Optical Performance of Reflectivity Control Devices (RCDs) for Solar Sail Applications

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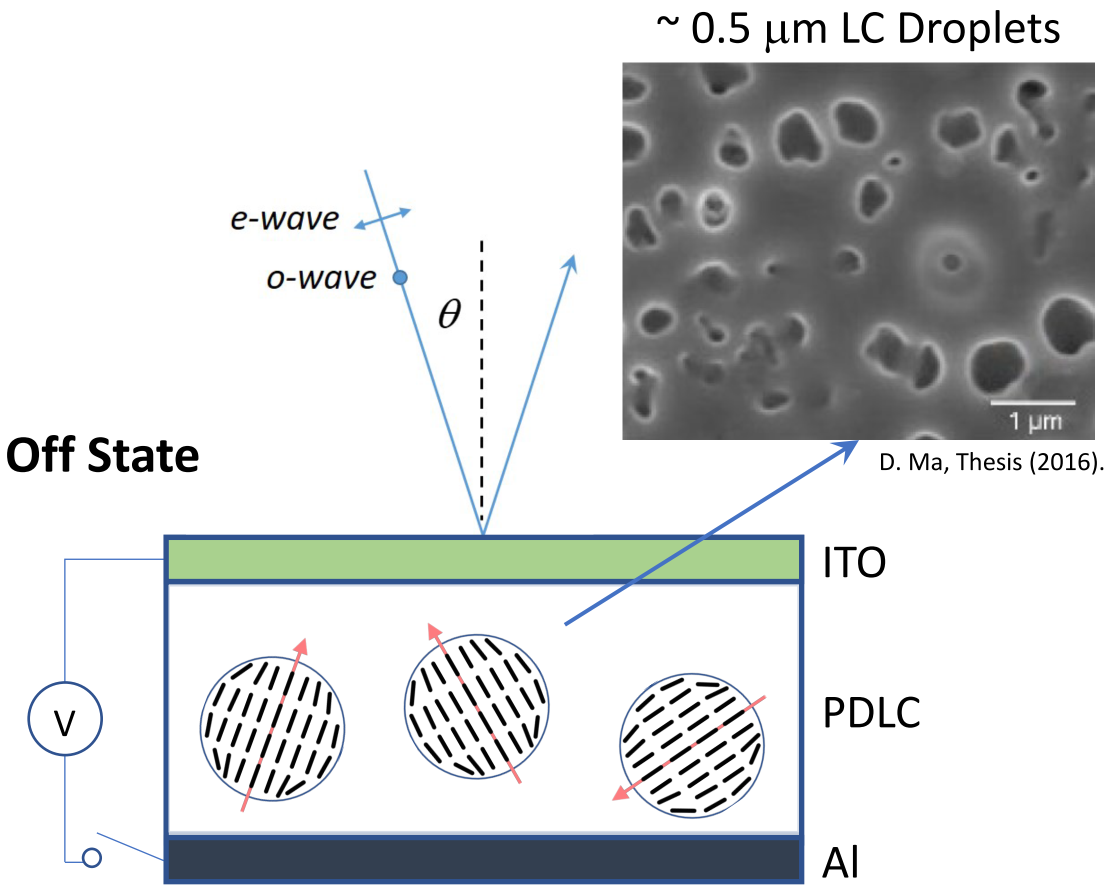
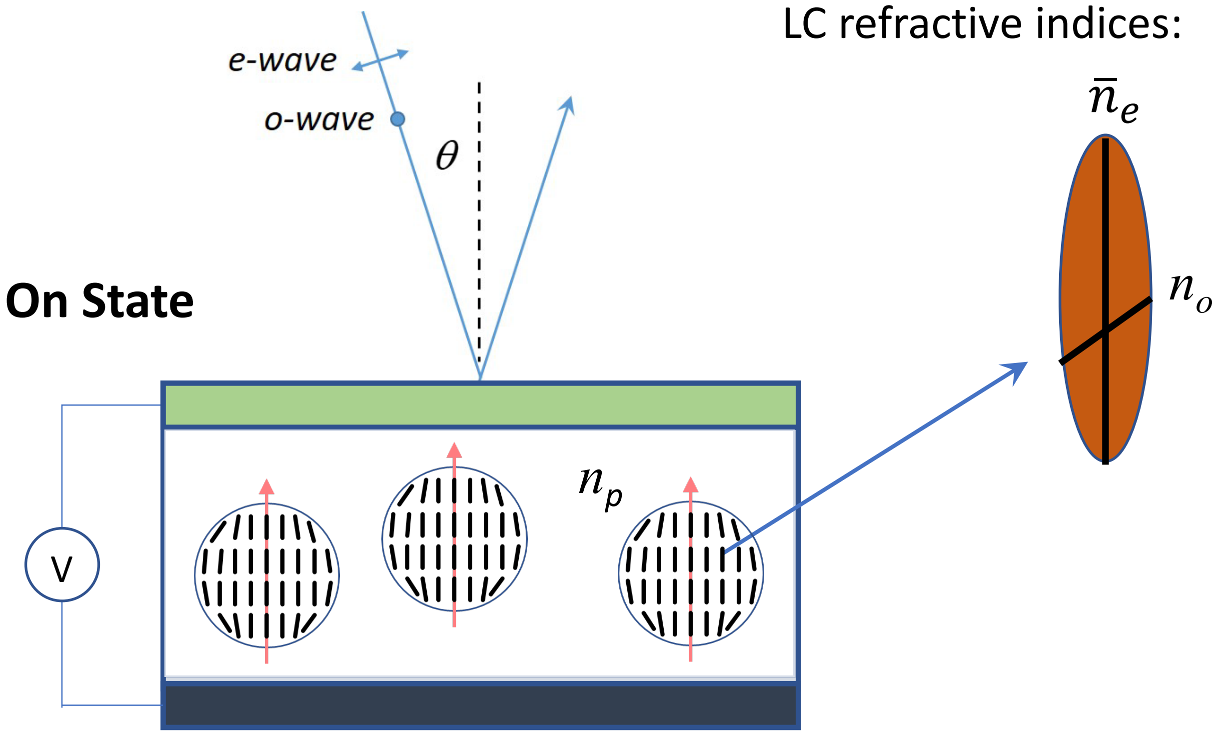
Solar Cruiser Mission

- Deployed Area: 1653 m^2
- Establish artificial equilibrium sunward of L1
- Propellantless – indefinite station keeping
  - Active Mass Translator for Pitch and Yaw
  - Embedded Reflectivity Control Devices (RCDs) for Roll

