Analysis of Systematic Effects in 0/45 Lamp-plaque Sensor Calibration

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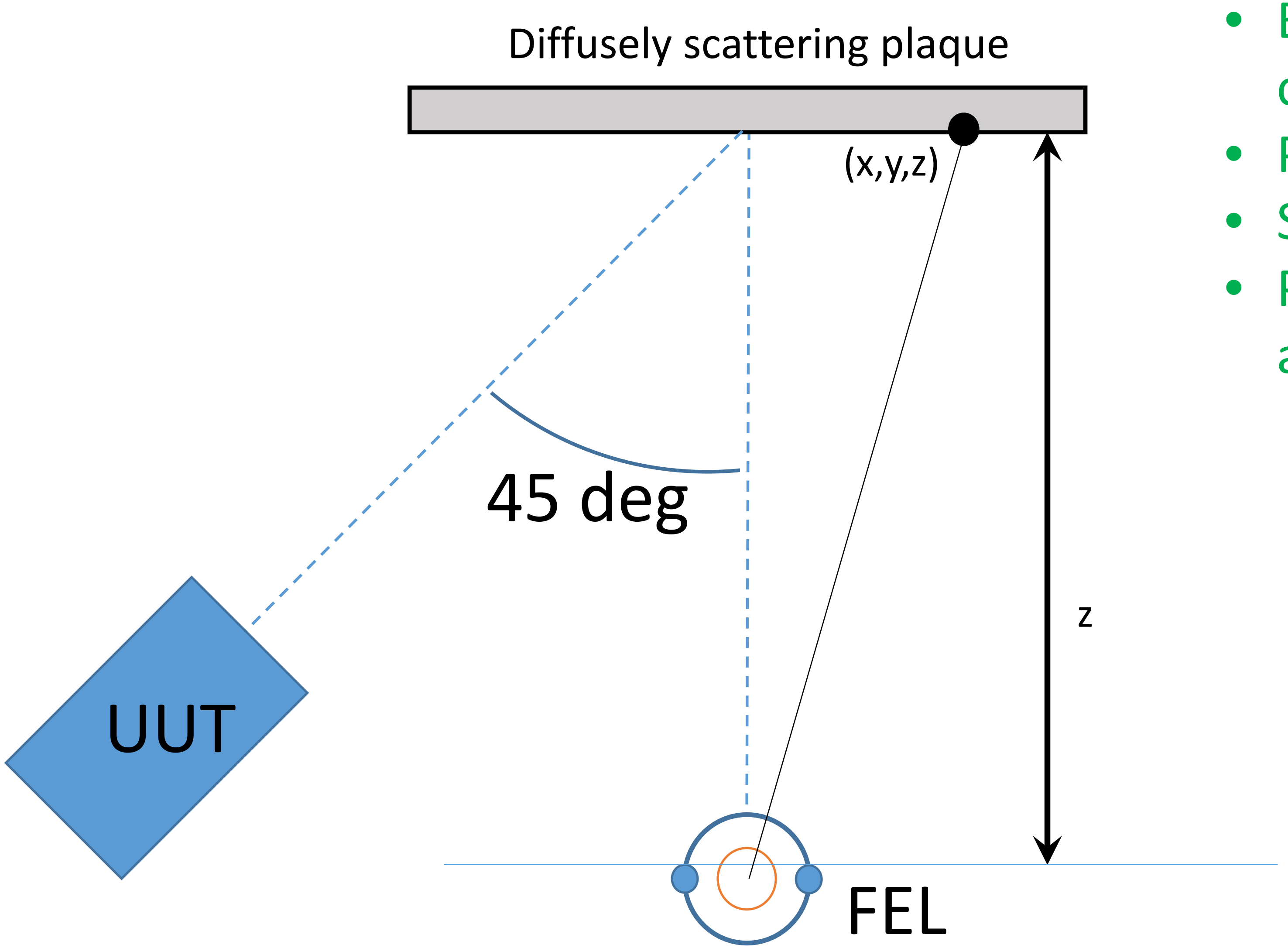
* Presenter

The 0/45 concept:

- Irradiance-calibrated lamp source (FEL)
- 0/45 BRDF-calibrated diffuse plaque (usu. PTFE)
- Known radiance presented to unit under test (UUT)



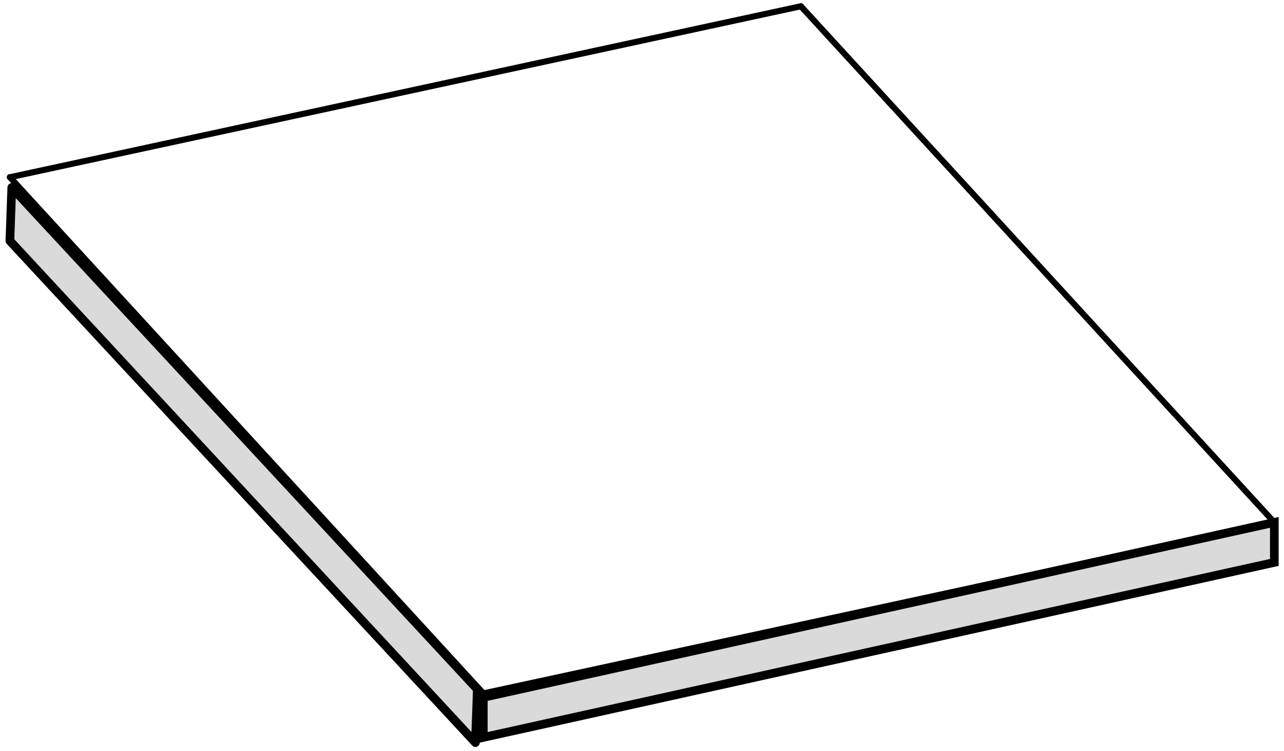
Radiometric analysis could include

- Lamp irradiance or intensity vs. distance
- Lamp intensity vs. direction
- BRDF variation when not in 0/45 configuration
- Polarization effects
- Spectral aspects
- Plaque uniformity (position, azimuthal, flatness)

