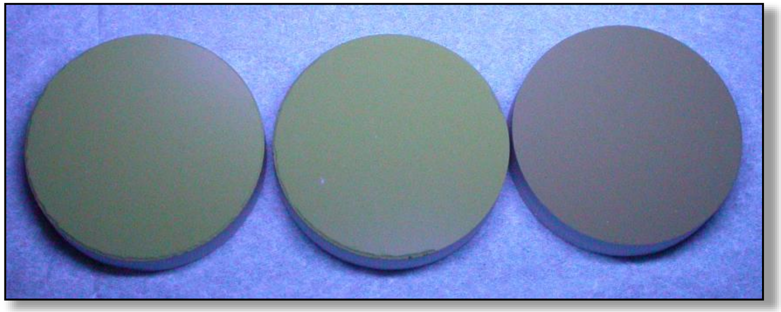


Objective: Test the scales for different magnitues and spectral variations of the BRDF in 0:45 (45:0) geometry.

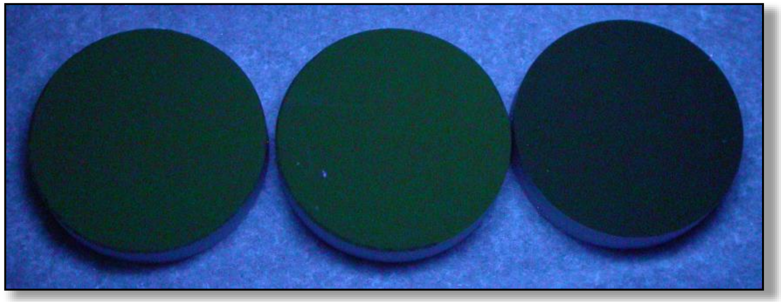
Precautions were taken for the distribution of the samples

And they were routinely inspected

88 %
white

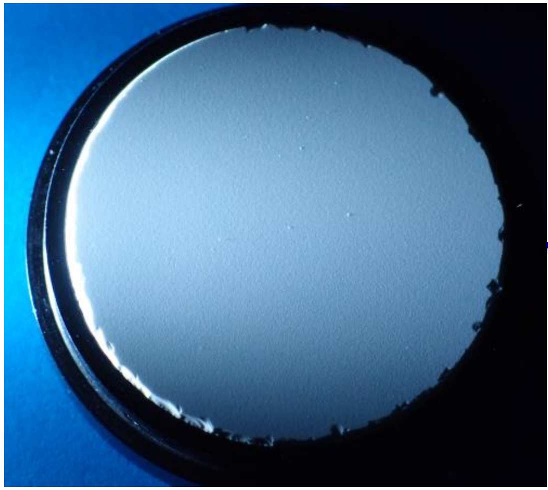


UV
254 nm

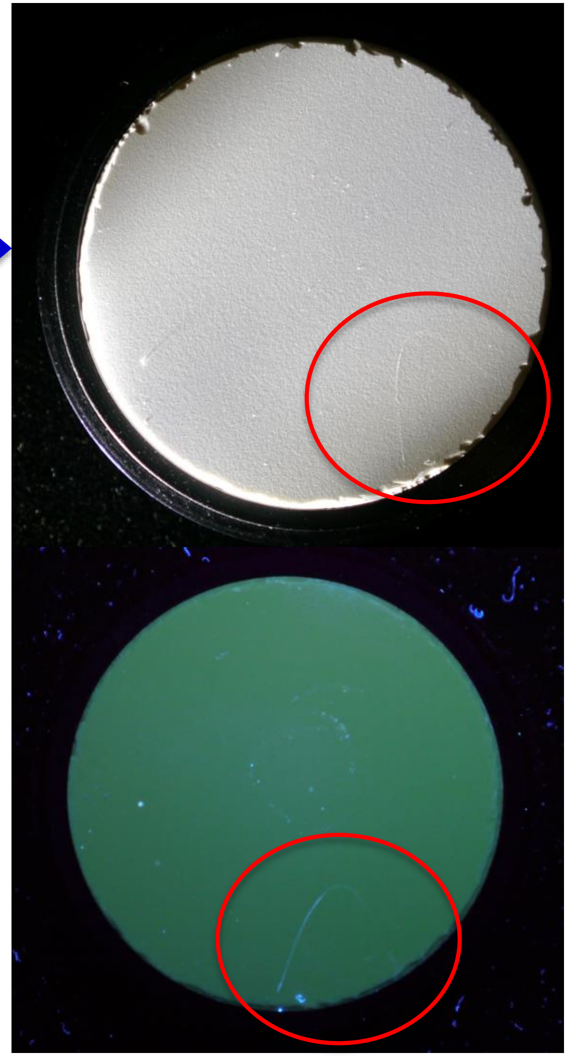


UV
365 nm

However….



Improper
Sample-Handling!



Sample bruised with finger?