Polymer Dispersed Liquid Crystals (PDLCs) as RCDs





High Birefringence: $\bar{n}_e >> n_o$

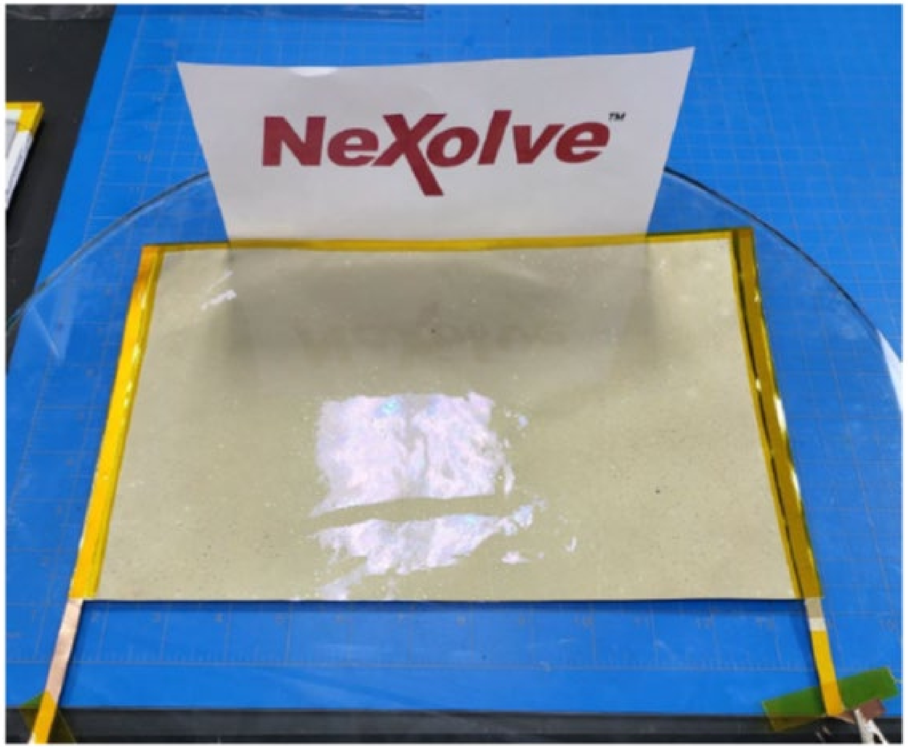
$\Rightarrow$ Diffuse Reflection

Index Matching (at $\theta = 0$): $n_p = n_o$

$\Rightarrow$ Transparent, Specular Reflection from Al

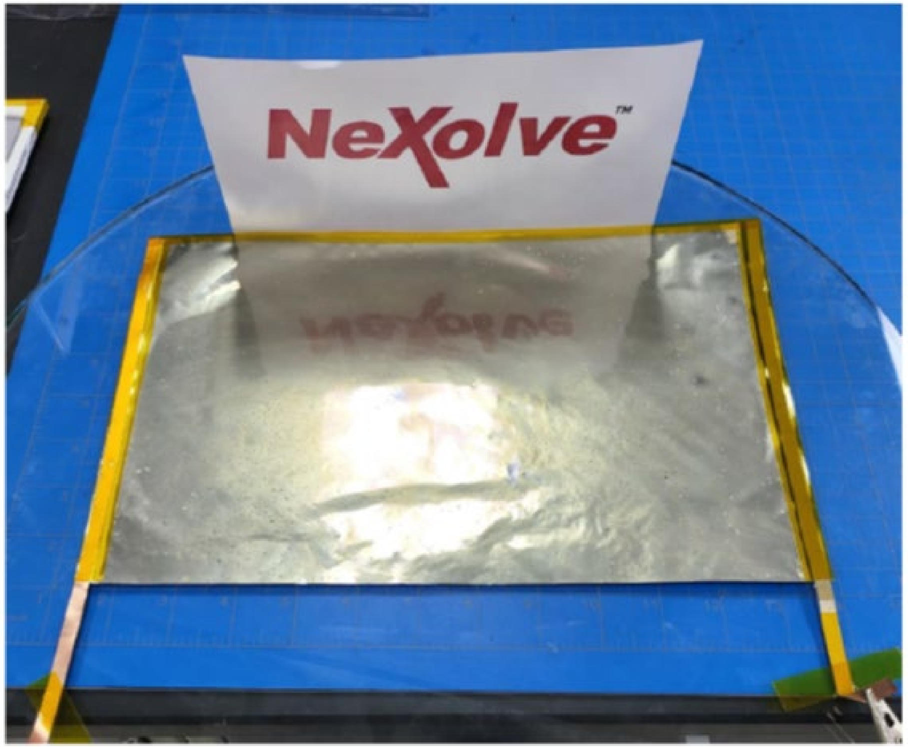
NeXolve RCDs

Off



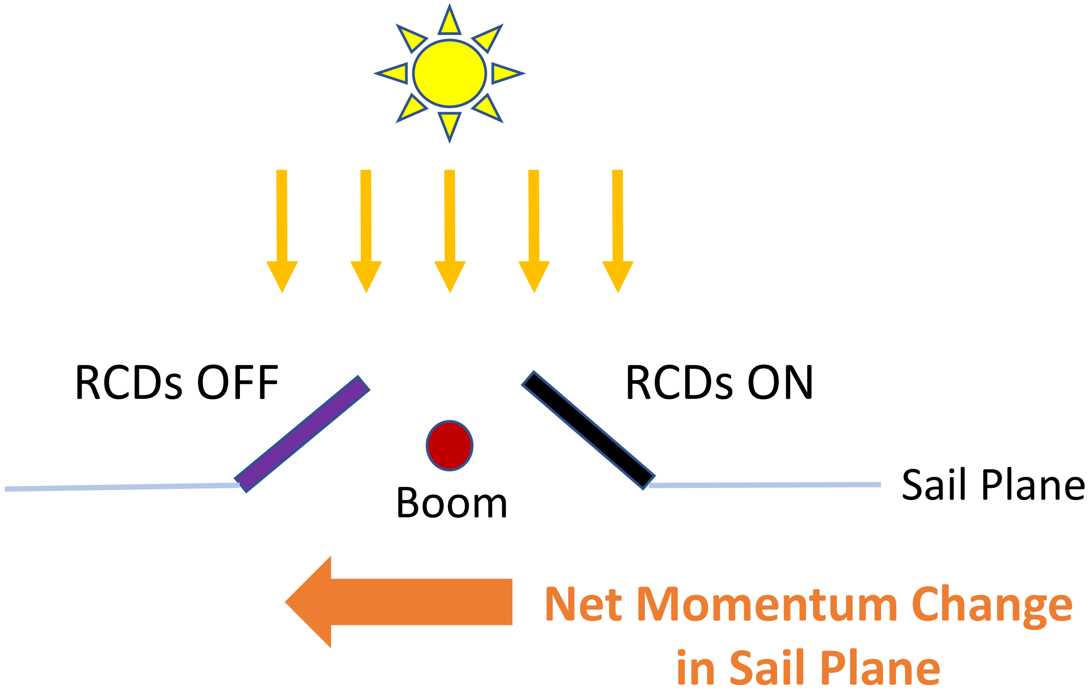
⇒ Diffuse Reflection

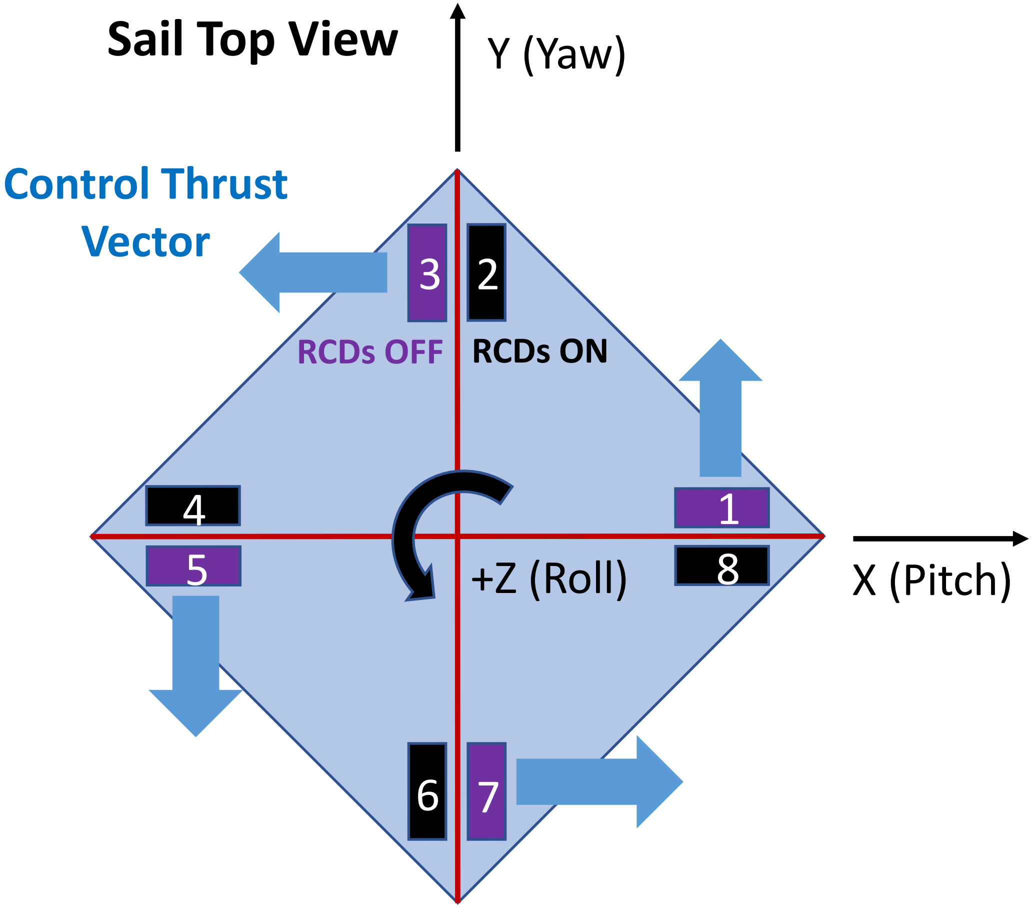
On



⇒ Transparent, Specular Reflection from Al

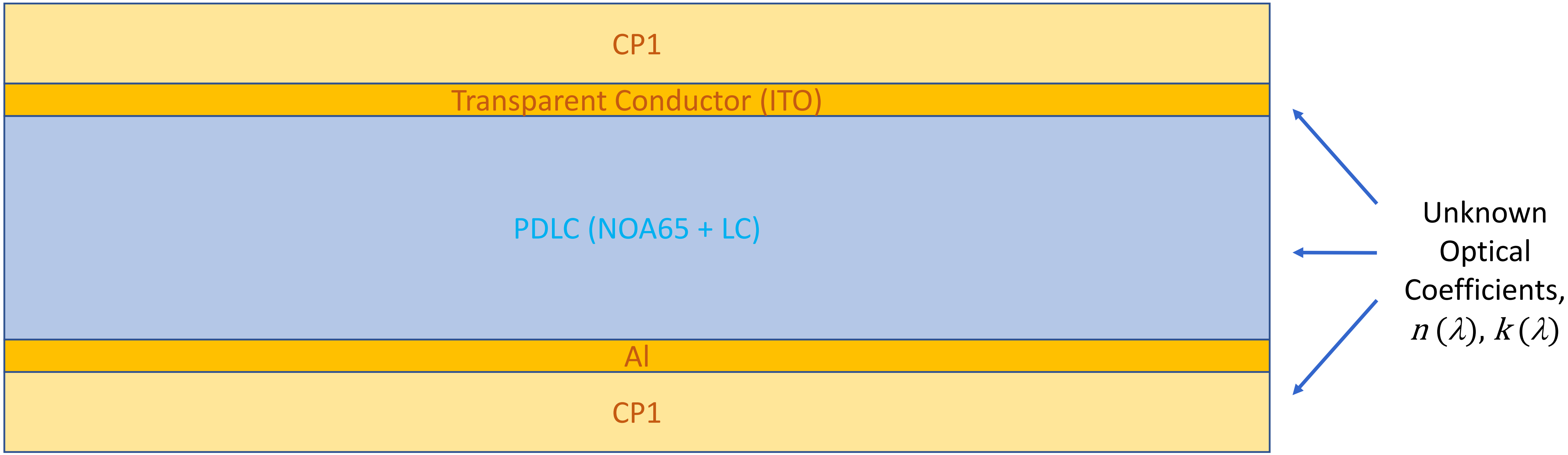
Solar Sail Roll Control with RCDs





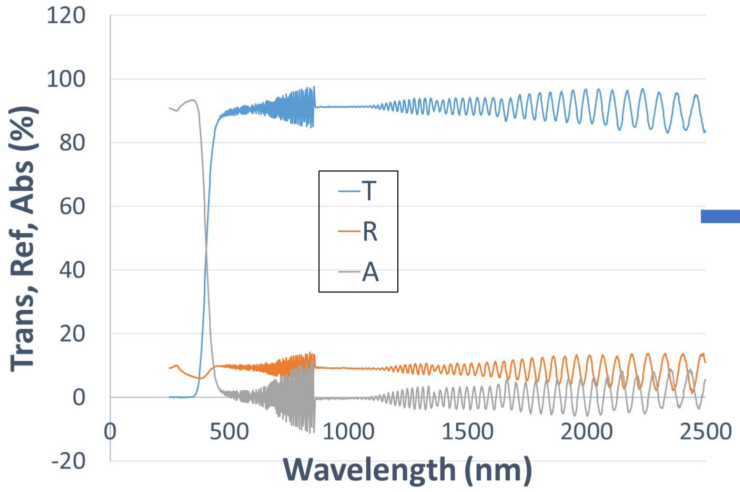
2 States: Clockwise and Counter-Clockwise

Notional Design

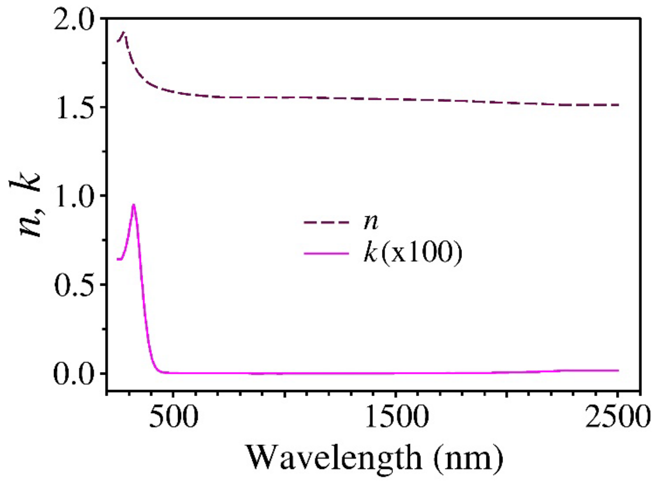