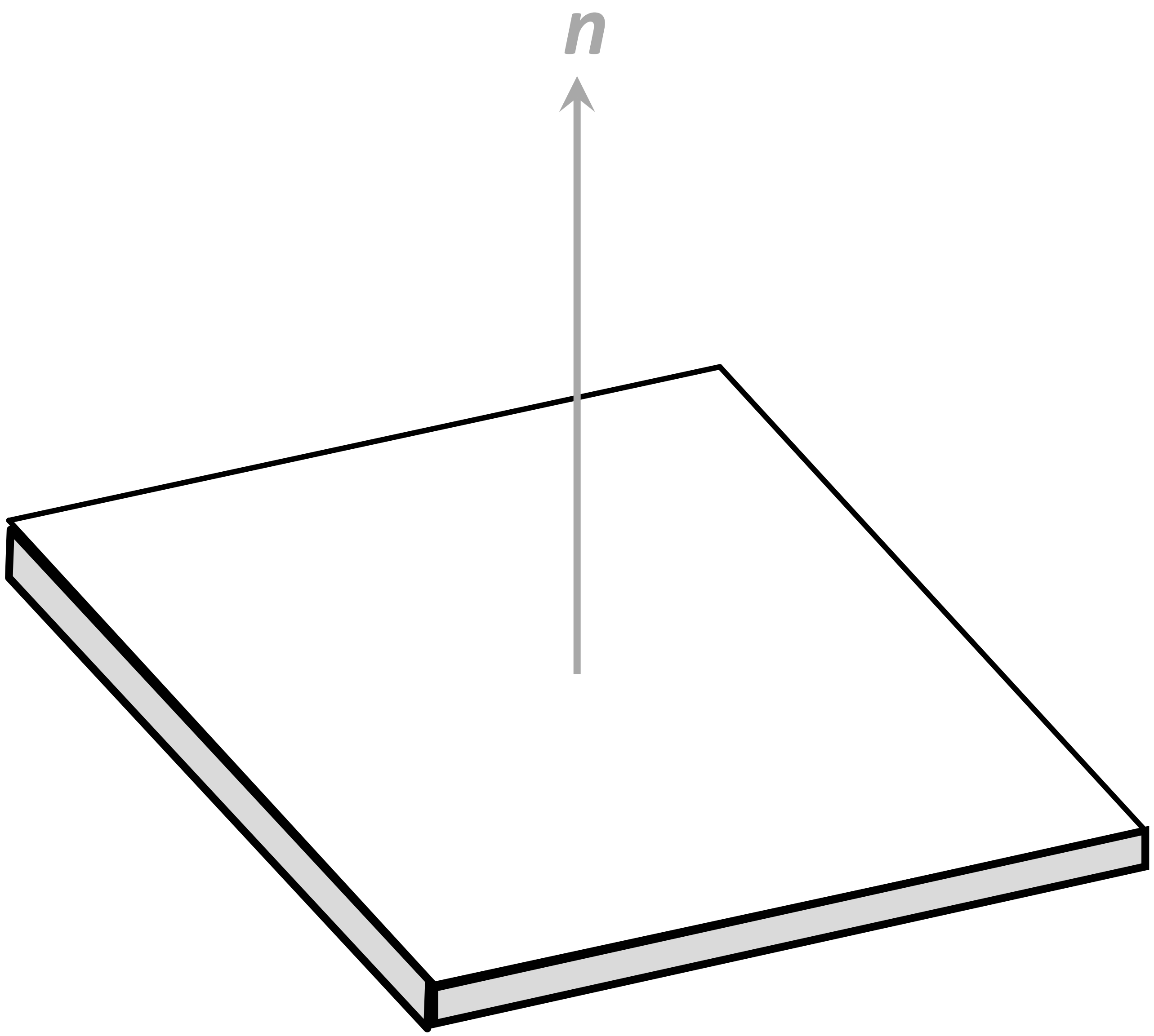
This talk:

- Lamp properties
- BRDF variation
- Comparison of lamp-plaque and integrating-sphere source (ISS) measured by an imager

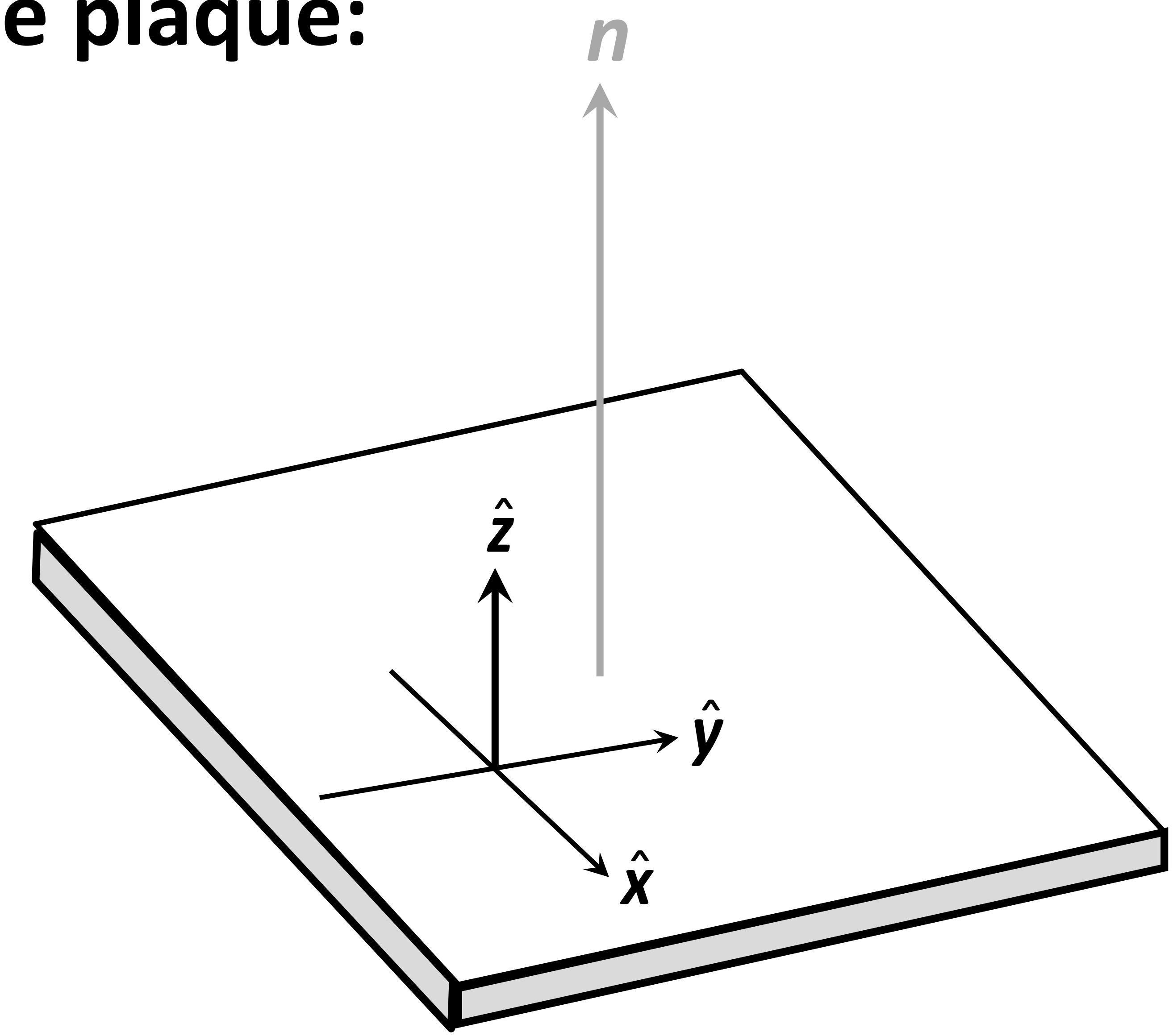
PTFE Plaque



PTFE Plaque



Geometrical notation at the plaque:

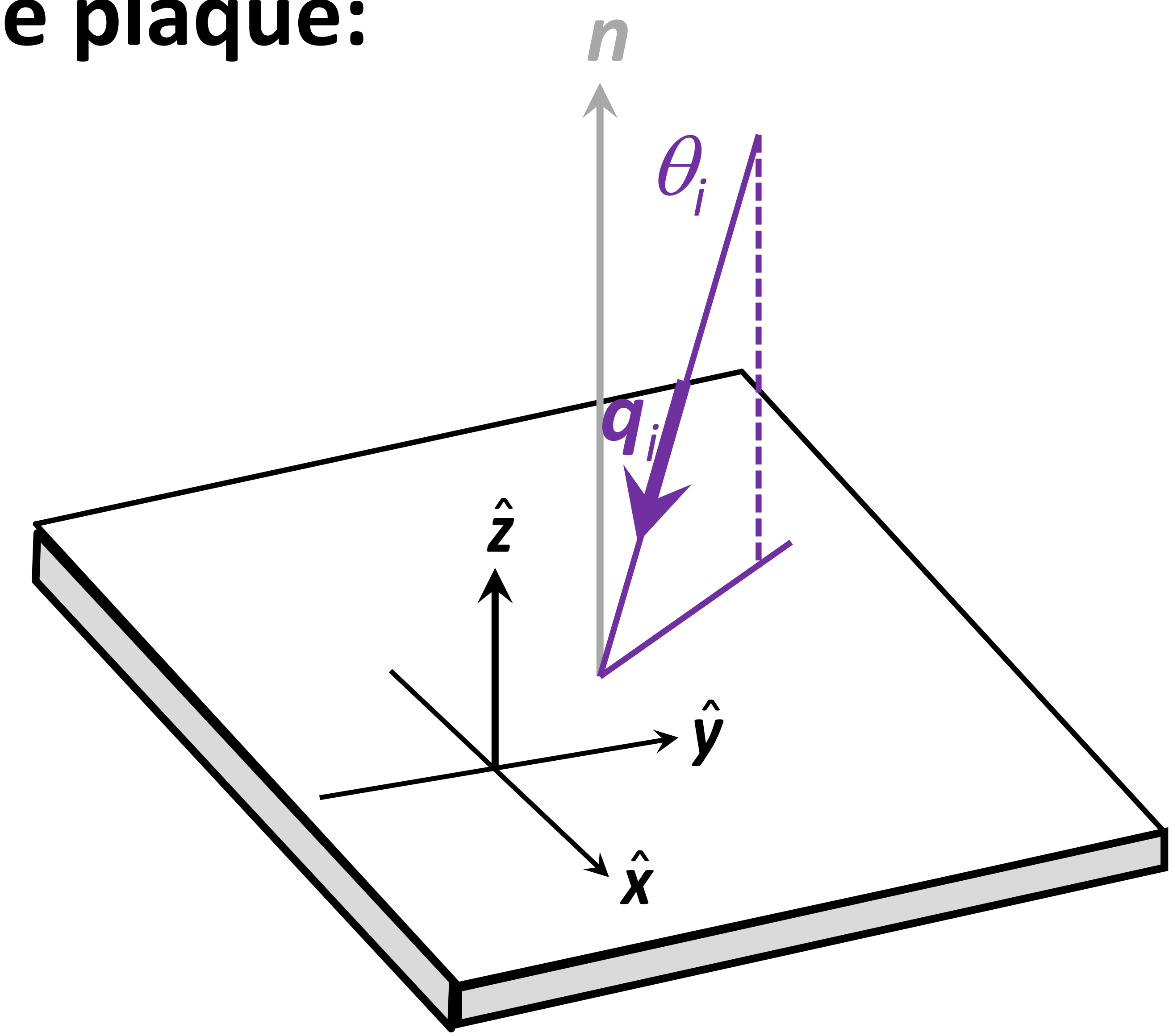


Geometrical notation at the plaque:

Angle of incidence: θ_i

Direction of incidence:

$$\boldsymbol{q}_i = c_{xi}\hat{\boldsymbol{x}} + c_{yi}\hat{\boldsymbol{y}} - |c_{zi}|\hat{\boldsymbol{z}}$$



Geometrical notation at the plaque:

Angle of incidence: θ_i

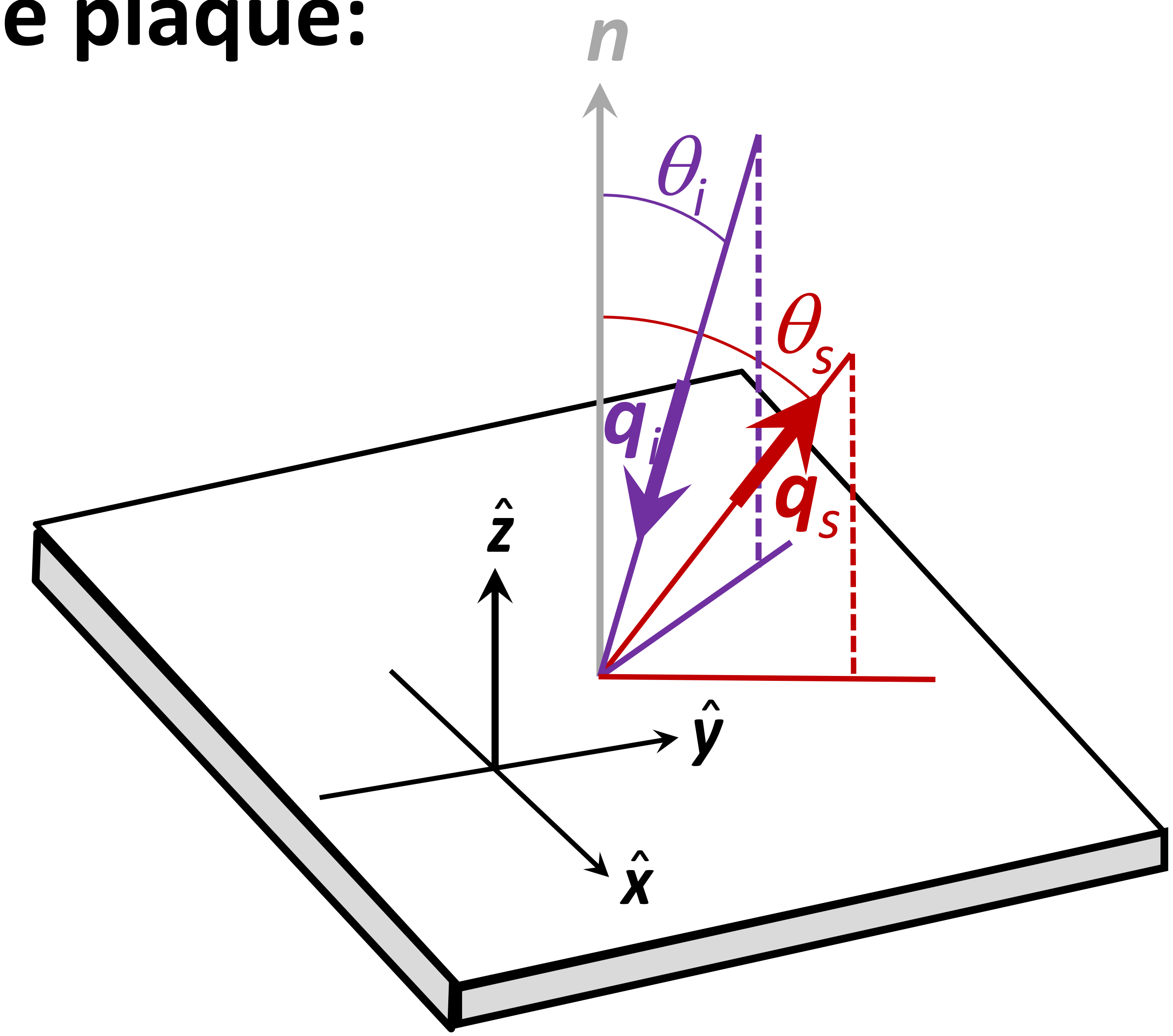
Direction of incidence:

$$\boldsymbol{q}_i = c_{xi}\hat{\boldsymbol{x}} + c_{yi}\hat{\boldsymbol{y}} - |c_{zi}|\hat{\boldsymbol{z}}$$

Angle of scatter: θ_s

Direction of scatter:

$$\boldsymbol{q}_s = c_{xs}\hat{\boldsymbol{x}} + c_{ys}\hat{\boldsymbol{y}} + |c_{zs}|\hat{\boldsymbol{z}}$$



Geometrical notation at the plaque:

Angle of incidence: θ_i

Direction of incidence:

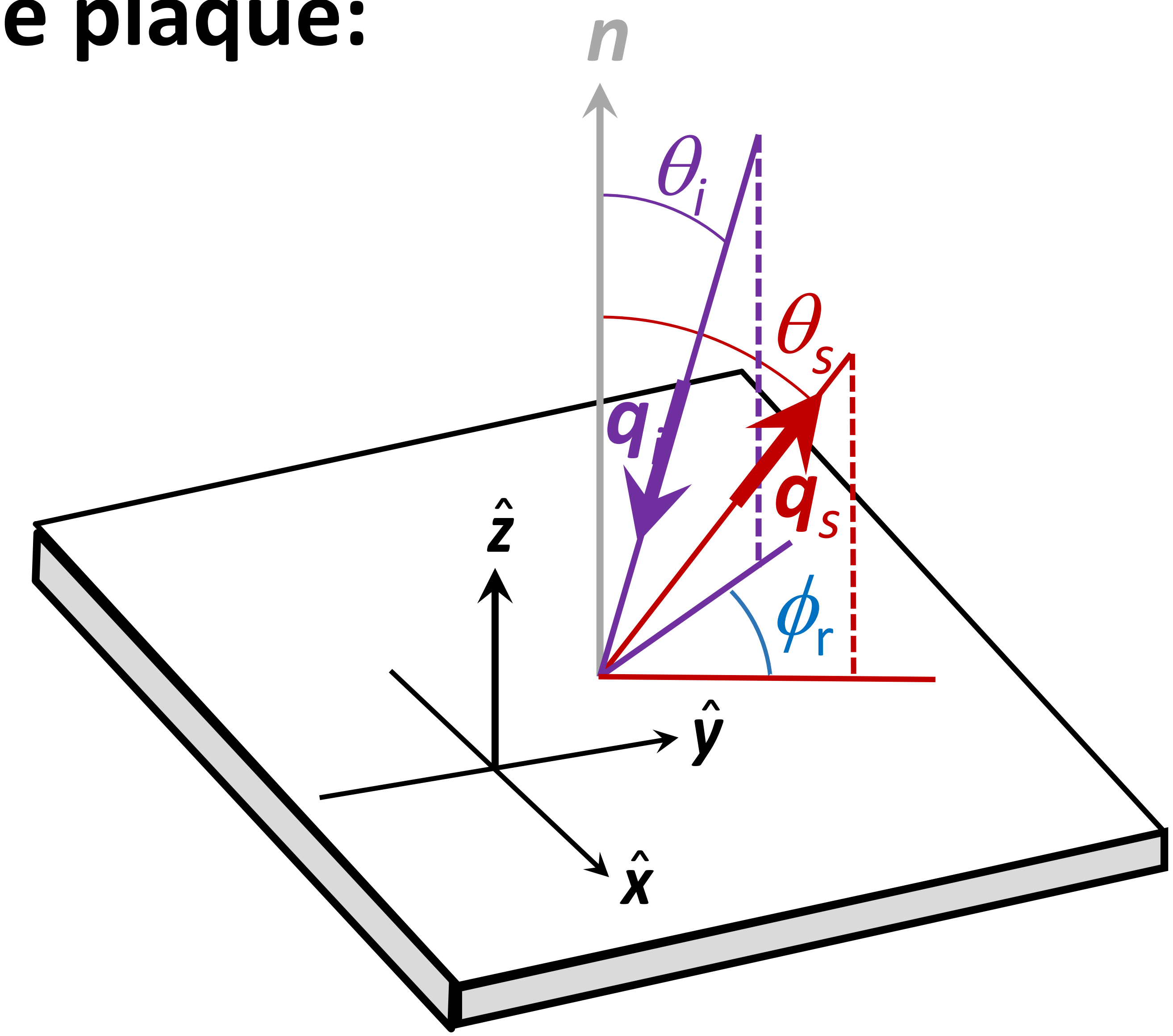
$$\boldsymbol{q}_i = c_{xi}\hat{\boldsymbol{x}} + c_{yi}\hat{\boldsymbol{y}} - |c_{zi}|\hat{\boldsymbol{z}}$$