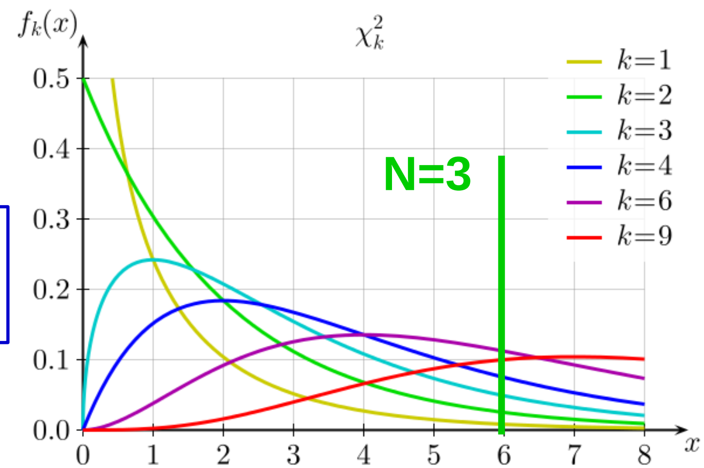
Each participant provides a β_n with uncertainty u_n

Calculate KCRV as weighted mean $\beta = \frac{\sum_n w_n \beta_n}{\sum_n w_n}$ and ist uncertainty $u = \left(\sum_n w_n\right)^{-1/2}$

$$\left(w_n = \frac{1}{u_n^2}\right)$$

Calculate χ^2 sum $\chi^2 = \sum_n \frac{(\beta_n - \beta)^2}{u_n^2}$

Sum in the 95% quantile of the χ^2 distribution with N-1 degrees of freedom?



yes

Calculate degree of equivalence $(d_n, U(d_n))$ for each participant with

$$d_n = \beta_n - \beta$$

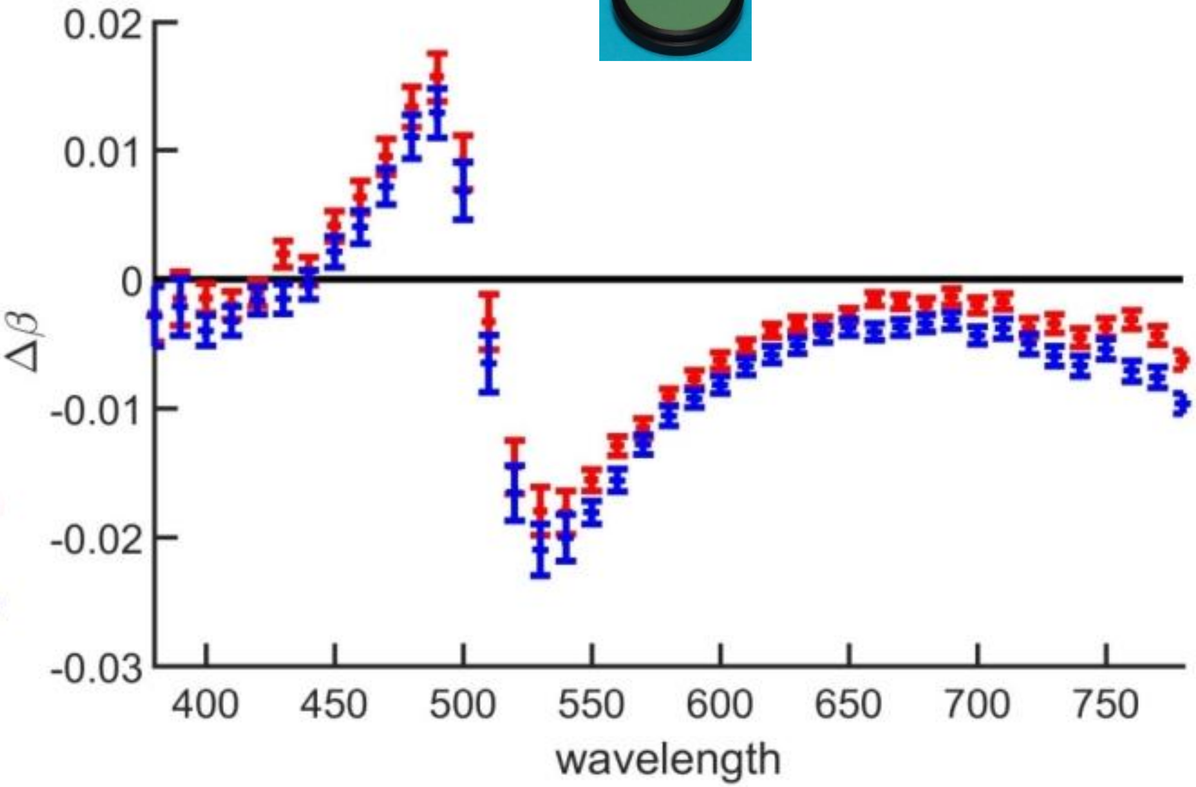
$$U(d_n) = 2\sqrt{u_n^2 - u^2}$$

no

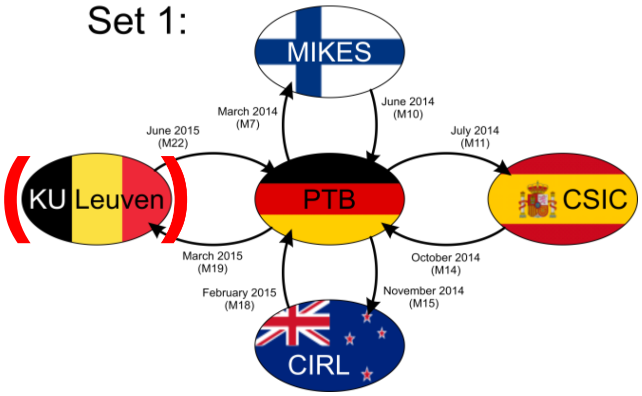
- Revise uncertainty budget
- Exclude participants
- Use more general data evaluation (e.g. median as the KCRV)