CP1 Optical Coefficients

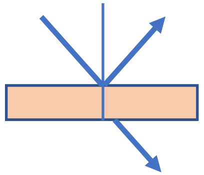
8° R, T measurements, 1 mil CP1



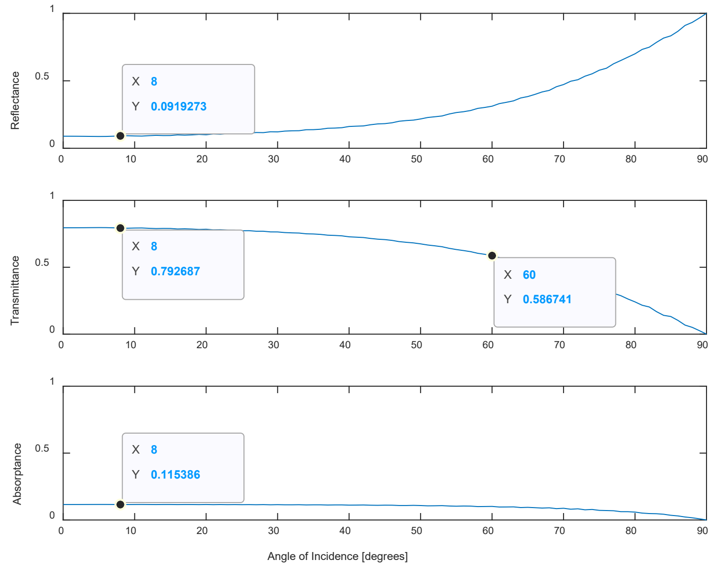
Optical Constants from Inversion



Thin Film Calculations (s-pol): CP1



25 μm CP1



Used slab model for R, T measurements. Inverted to obtain n, k.

Could improve by using specular, rather than total, R & T.

Only known n(λ), k(λ) data for CP1!

Agrees with measurement!

NOA65 Optical Coefficients

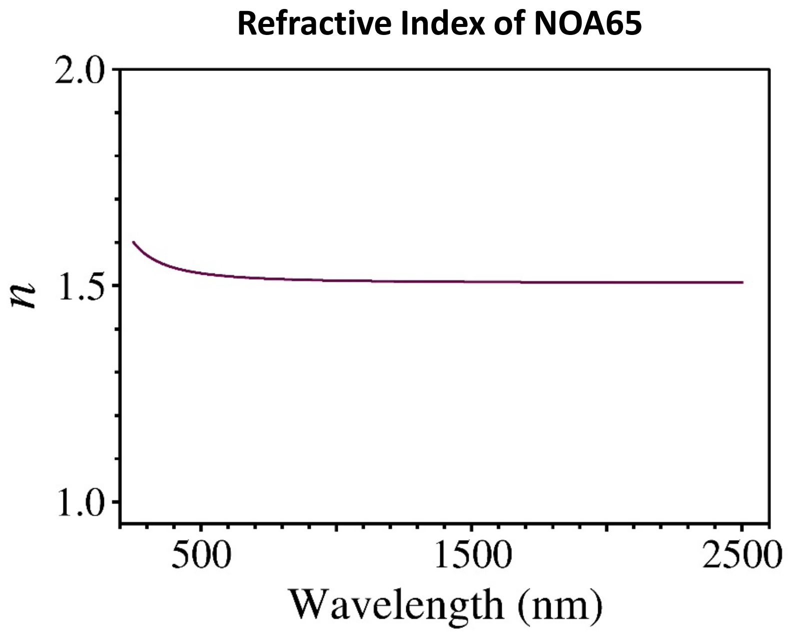
- Nordland Optical Adhesives (NOA) – a flexible epoxy that minimizes strain
- Assumed $k = 0$. (see caution below).
- Refractive Index (*n*) determined by Cauchy dispersion equation at 25° C:

$$n = A + B / \lambda^2 + C / \lambda^4$$

$$A = 1.50631$$

$$B = 5435.62$$

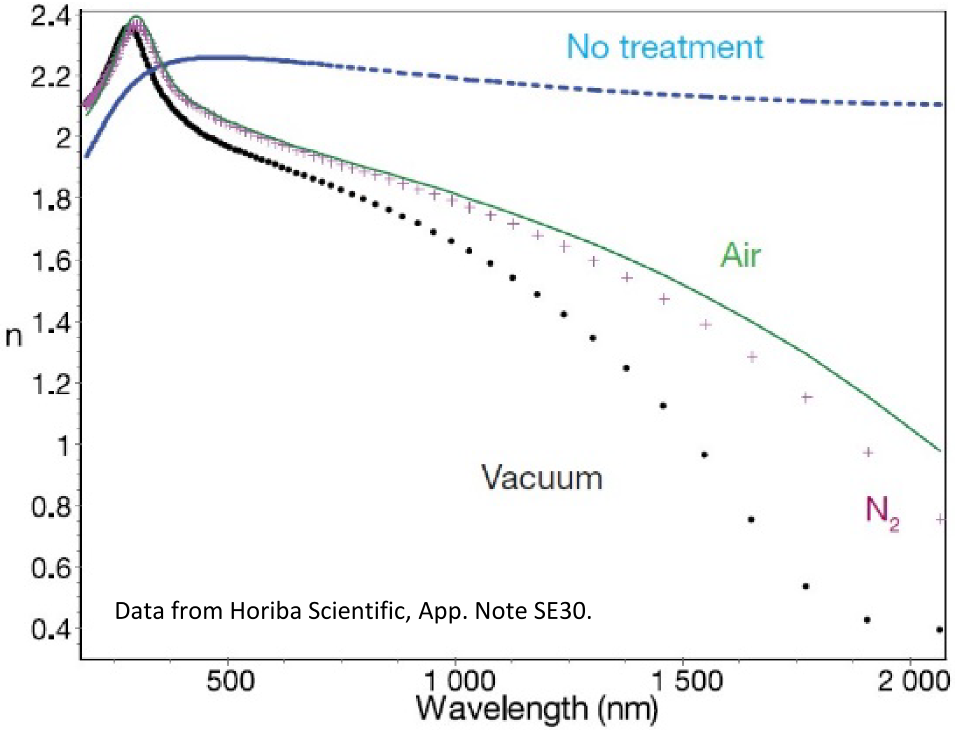
$$C = 2.77798 \times 10^7$$



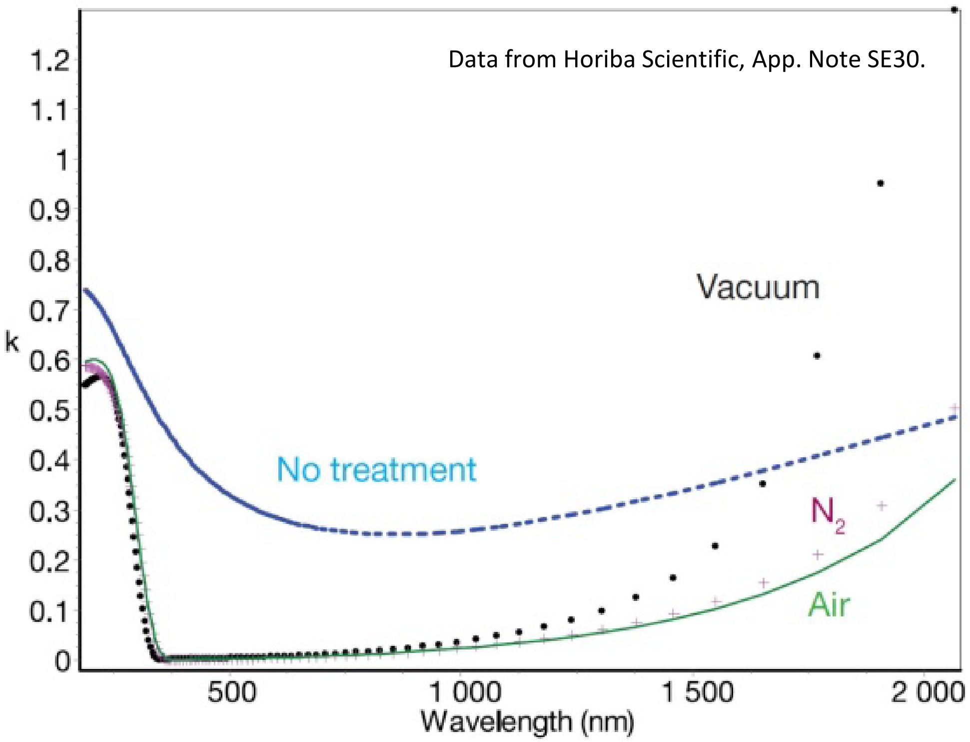
- Caution: volume and refractive index of epoxies can depend strongly on temperature as well as extent of cure. In addition, many epoxies absorb below 350 nm and above 2200 nm.

ITO Coeffs: Best and Worst Cases

Refractive Index, n



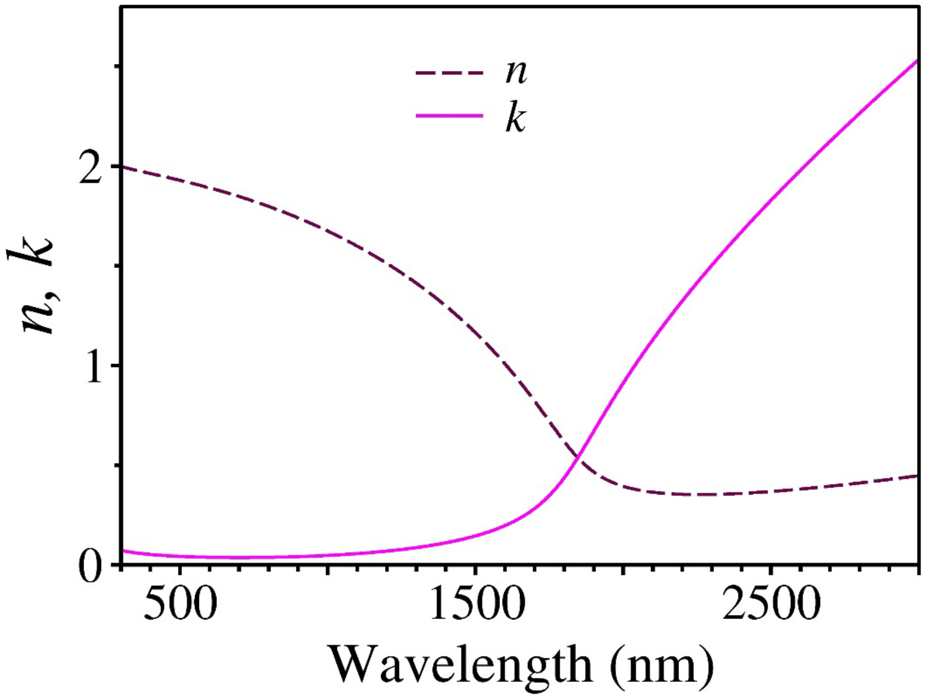
Extinction Coeff., k



- n and k vary significantly with post-treatment
- **Best case**: annealed at 500 C on glass; **Worst case**: as-deposited, no post-treatment
- ITO on CP1 annealed at 250 C (glass transition at 263 C). Expect somewhere between these limits.

ITO Optical Coefficients

- Ion-assisted deposition at 0.3 nm/s in 2.5 x 10^{-5} Torr O_2 background on a 1mm glass substrate.
- Post-annealed at 245 C in air for 1 hour
- Thickness was 106.6 nm
- Low surface resistance (75 Ohms/sq.) with good transparency

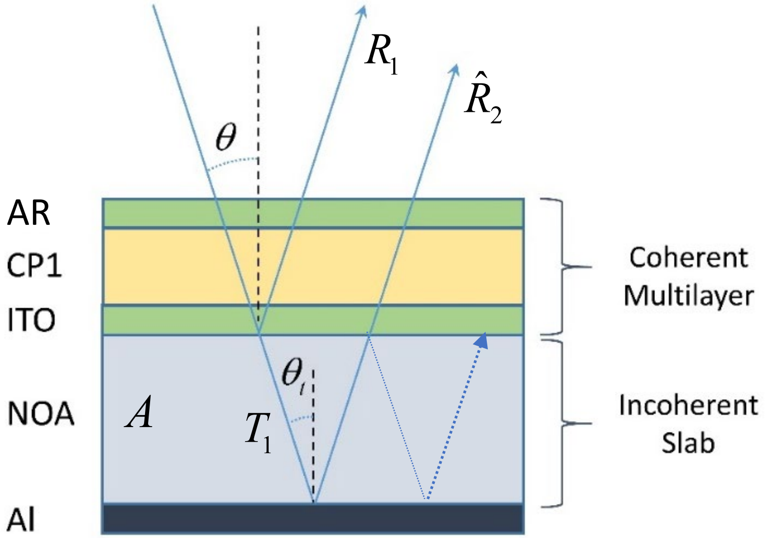


Conclusions:

- *n, k* found from transmission measurements using a Lorentz-Drude model. Results look like Horiba samples cooled in vacuum.
- Substrate limits accuracy in UV – could improve by using fused silica substrate but not much solar flux there.
- Can improve confidence using iterative approach and by fitting reflection if needed in future.