Angle of scatter: θ_s

Direction of scatter:

$$\boldsymbol{q}_s = c_{xs}\hat{\boldsymbol{x}} + c_{ys}\hat{\boldsymbol{y}} + |c_{zs}|\hat{\boldsymbol{z}}$$

Relative azimuthal angle: ϕ_r



Parametrization of ratio:

Expansion about 0/45 configuration…

(1.) Introduce 3 small parameters

$$l_s = \sin\theta_s - \sin(45°)$$

$$l_i = \sin\theta_i \cos\phi_r$$

$$t_s = \sin\theta_i \sin\phi_r$$

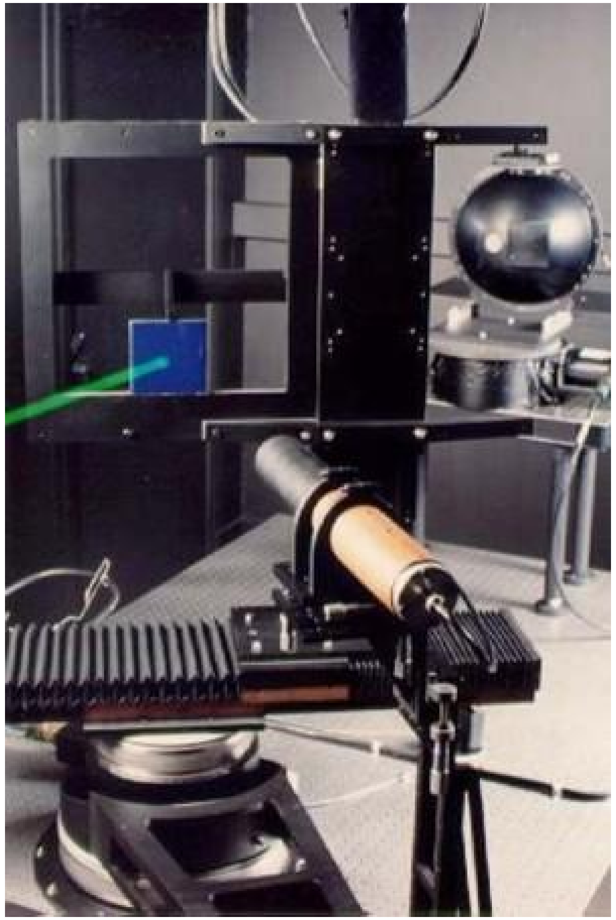
(2.) Use a low-order polynomial:

$$\frac{\mathrm{BRDF}(\theta_i,\theta_s,\phi_r)}{\mathrm{BRDF}(0°,45°,-)}$$

$$= g(c_{xi},c_{yi};c_{xs},c_{ys}) = h(l_i,l_s,t_s) = 1 + \sum_{\substack{\mu=0,1,2,\\ \nu=0,1,2}} c_{\mu\nu} l_i^{\mu} l_s^{\nu} + c_t t_s^2 + \ldots$$

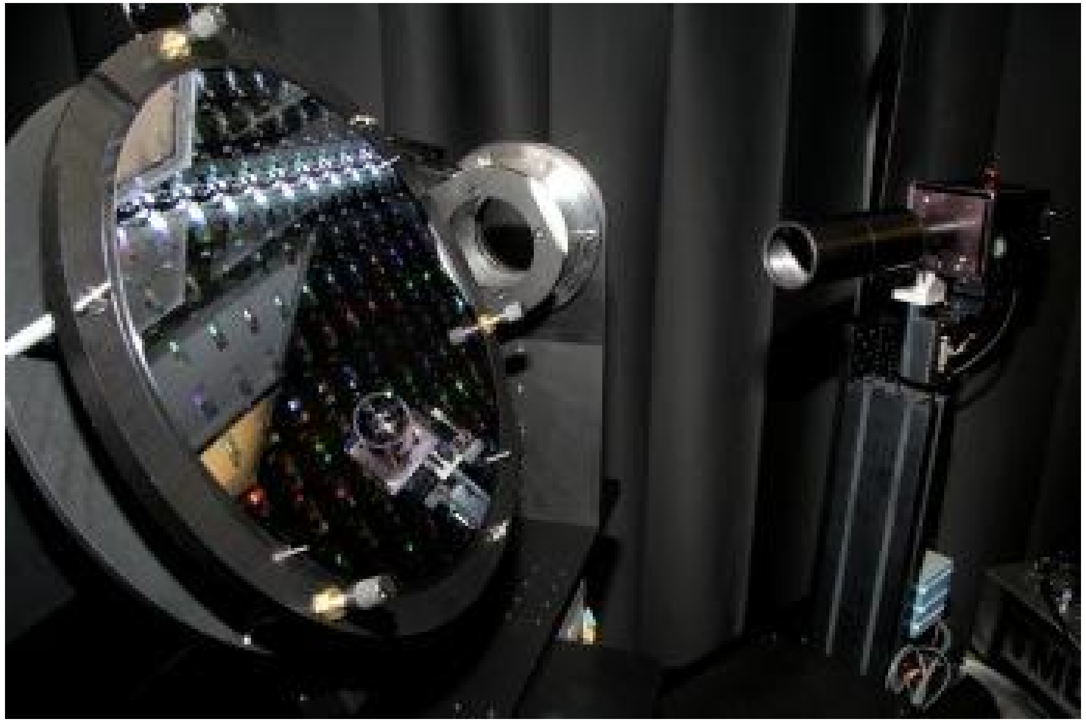
Spectral tri-function automated reference Reflectometer (STARR)
Catherine C. Cooksey

- In-plane BRDF (ϕ_r=0° or 180°)
- Variable θ_i, θ_r
- Directional/hemispherical
- 250 nm to 2500 nm



Goniometric optical scatter instrument (GOSI)
Thomas A. Germer, Heather Patrick

- Full BRDF, laser-based (Si region)
- Includes out-of-plane

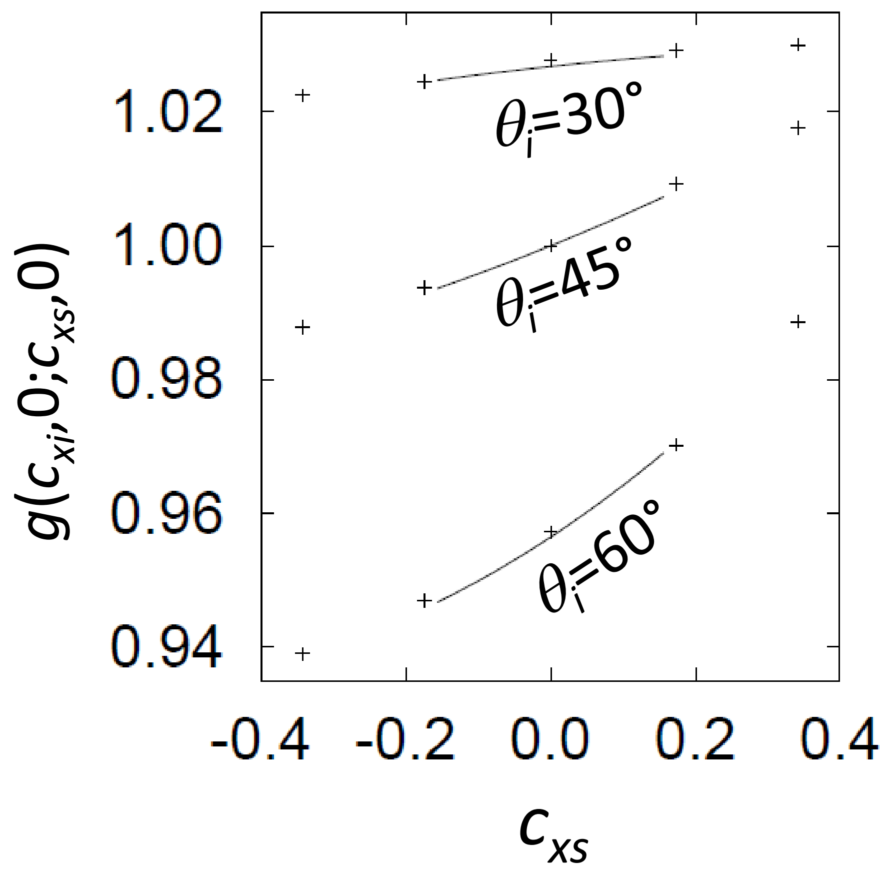


Future: ROSI (Robotic Optical Scatter Instrument), which is slated to take on STARR capabilities for customers, with full BRDF
Heather Patrick