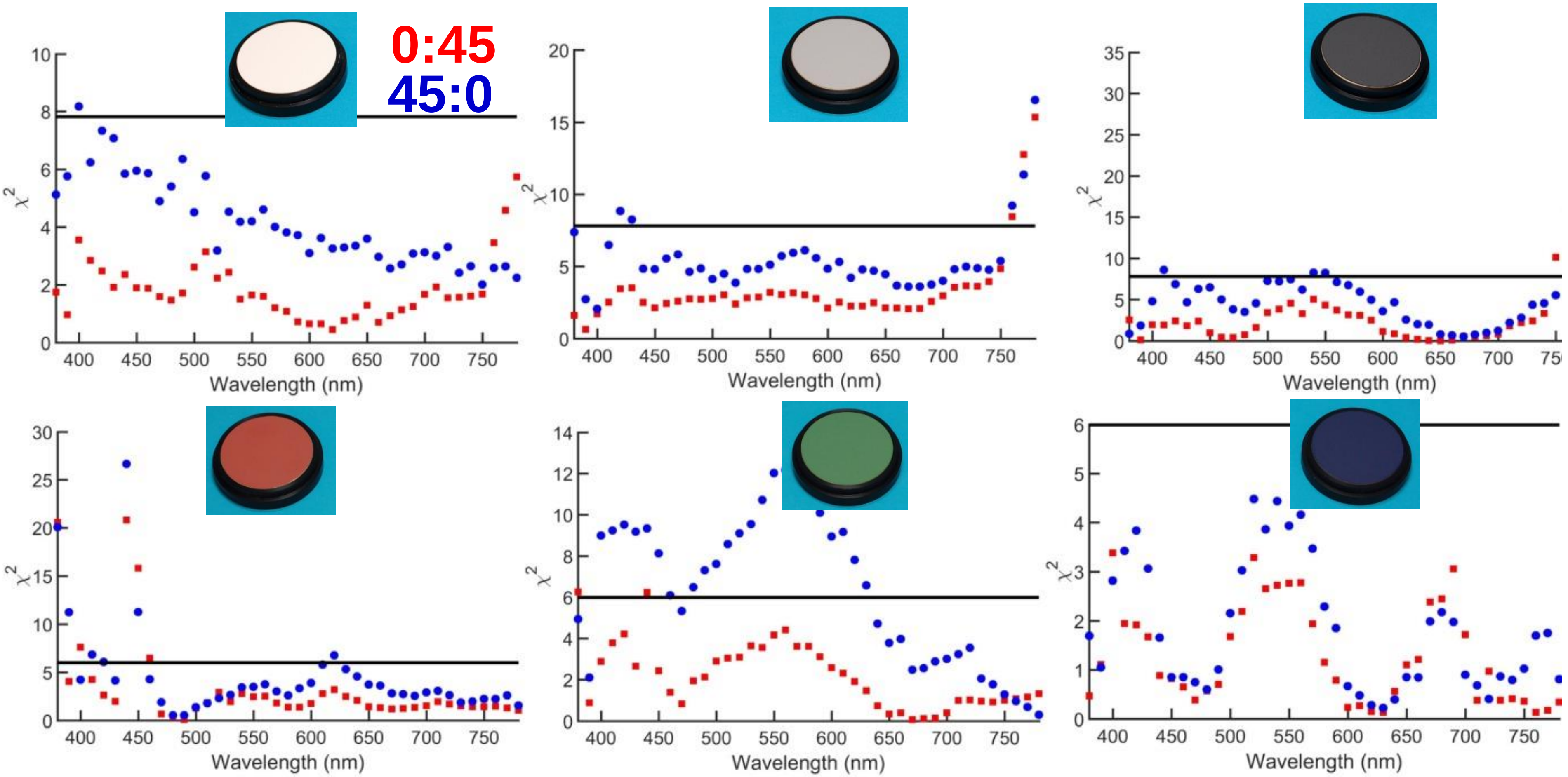
Example where results don‘t fit

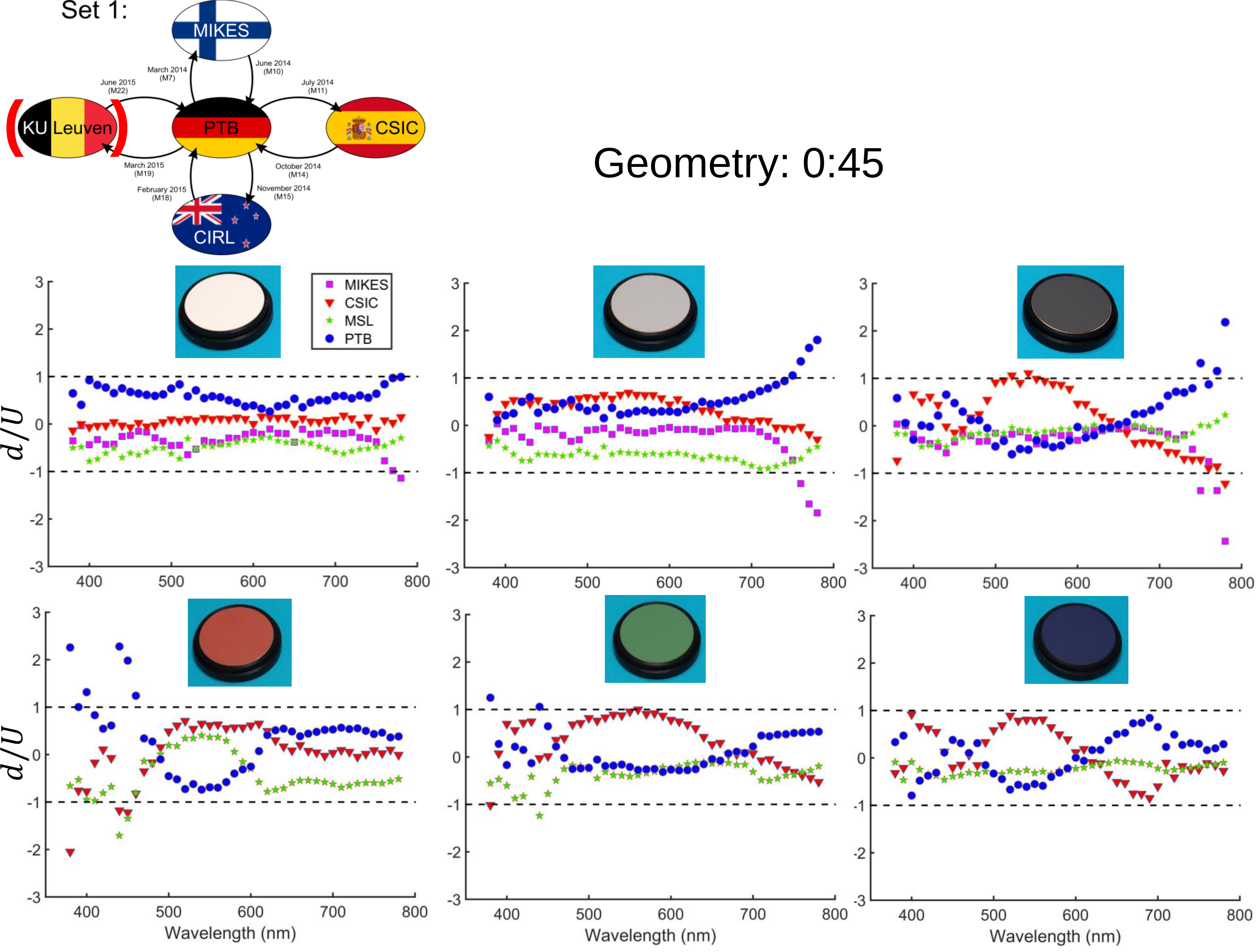
Deviation of KU Leuven to KCRV from PTB, MIKES, CSIC and MSL



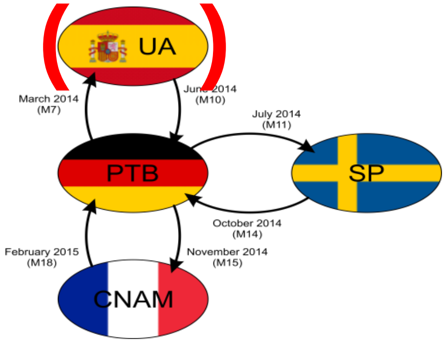
Set 1:


MIKES
March 2014
(M7)
June 2014
(M10)
June 2015
(M22)
July 2014
(M11)
KU Leuven
PTB
CSIC
March 2015
(M19)
October 2014
(M14)
February 2015
(M18)
November 2014
(M15)
CIRL