Semiempirical Thin-Film Model

Hybrid Reflection Model:



$R(\theta,\lambda) = R_1 + \hat{R}_2$ ***Specular Reflection***

coherent multilayer (R_1)

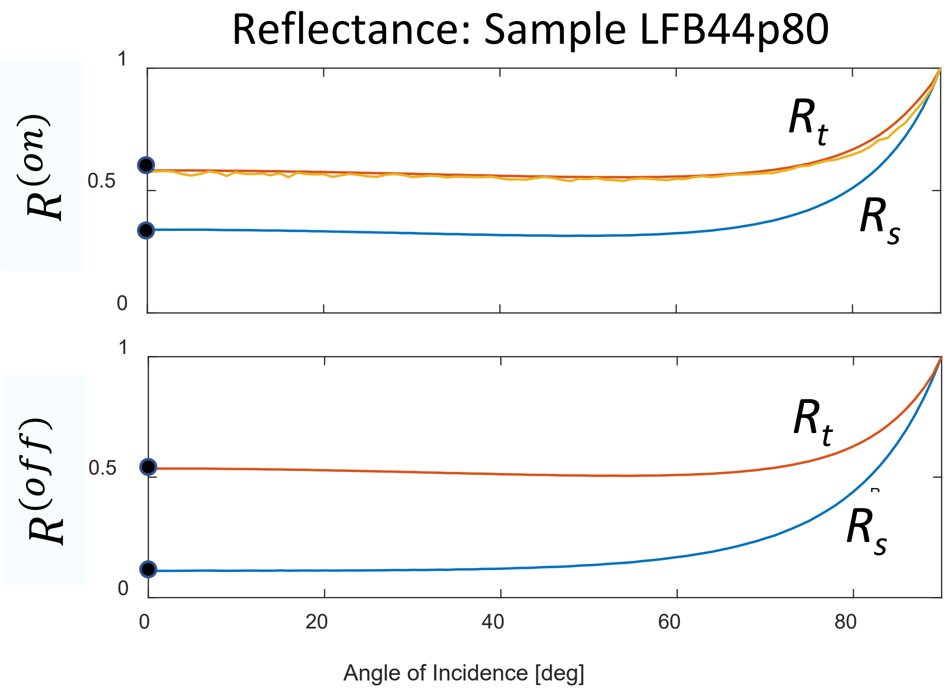
slab: $\hat{R}_2 = R_2 T_1^2 A^2 \sum_{m=0}^{\infty} (R_1 R_2 A^2)^m$

where $A(\theta,\lambda) = A_0^{1/\cos(\theta_t(\theta,\lambda))}$

fitting parameter (A_0)

$$R(\theta) = \int R(\theta,\lambda)\, I_{sun}(\lambda)\, d\lambda$$

Integrated Reflection



Assumptions:

$R_s^{(on)}(\theta, A_0) = R(\theta, 0.715)$

$R_t^{(on)}(\theta) = R(\theta)$

$R_s^{(off)}(\theta) = R_1(\theta)$

No free parameters

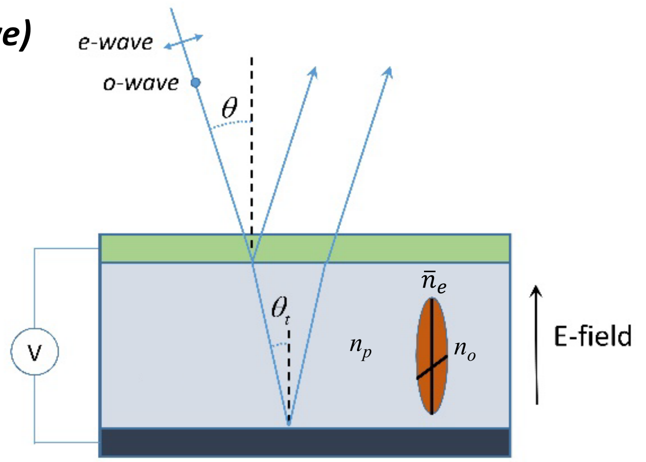
$R_t^{(off)}(\theta, A_0) = R(\theta, 0.954)$

- Benefits: ***Guides improvements in RCD design***, immediate feedback as new materials or processes are introduced. (whereas BRDF only provides end results for whole structure)
- Fresnel reflection ***reduces RCD effectiveness***, esp. at large AOI, by reducing amount of light that enters PDLC.
  - ✓ Use AR coating
- Absorption also deleterious
  - ✓ High quality ITO quality is crucial

Limitation of Thin-Film Model

Extraordinary (e-wave)
Ordinary (o-wave)

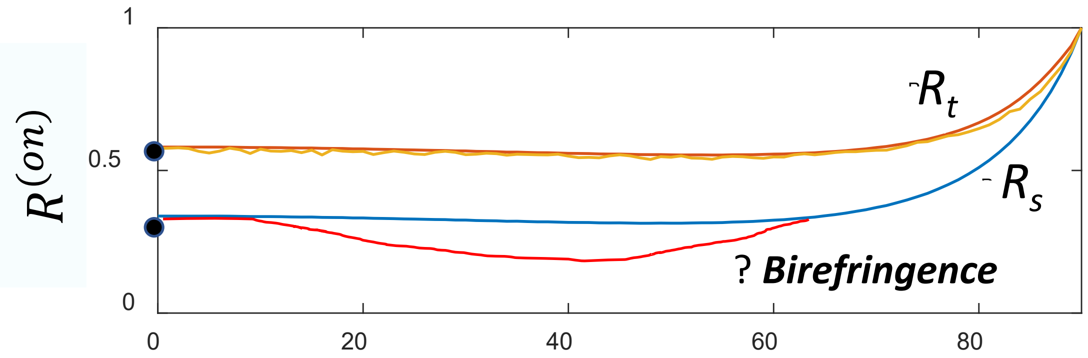
Birefringent Scattering Active Layer



Index Matching (at $\theta = 0$): $n_p = n_o \Rightarrow$ Specular Reflection

But, $$\frac{1}{n_e^2} = \frac{\sin^2\theta_t}{\bar{n}_e^2} + \frac{\cos^2\theta_t}{n_o^2}$$

$\therefore$ ***At higher θ, e-wave may not be index matched!***



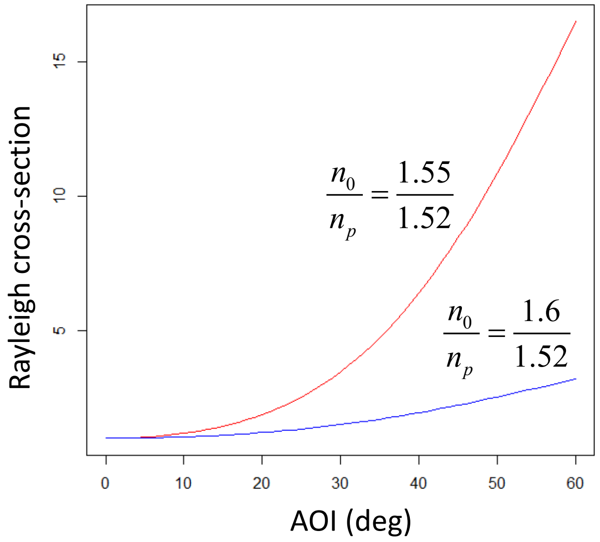
Birefringence Problem:

Why it might not be so important:

- For Solar Cruiser, θ_t not larger than about 40 degrees, so index n_e primarily determined by n_o.
- Incident light is equal mixture of two polarizations.