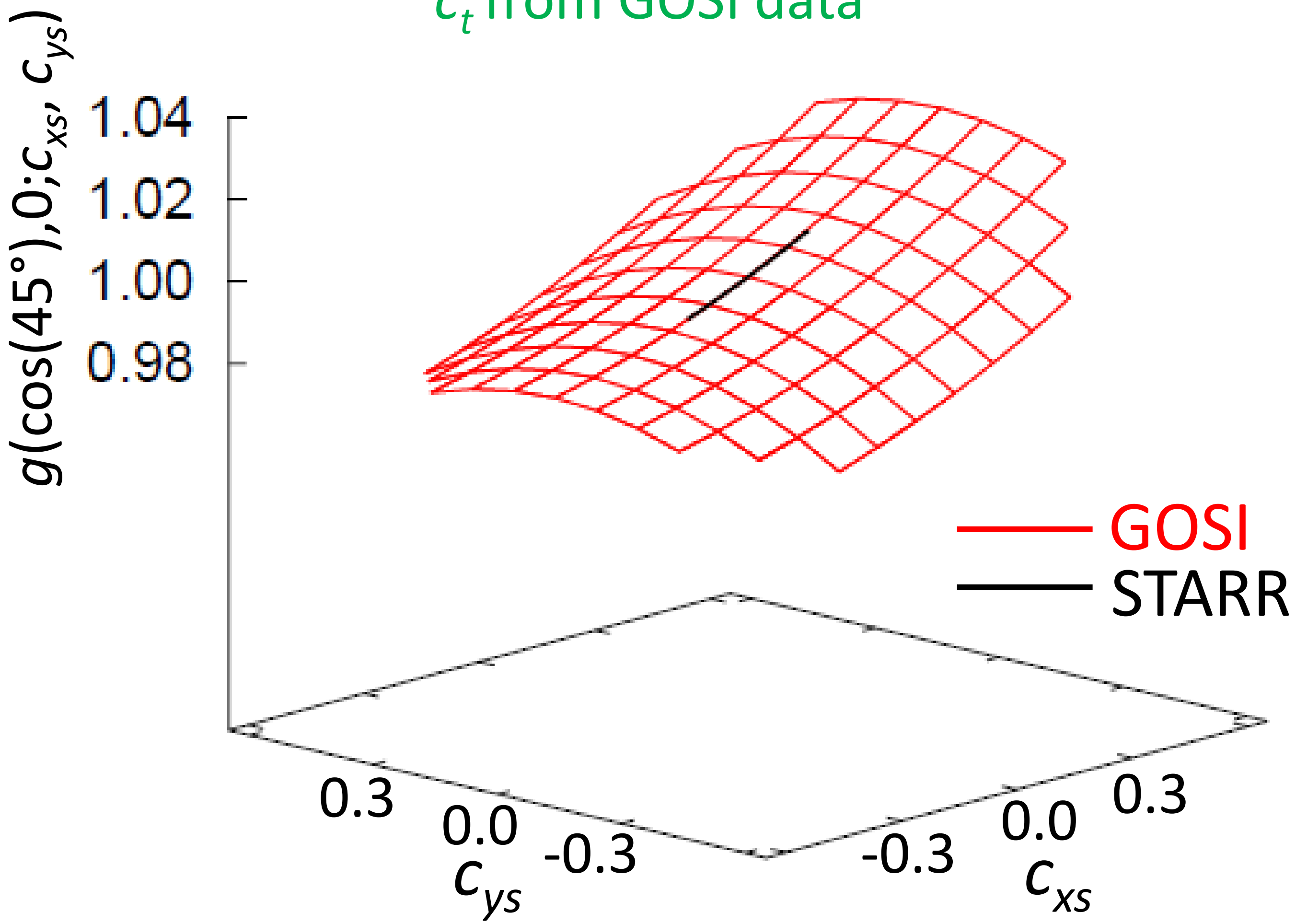
Parametrization of ratio

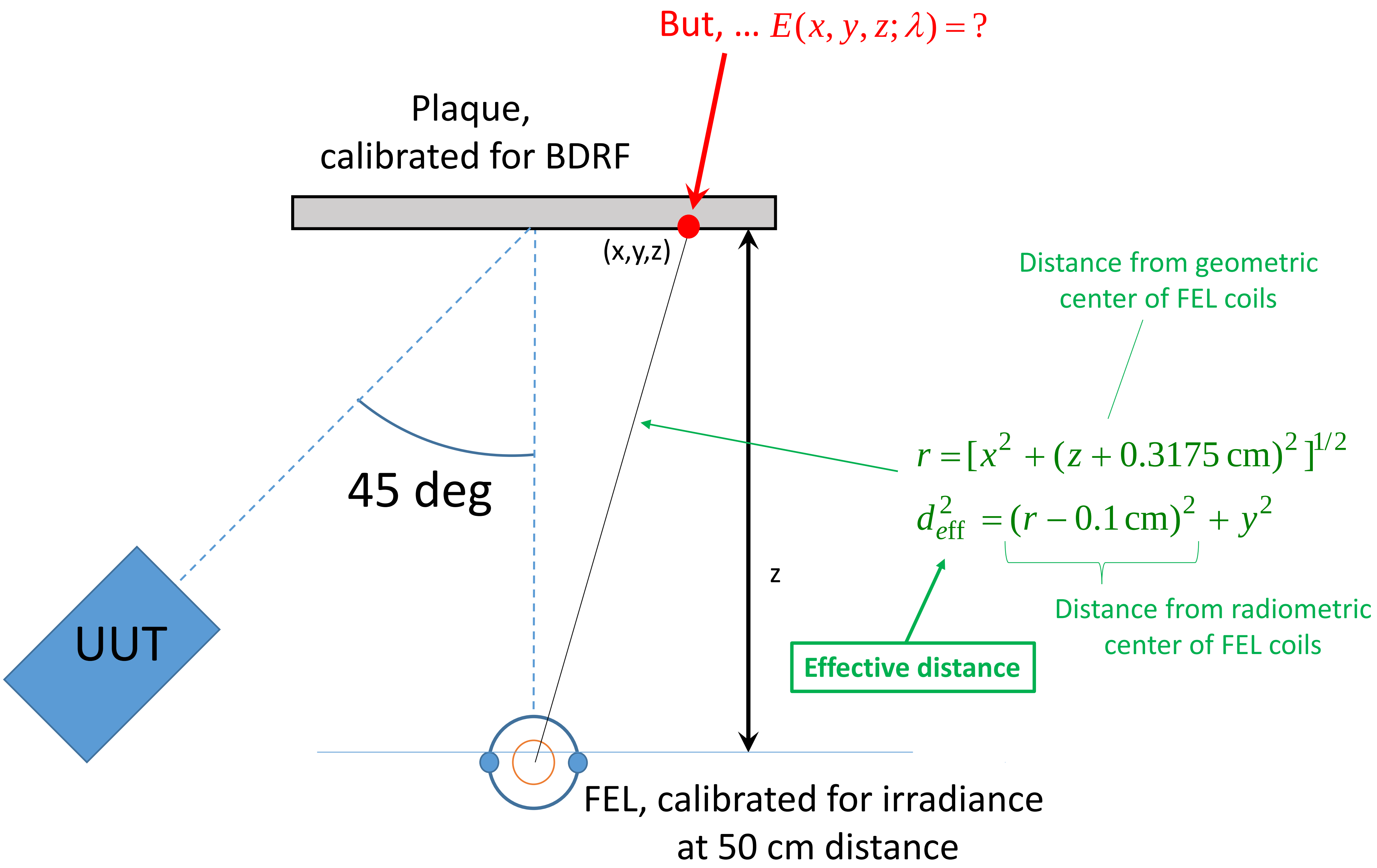
$$\frac{\mathrm{BRDF}(\theta_i,\theta_s,\phi_r)}{\mathrm{BRDF}(0°,45°,-)} = g(c_{xi},c_{yi};c_{xs},c_{ys}) = 1 + \sum_{\substack{\mu=0,1,2,\\ \nu=0,1,2}} c_{\mu\nu} l_i^{\mu} l_s^{\nu} + c_t t_s^2 + \ldots$$

$c_{\mu\upsilon}$ from legacy STARR data



c_t from GOSI data





But, ... $E(x, y, z; \lambda) = ?$
Plaque,
calibrated for BDRF
(x,y,z)
Distance from geometric
center of FEL coils
$r = [x^2 + (z + 0.3175\ \text{cm})^2]^{1/2}$
$d_{\text{eff}}^2 = (r - 0.1\ \text{cm})^2 + y^2$
45 deg
z
Distance from radiometric
center of FEL coils
Effective distance
UUT
FEL, calibrated for irradiance
at 50 cm distance