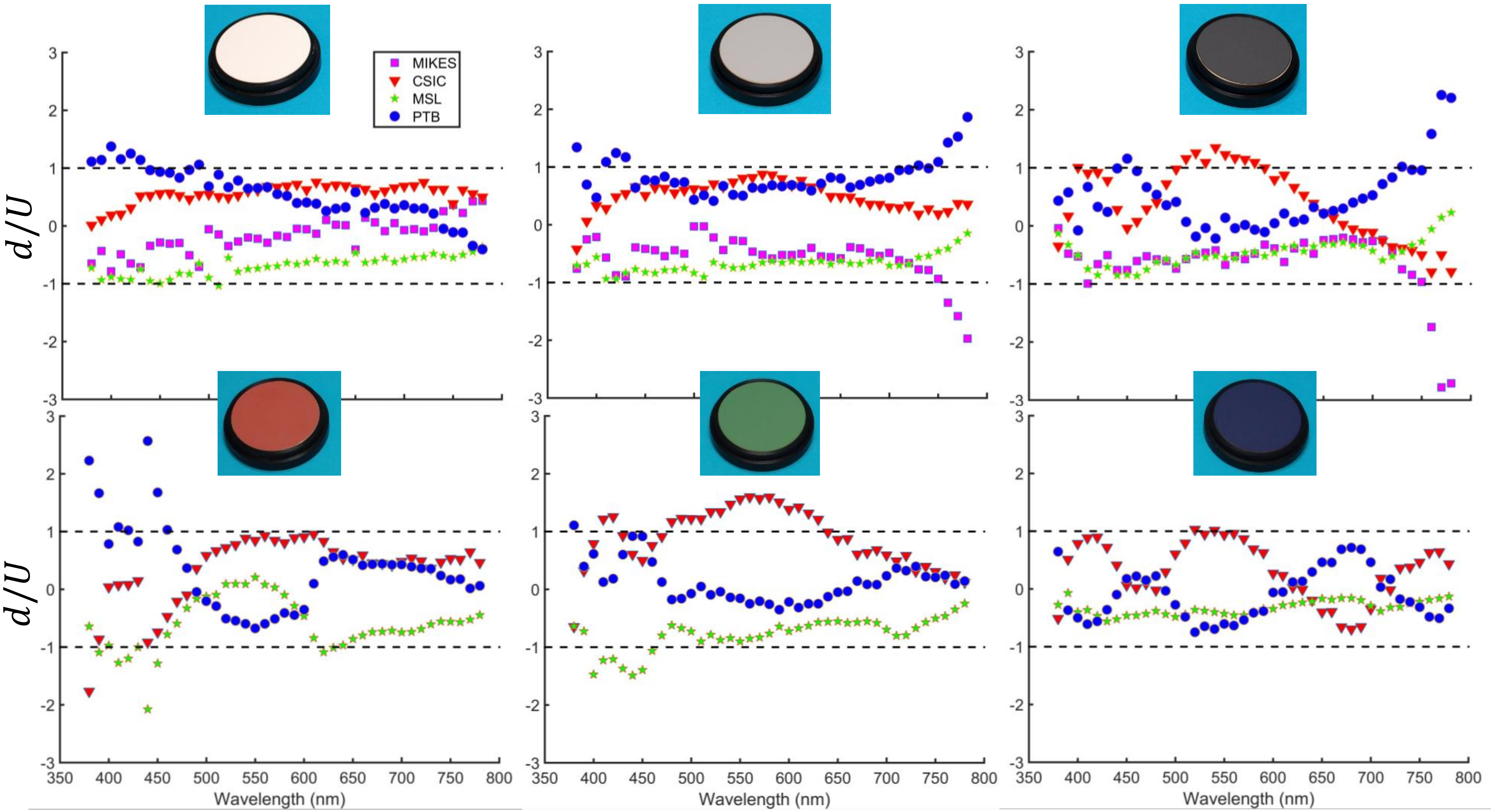

0:45
45:0
χ^2
Wavelength (nm)


Set 1:
MIKES
PTB
CSIC
KU Leuven
CIRL
March 2014 (M7)
June 2014 (M10)
July 2014 (M11)
October 2014 (M14)
November 2014 (M15)
February 2015 (M18)
March 2015 (M19)
June 2015 (M22)
Geometry: 0:45
MIKES
CSIC
MSL
PTB
d/U
Wavelength (nm)

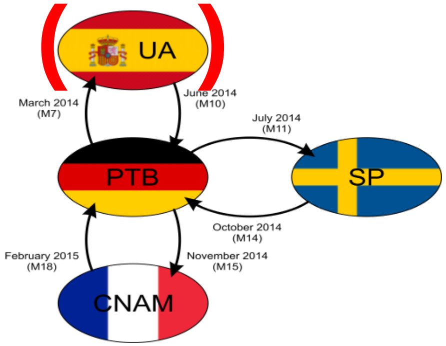
Set 2:



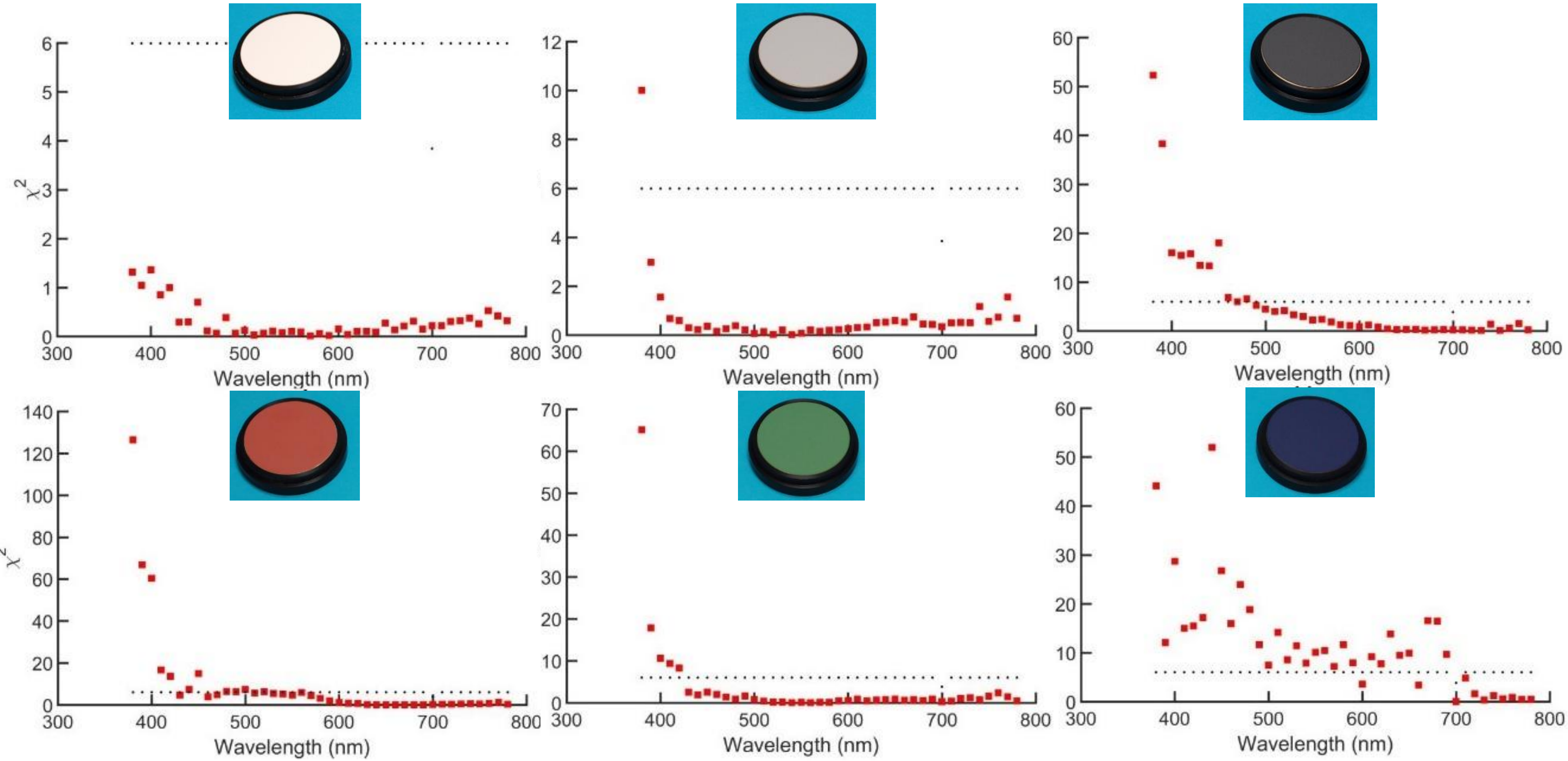
Geometry: 45:0



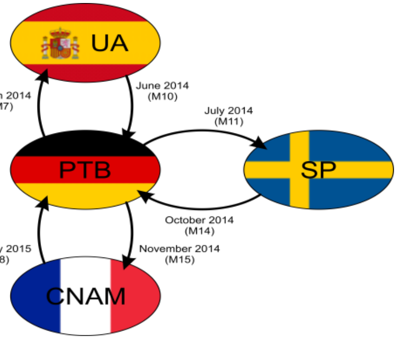
Set 2:



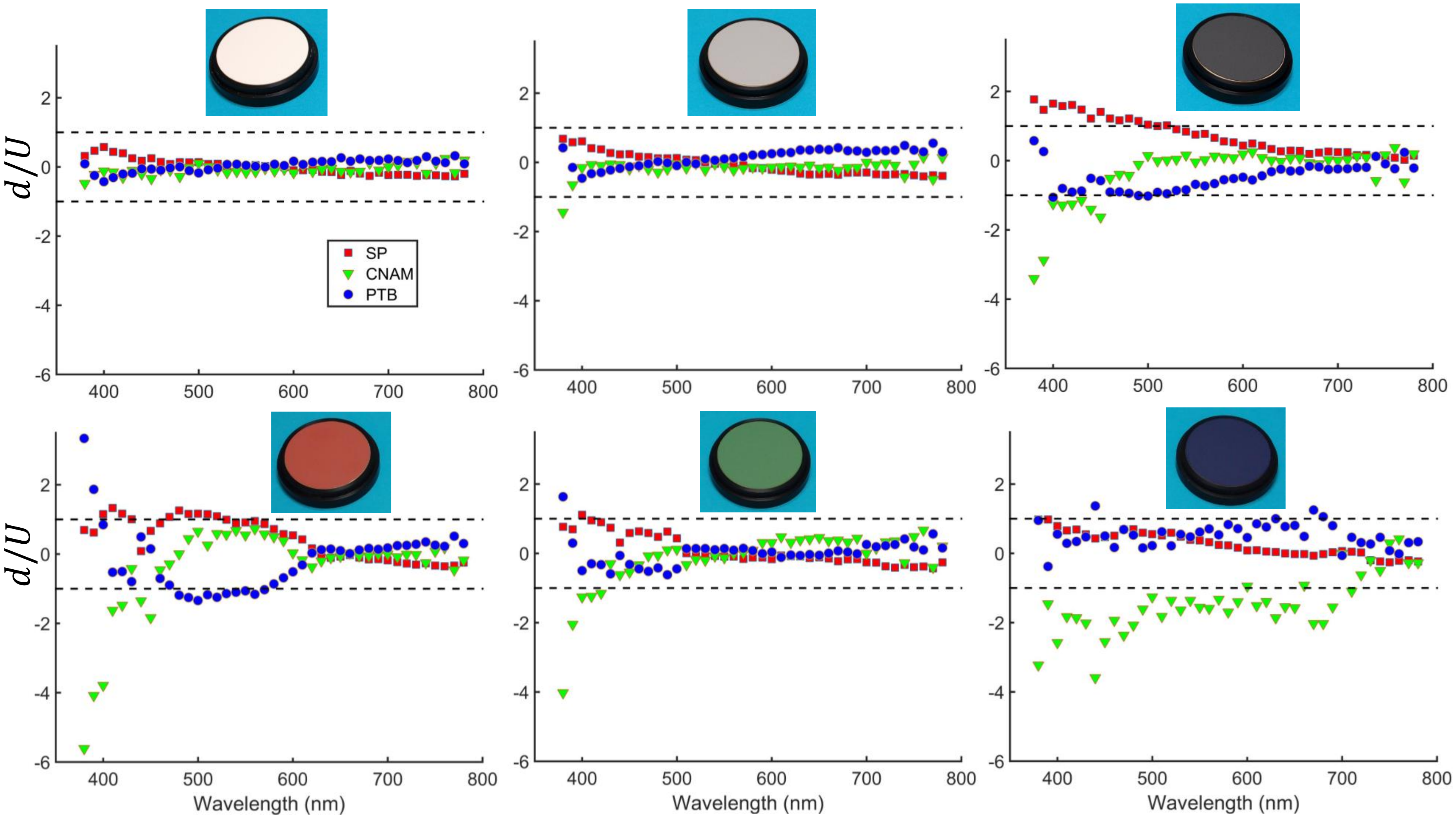
Geometry: 0:45



Set 2:



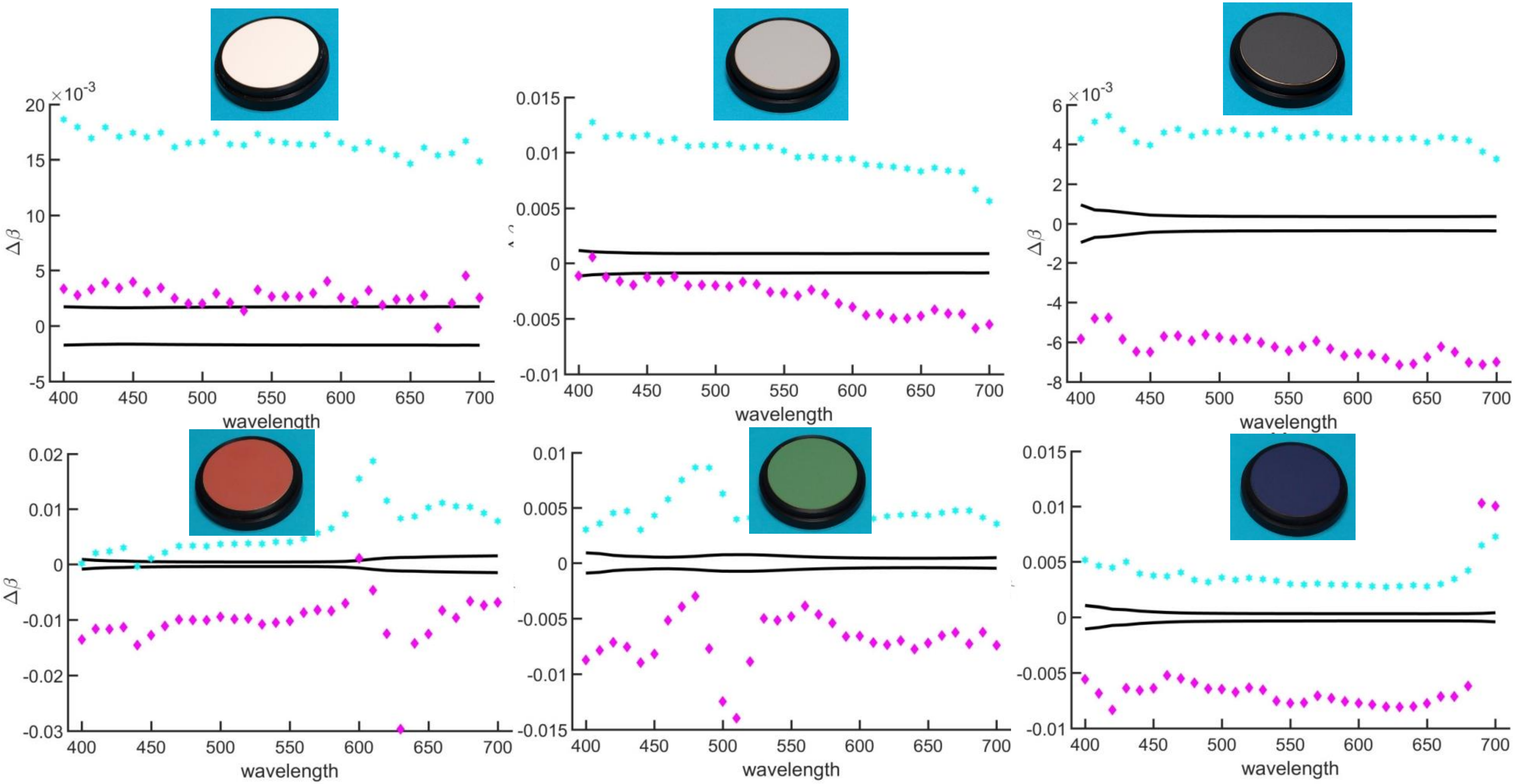
Geometry: 0:45



Deviation of the commercial instruments from the KCRV

BYK-mac

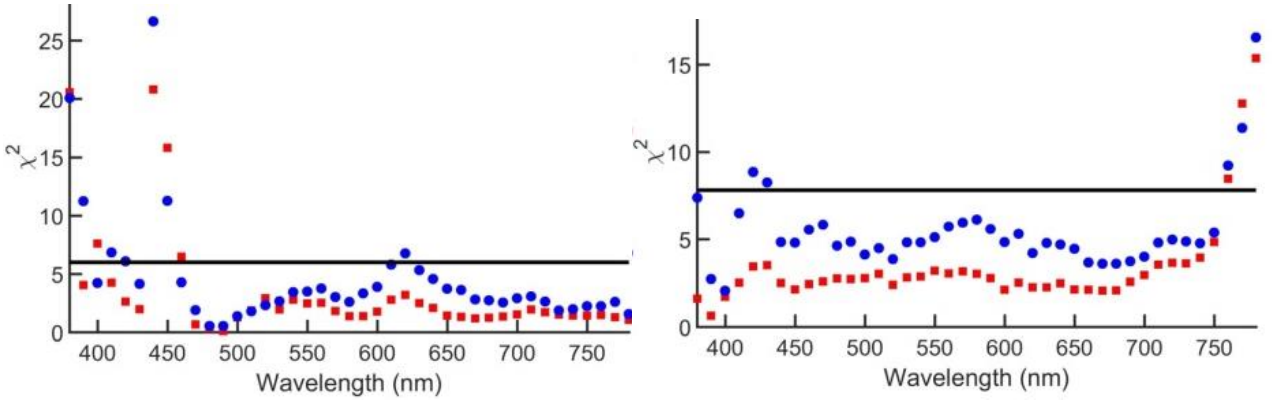
MA98



- The results are consistent and the scales of the involved NMIs agree in 0:45 and/or 45:0 geometry

- Commercial instruments haver larger uncertainties, respectively, deviate by a bigger margin from the NMI results.

- Extended scale comparison (wavelength, geometries) should be planned



- Of special interest are geometries with a very high polar angle for detection or illumination as they are particularly suitable to assess systematic effects

$$\beta \approx \frac{1}{\cos\theta}$$

You‘ll have the opportunity to catch up more details

The quantity that is derived from the measurements and compared between the different instruments is the spectral radiance factor (SRF):

$$\beta(\theta_i, \varphi_i; \theta_r, \varphi_r; \lambda) = \frac{L_r(\theta_i, \varphi_i; \theta_r, \varphi_r; \lambda)}{L_{PRD}}, \qquad (1)$$

where L_r denotes the radiance of a sample and L_{PRD} ~~is~~ the radiance of the perfectly reflecting diffuser (Lambertian reflection and therefore independent of the bidirectional geometry) under identical conditions of illumination. The BRDF on the other hand, is defined by the ratio of L_r to the irradiance E_i on the sample. The BRDF can be related with the SRF by relating this irradiance with the term L_{PRD} in Eq. 1. Since~~As~~ the radiance is independent of the geometry~~constant~~ for the PRD, i.e.

$$L_{PRD} = \frac{\partial^2 \Phi(\theta_r, \varphi_r)}{\partial\Omega\partial A \cos\theta_r} = const, \qquad (2)$$

a simple relation can be derived for the irradiance and the radiance in that case because

$$\int L_{PRD} \cos\theta_r \, d\Omega = L_{PRD} \cdot \pi = \frac{\partial I}{\partial A} = E_i \qquad (3)$$

so that

$$L_{PRD} = \frac{1}{\pi} E_i, \qquad (4)$$

Therefore the SRF and the BRDF differ only by a constant factor of π. The BRDF is more common than the SRF, especially in the realm of computer graphics. However, we use the latter in this paper because we feel that normalization to the perfectly reflecting ~~diffusor~~ diffuser is more intuitive and is the quantity in the calibration services provided by NMI.

Instruments that perform absolute measurements (PTB, CNAM, MSL and MIKES) do the normalization of the samples radiance to L_{PRD} different than those that perform relative measurements. In the case of absolute measurements, the irradiance E_i on the sample is acquired by measuring the radiance L_i of the light source. If θ_i denotes the angle of incidence of the illumination on the sample and $\omega\Omega_i = A_i/d^2$, with the area A_i of the light source and its distance d from the sample surface, is the solid angle of the illumination as viewed from the sample, then

$$L_i = \frac{E_i}{\cos\theta_i \, \omega\Omega_i}. \qquad (5)$$

Deviation of KU Leuven