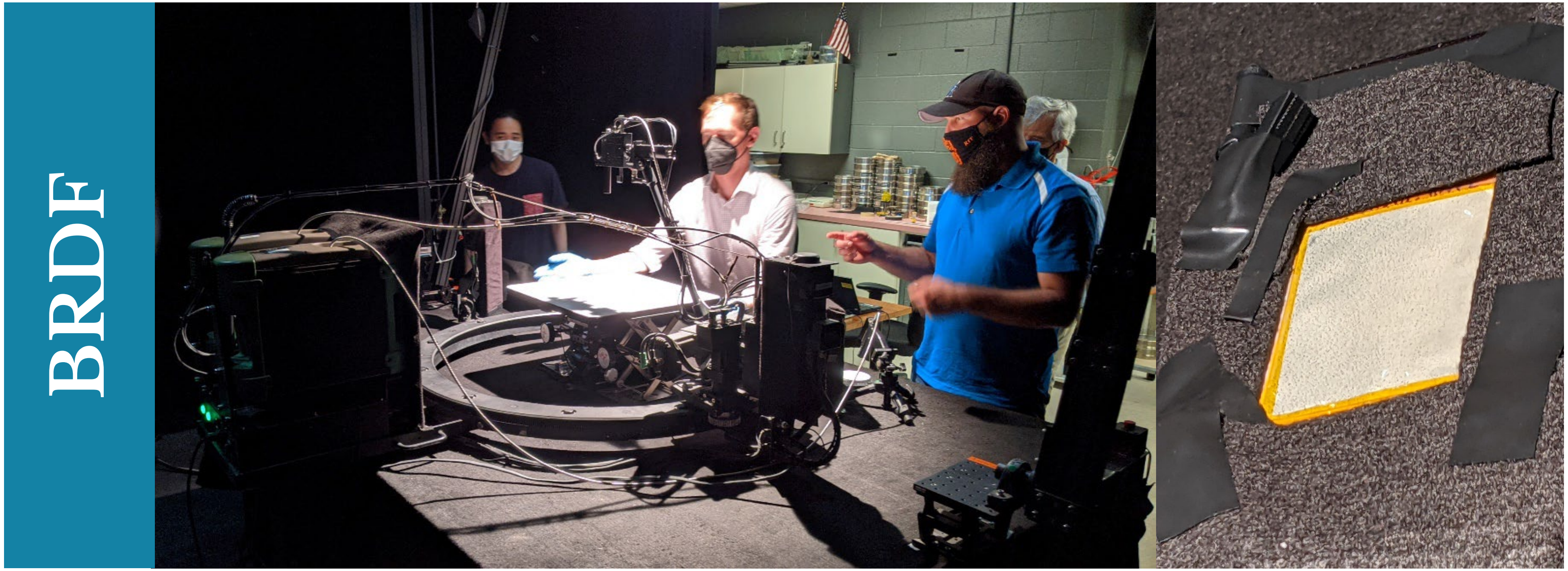
Why it could be important:

- Rayleigh scattering cross section increases dramatically with angle, especially when index matched

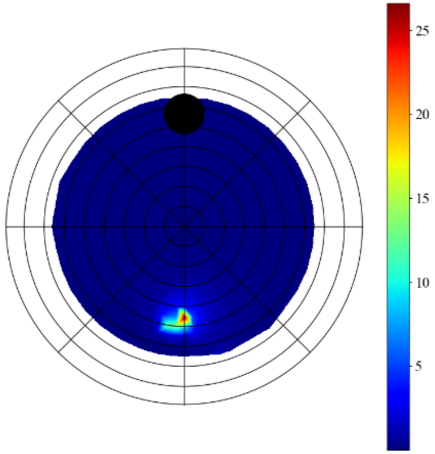


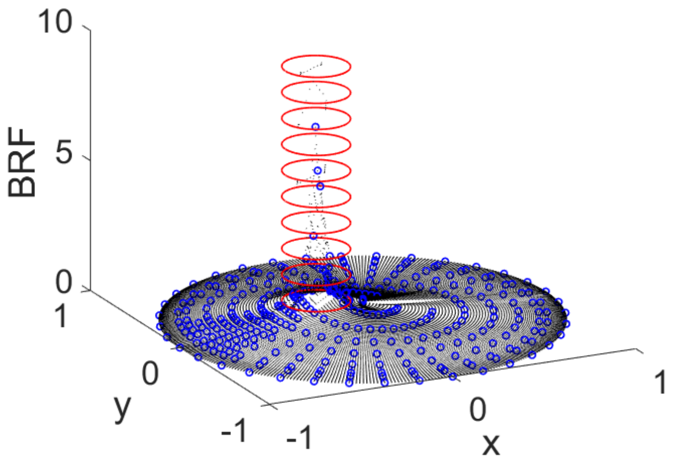
How to know: BRDF Measurements! (vs. AOI)

BRDF Measurements at RIT



- Hyperspectral (1 nm increments, 350 – 2500 nm)
- For each incident angle (5 AOIs chosen) data taken over entire viewing hemisphere ($\theta = 0 - 65^\circ$ zenith) and full azimuth ($\varphi = 0 - 360^\circ$)





Photon Force Model

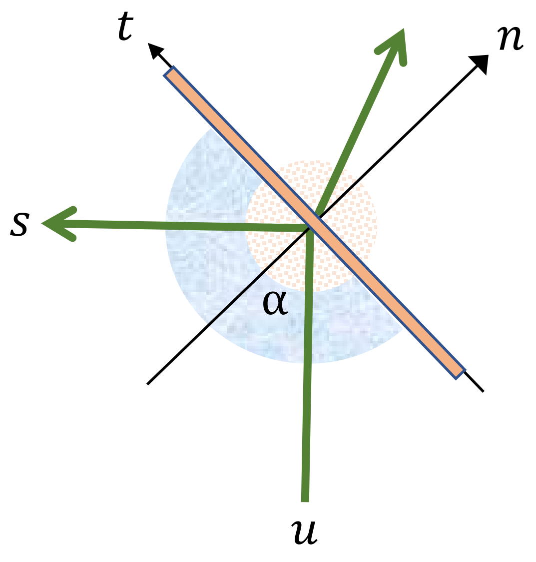
$$F_t = \frac{EA}{c}(1 - \tilde{r}s)\ \cos\alpha \sin\alpha$$

$$F_n = \frac{EA}{c}\left\{(1 + \tilde{r}s)\ cos^2\alpha + B_f(1 - s)\tilde{r}\cos\alpha + (1 - \tilde{r})\frac{\varepsilon_f B_f - \varepsilon_b B_b}{\varepsilon_f + \varepsilon_b}\cos\alpha\right\}$$

Absorption & Specular Reflection

Diffuse Reflection

Thermal Emission



Adapted from CR McInnes, "Solar Sailing" Springer (2004).

where:

$\tilde{r}$ = total reflection coeff.

s = portion of $\tilde{r}$ that is specular

B_f, B_b = front and back surface non-Lambertian coeffs.

Determined from BRDF

$\varepsilon_f, \varepsilon_b$ = front and back surface emissivity

Analysis Steps

At each incident angle, α:

1) Integrate BRDF $f_r(\theta, \varphi, \lambda)$ over solar spectrum
2) Interpolate over zenith ($\theta = 0 - 65°$) and azimuth ($\varphi = 10 - 360°$) angles in experiment
3) Add boundary conditions and extrapolate to edge of hemisphere
4) Integrate over all solid angle elements in σ to get total hemispherical reflection

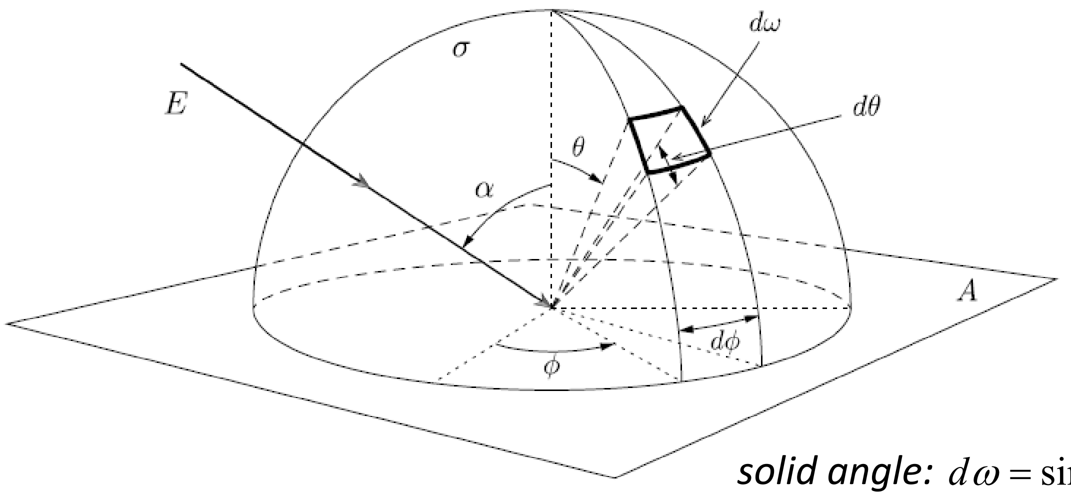
$$\tilde{r} = \rho_\sigma = \int_\sigma f_r(\theta, \varphi)\, d\Omega$$