Lamp cal: FASCAL-2 (50 cm, on axis)

Distance effect: "uniformity test" [Yoon et al., Proc. SPIE 8510, 85100D (2012)]

$$E(x,y,z;\lambda) = E_{\mathrm{cal}}(\lambda)\left(\frac{d_{\mathrm{eff}}}{d_{\mathrm{cal}} + 0.2175\,\mathrm{cm}}\right)^2 \left(\frac{I(x,y,z)}{I(0,0,z)}\right)_{\mathrm{GSF}} \cos\theta_i$$

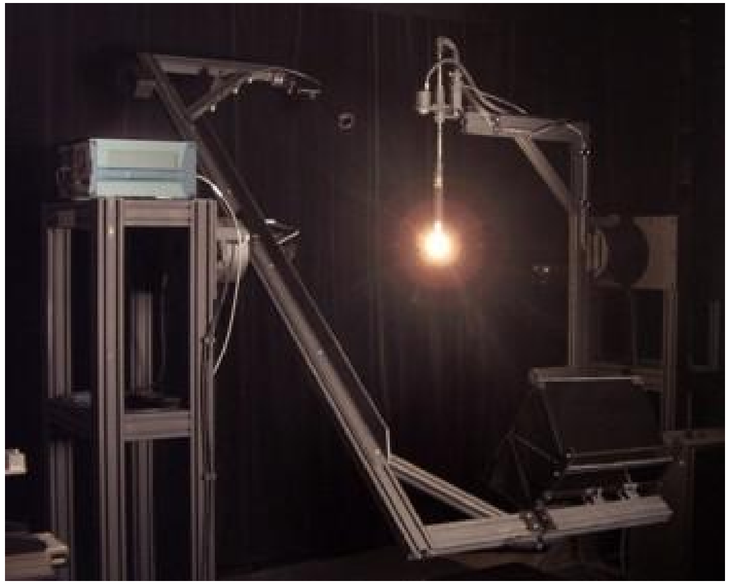
Validation of $1/r^2$ law presented by Yoon *et al.*

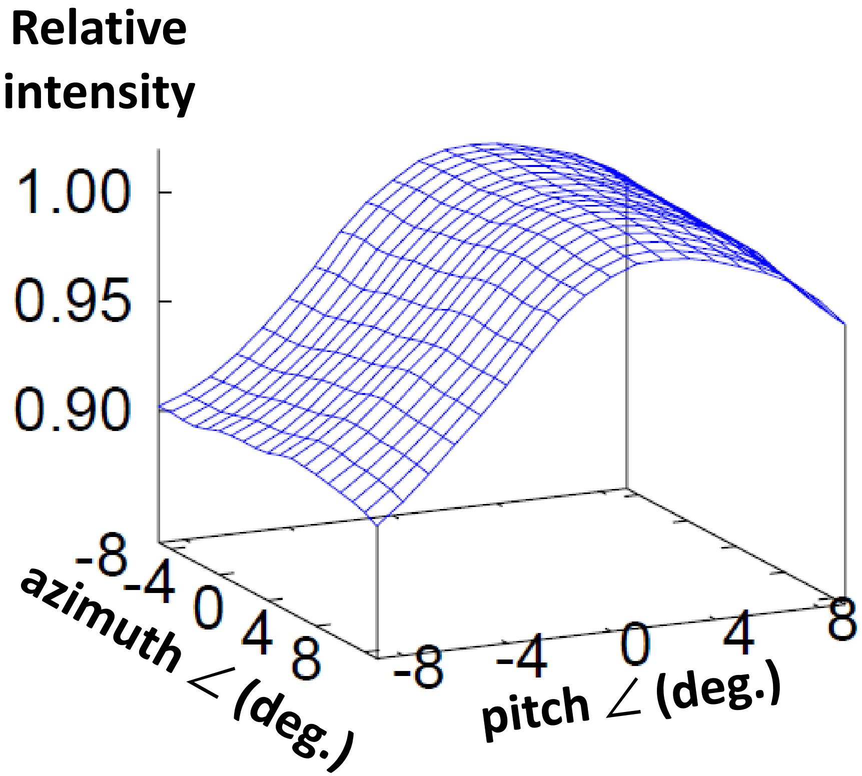
Angular effects on intensity: Gonio Spectroradiometer Facility (GSF, Yuqin Zong)

361 directions:

-9 deg lat. To +9 deg lat.

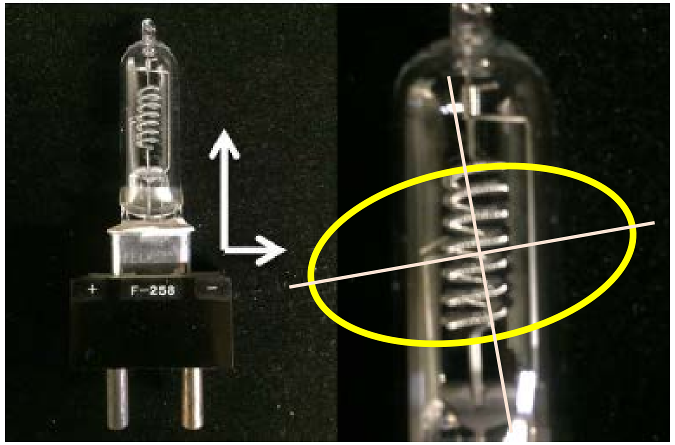
-9 deg long. to +9 deg long.





Polarization aspects:

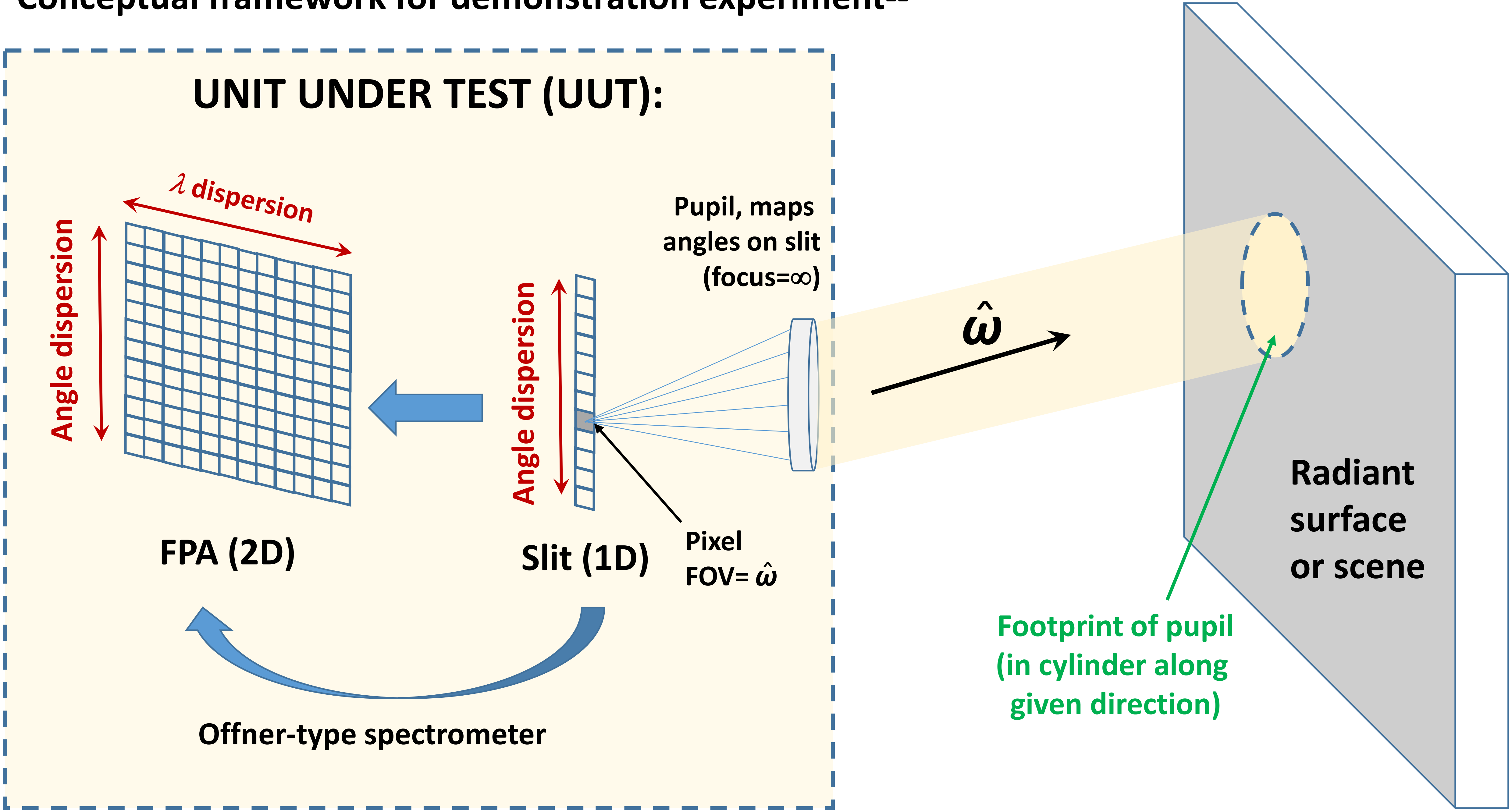
- 2.5 % polarized, tipped about 10° (like coils of large helix towards the viewer.)
- Ellipse exaggerates anisotropy.
- Plaque reduces polarization
- Total flux barely affected.