5) Define a cone and integrate over solid angle elements within it to obtain the specular reflection

$$\tilde{r}s = \rho_{cone} = \int_{cone} f_r(\theta, \varphi)\, d\Omega$$

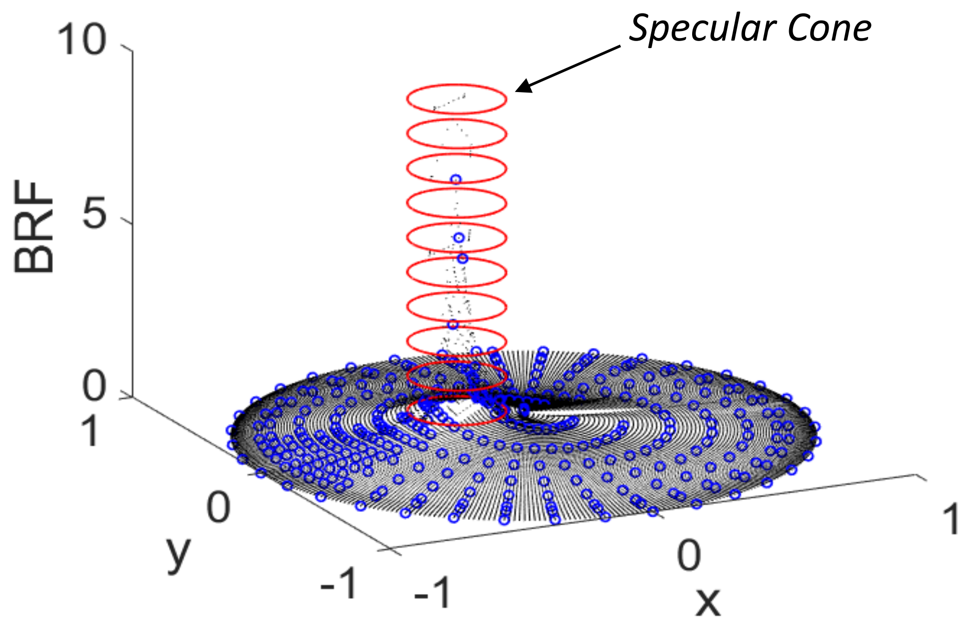
6) Perform integration to obtain the non-Lambertian coefficient

$$B_f = \frac{\int_\sigma f_r(\theta,\varphi)\cos\theta\, d\Omega}{\int_\sigma f_r(\theta,\varphi)\, d\Omega}$$