K.J. Voss and L.B. da Costa, Appl. Opt. **55** (31) 8829 (2016).

Note: spectral effects are weak.

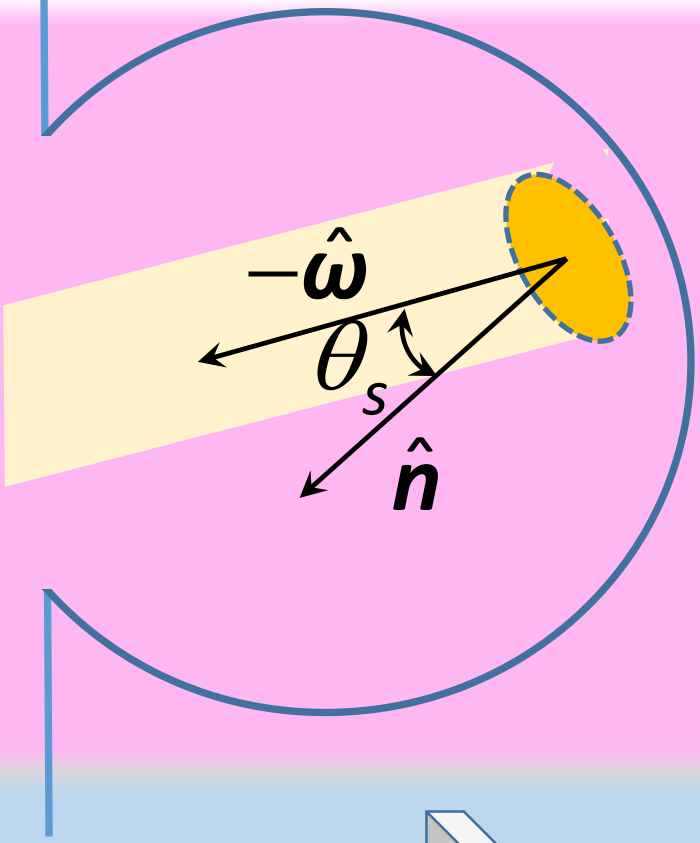
Conceptual framework for demonstration experiment--



Power delivered to pixel for integrating-sphere source (ISS) & lamp/plaque cases:

ISS case

$$\Phi_\lambda = d\omega \left[A_{\substack{\mathrm{UUT}\\ \mathrm{PUPIL}}} \cos\theta_{\mathrm{Pixel}} \sec\theta_s \right] \left[L_{\mathrm{ISS}} \cos\theta_s \right]$$



Pixel FOV

ISS wall or plaque area enclosed In cylinder

Cosine factor (projected UUT pupil area)

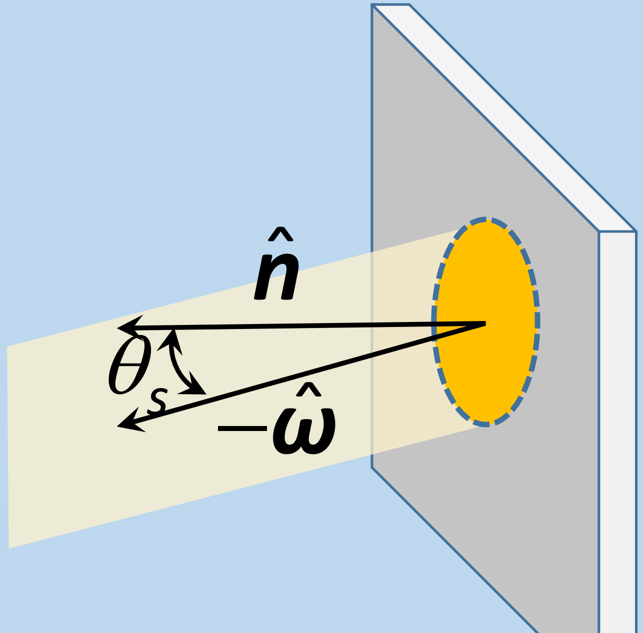
ISS radiance, cosine factor

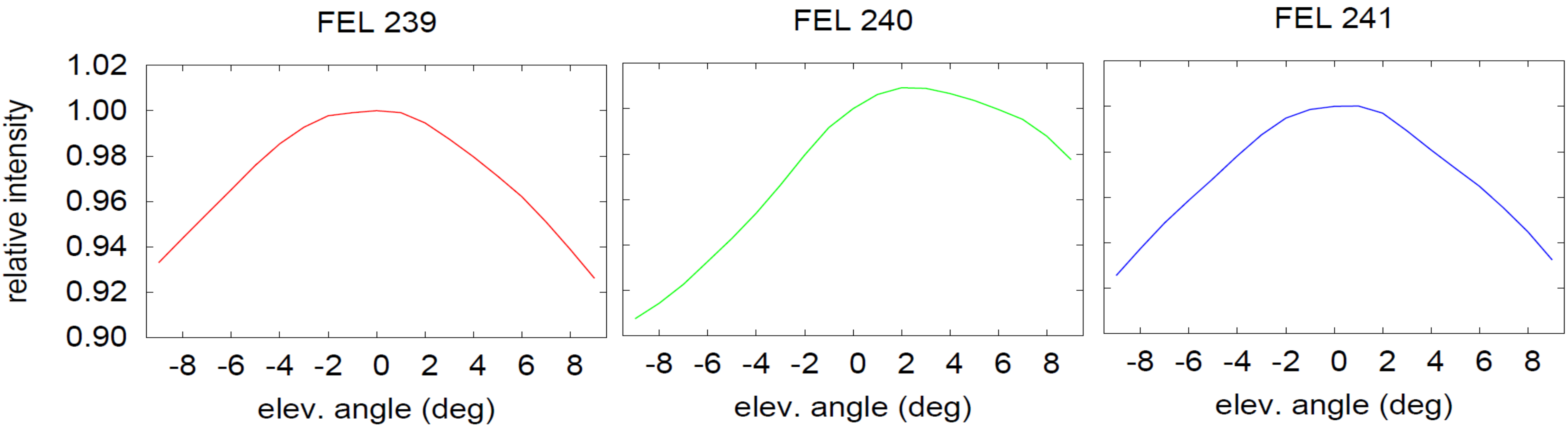
Lamp/plaque case

$$\Phi_\lambda = d\omega \left[A_{\substack{\mathrm{UUT}\\ \mathrm{PUPIL}}} \cos\theta_{\mathrm{Pixel}} \sec\theta_s \right]$$

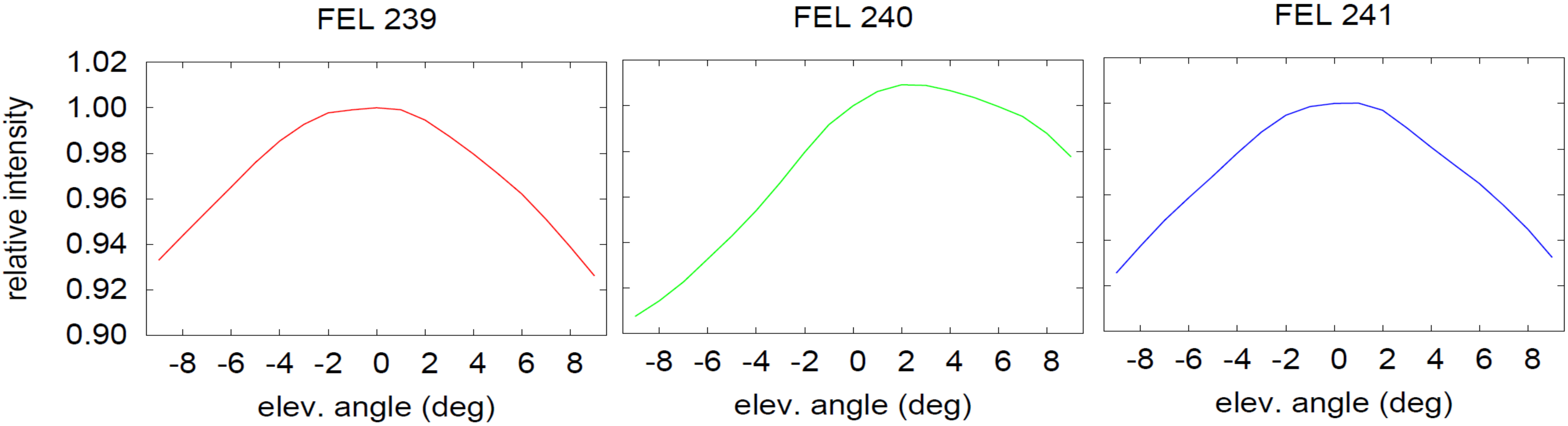
$$\times \left\{ E_\lambda \cdot g(\ldots) \cdot \mathrm{BRDF}(0/45) \cdot \cos\theta_s \right\}$$

Irradiance in FOV, g-factor, BRDF, cosine factor





FEL 239
FEL 240
FEL 241
relative intensity
1.02
1.00
0.98
0.96
0.94
0.92
0.90
-8 -6 -4 -2 0 2 4 6 8
elev. angle (deg)
elev. angle (deg)
elev. angle (deg)


FEL 239
FEL 240
FEL 241
relative intensity
1.02
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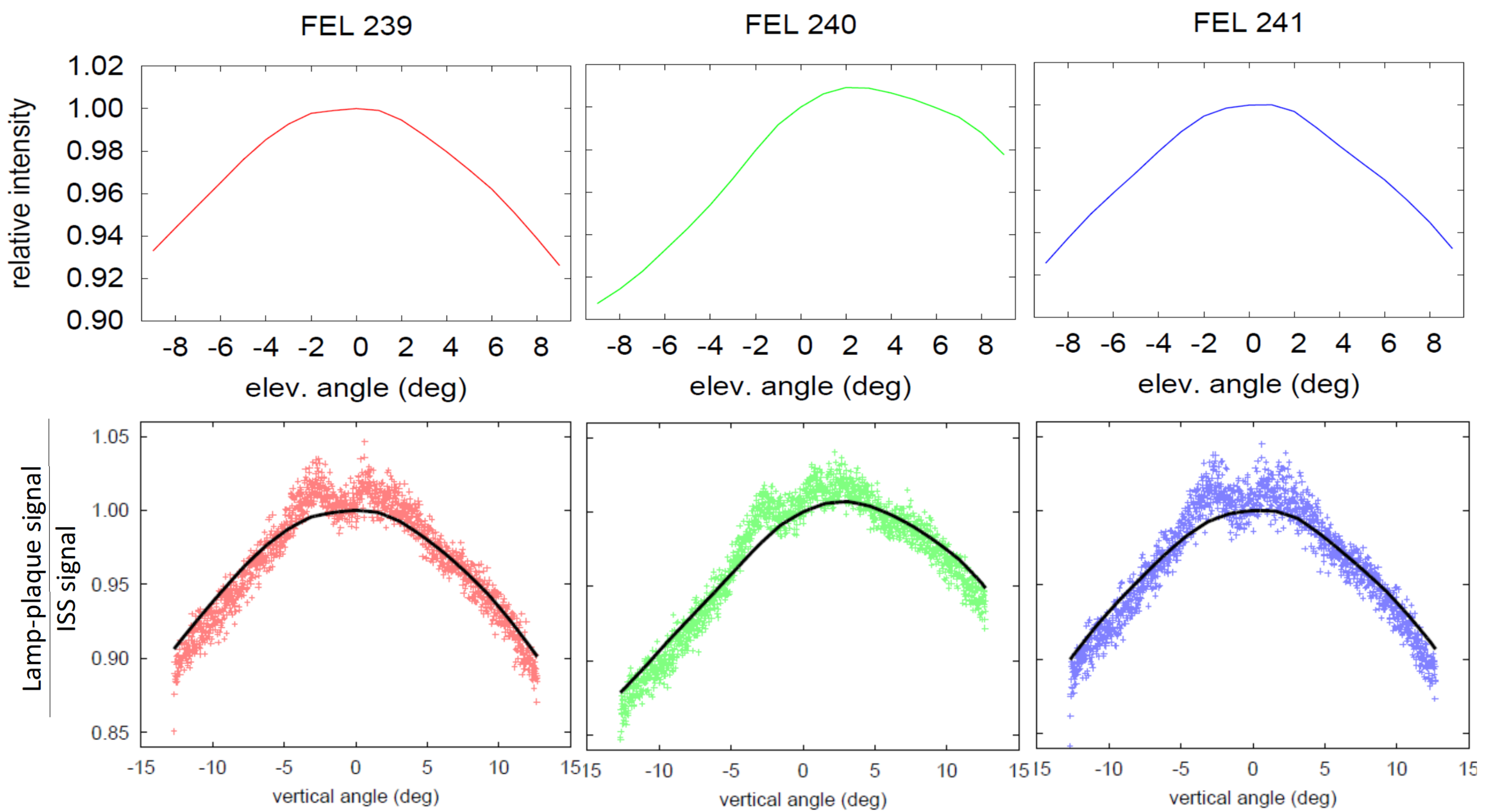
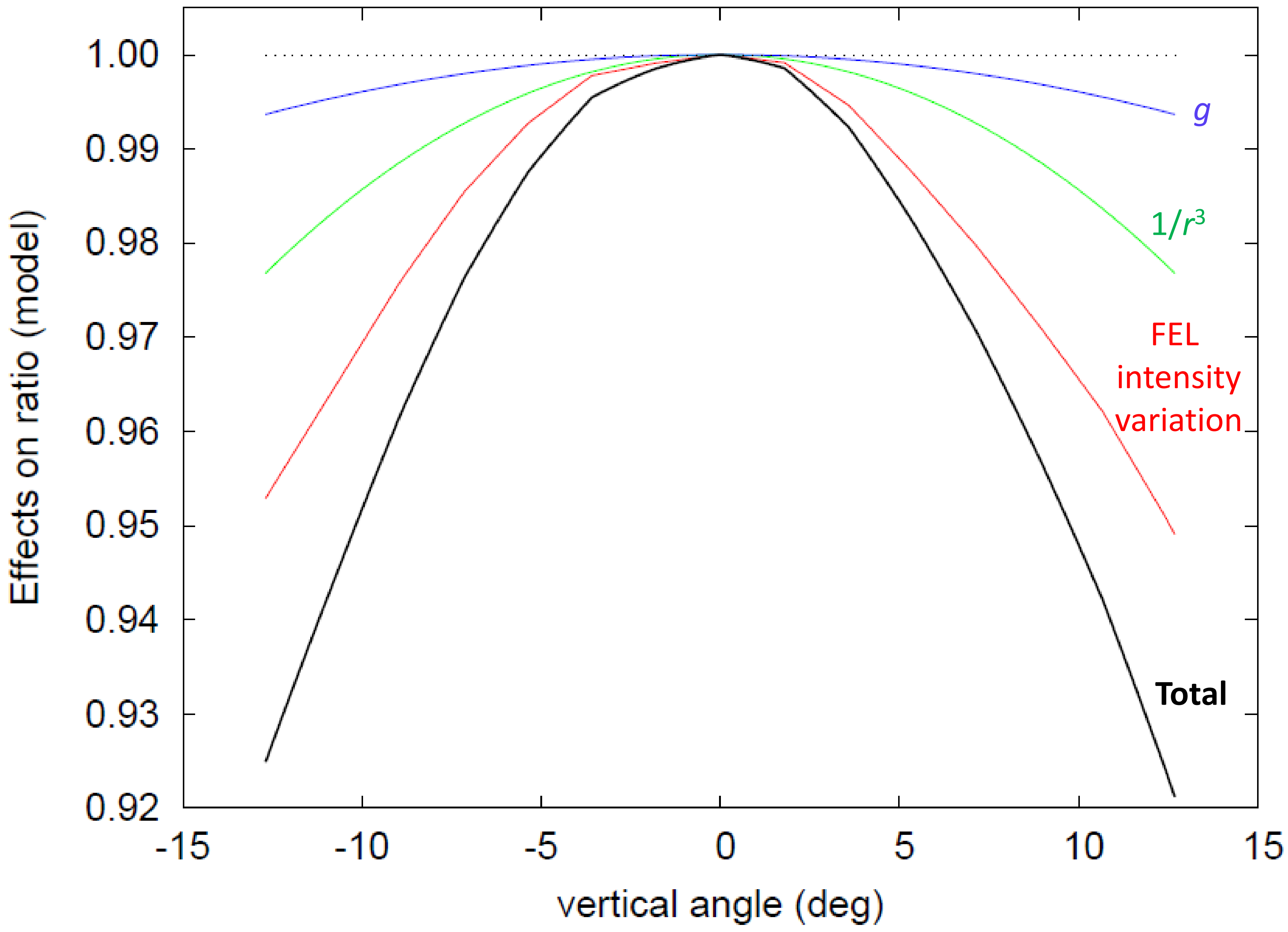
-8 -6 -4 -2 0 2 4 6 8
elev. angle (deg)



Note: (1.) UUT & lamp distance to plaque differ; (2.) need to map sphere; (3.) minimum work distance effects may also matte

Various effects on signal in lamp-plaque case:



Conclusions—

Lamp/plaque introduces effects in sensor calibrations that differ from those of integrating spheres

The effects can depend on the lamp

Optics of sensors (e.g., working distance) may need to be known

Further work is needed to finalize quantitative analysis