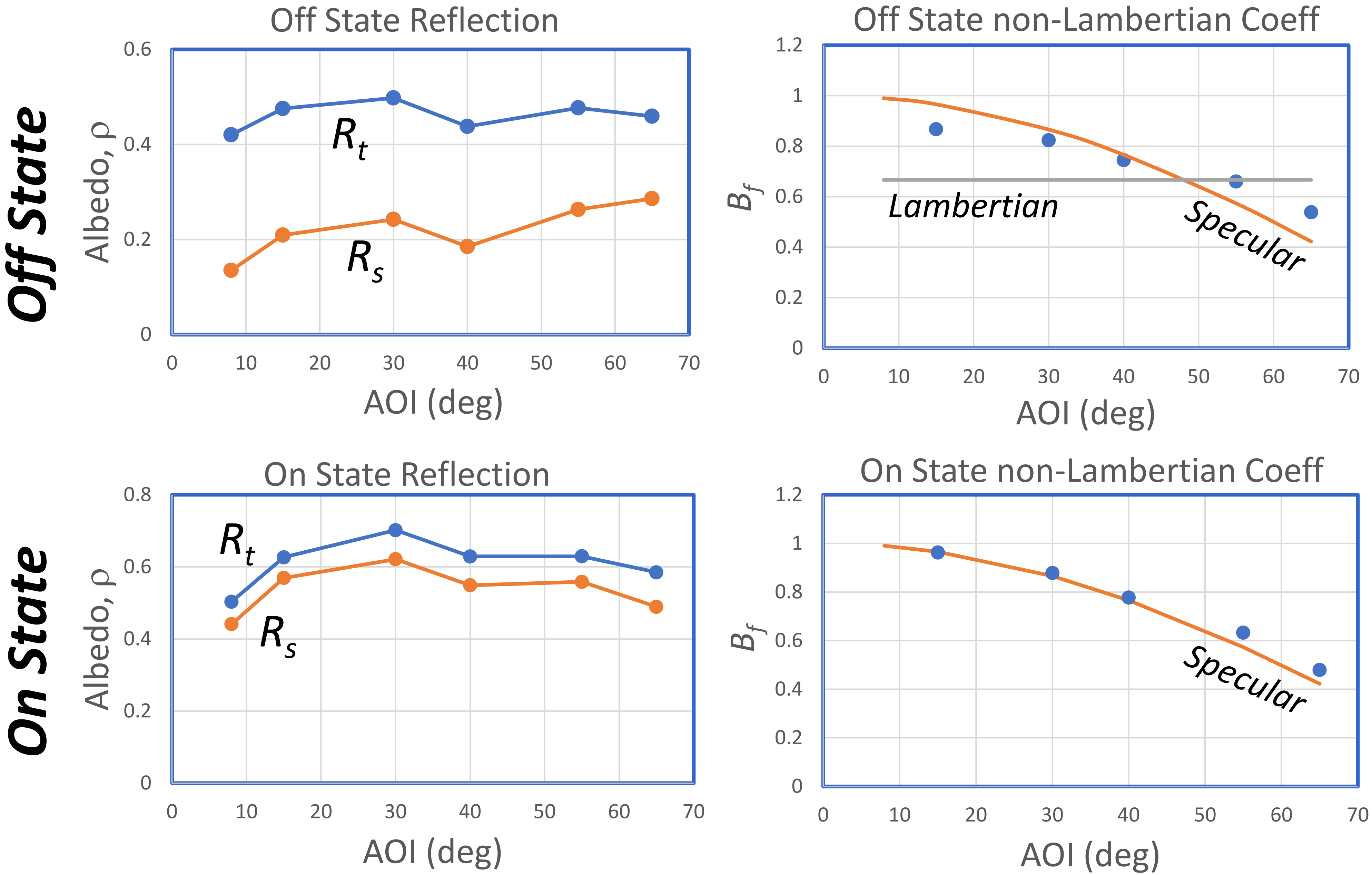


solid angle: $d\omega = \sin\theta\, d\theta\, d\varphi$

projected solid angle: $d\Omega = \cos\theta\, d\omega$

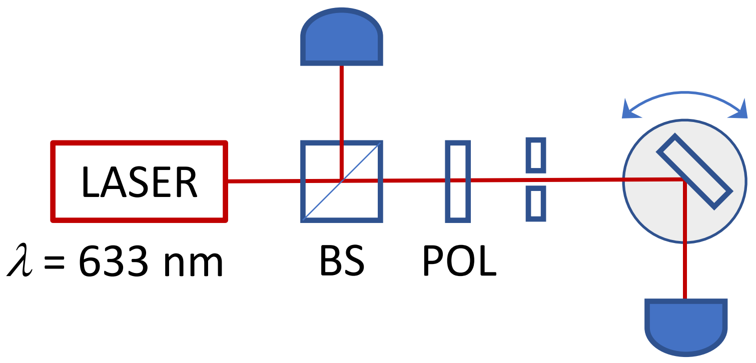


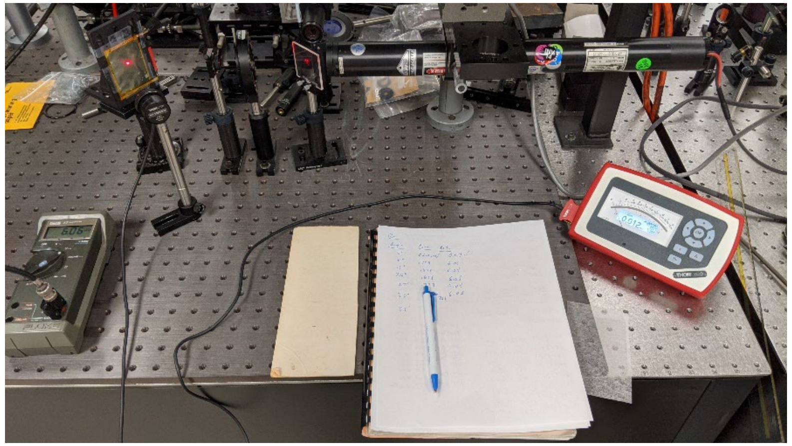
BRDF Results



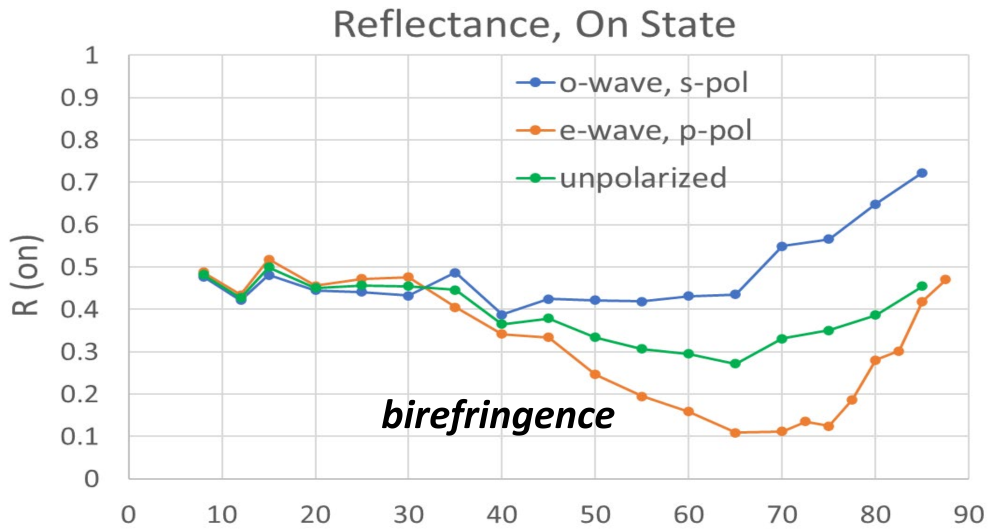
Birefringence Test

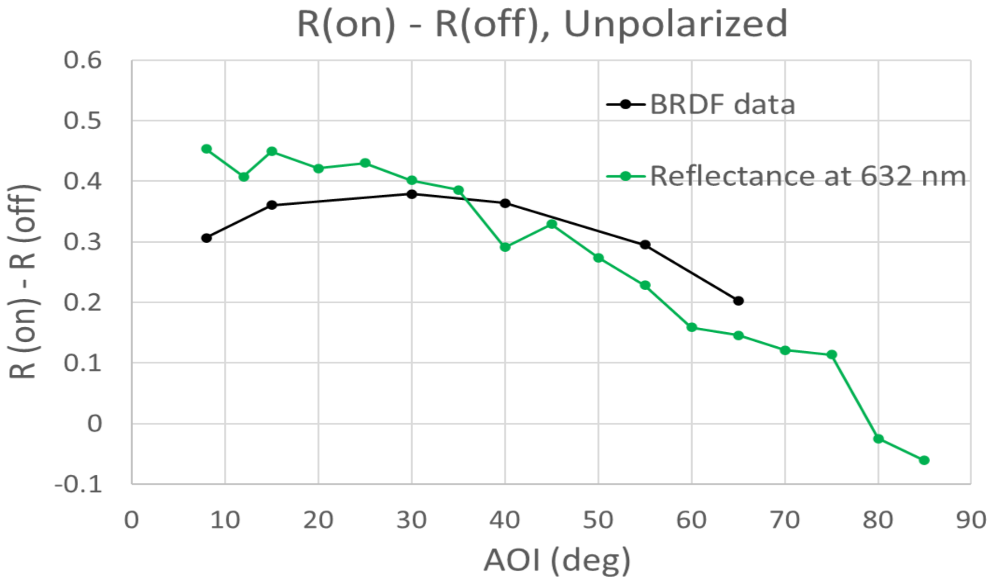
Polarized Specular Reflection Setup:



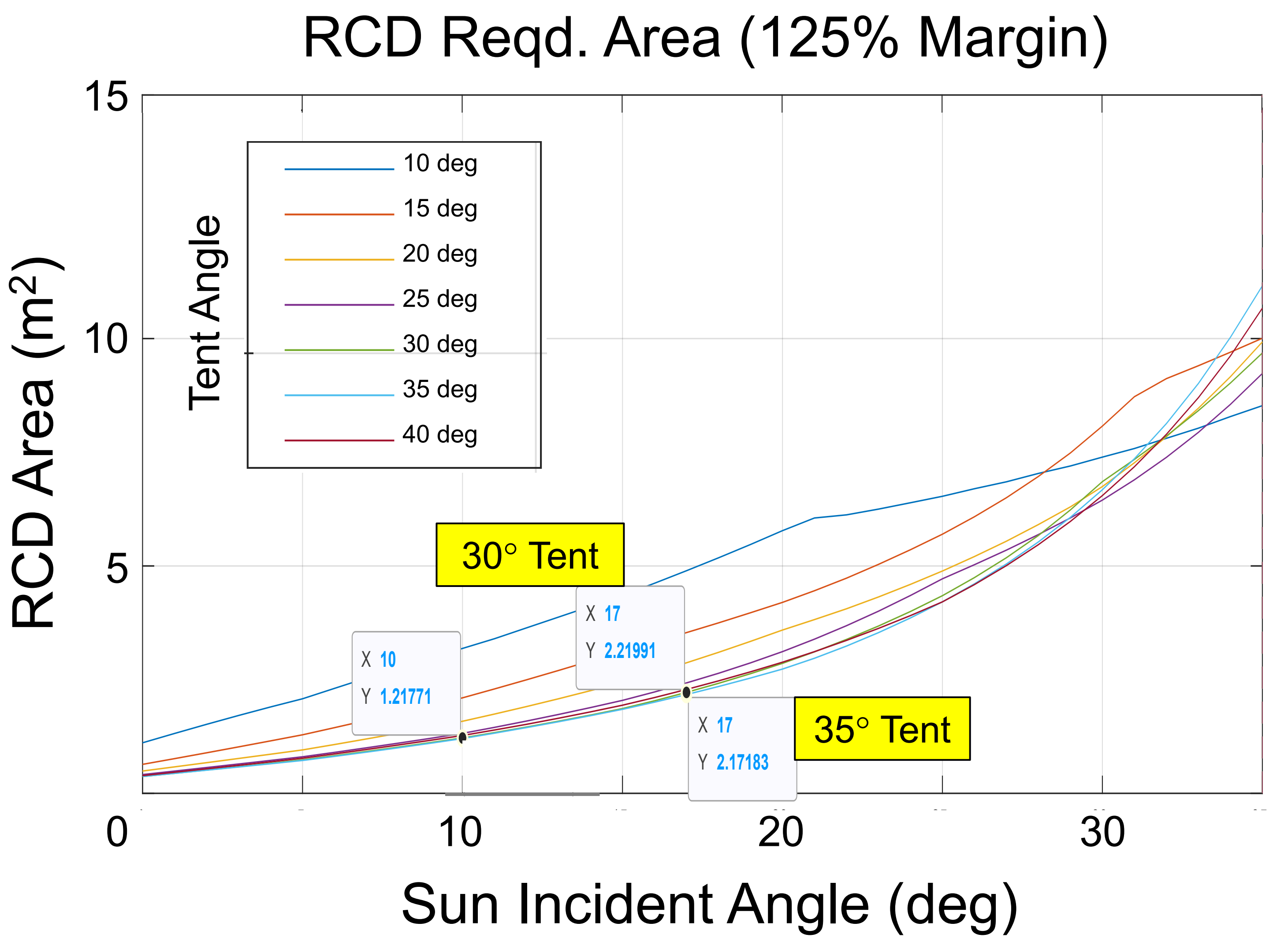


Measurements in AvMC Bowden Research Laboratory, Bldg. 7804





RCD Area Required (using coeffs from BRDF)



Conclusions

- First measurement of optical constants of CP1 sail material over solar spectrum
- Extraction of integrated RCD coefficients from fully hemispheric BRDF measurements. Same is needed for solar sail material.
- ITO absorption, Fresnel reflection, and birefringence are not showstoppers.
- RCD optical performance is more than sufficient for solar sail roll control (only ~0.1% of sail area needed)

Acknowledgment

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