Optical Surface Reflectivity Characterization in Water Cherenkov Detectors Methodologies and Industrial Applications

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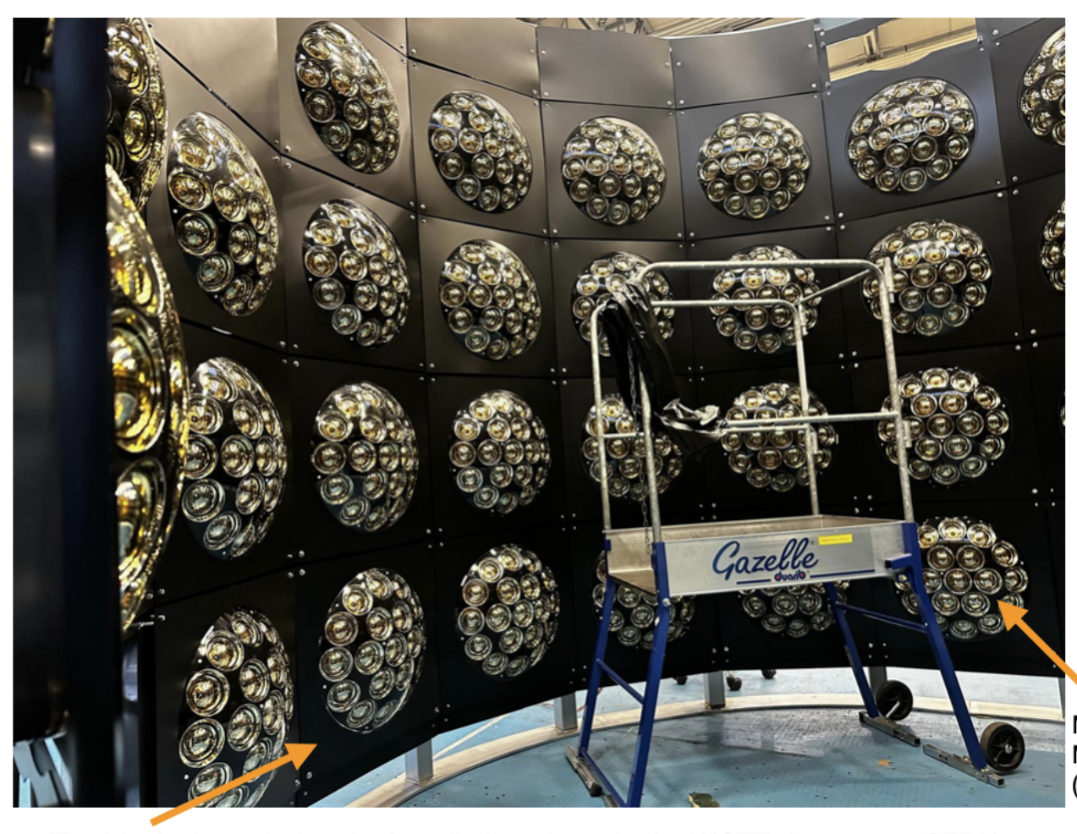
Abstract

Understanding the optical properties of various components in water Cherenkov (WC) neutrino experiments is essential for accurate detector characterization, which is critical for precise measurements. Of particular importance is the characterization of surface reflectivity within the Cherenkov volume. We present a methodology for surface reflectivity characterization using a goniometer setup, addressing the challenges associated with measurements in the air and water (or other optical media. Additionally, we discuss the broader implications of Bidirectional Reflectance Distribution Function (BRDF) measurements using a goniometer, including their industrial applications.

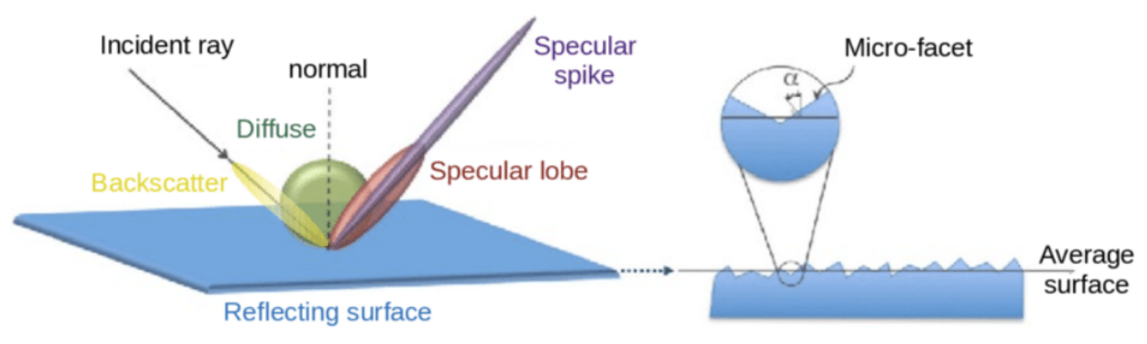
Motivation

The next generation of neutrino experiments geared towards precise neutrino measurements demands strong constraints on detector systematic errors. The 'inner black lining' or 'black sheet' of the Water Cherenkov Test Experiment (WCTE) detector should have an overall low total reflectivity. Further, the reflectivity should be ideally diffused without the presence of prominent specular components. This is important to absorb stray photons and minimize the overall background, ensuring that only the direct Cherenkov light is detected by the photomultiplier tubes (PMTs). Leading to a better signal-to-noise ratio thereby improving the precision of particle identification and energy reconstruction. With that goal, at the IBS, we performed detailed total reflectivity measurements using an integrating sphere & specular component investigation using a goniometer.



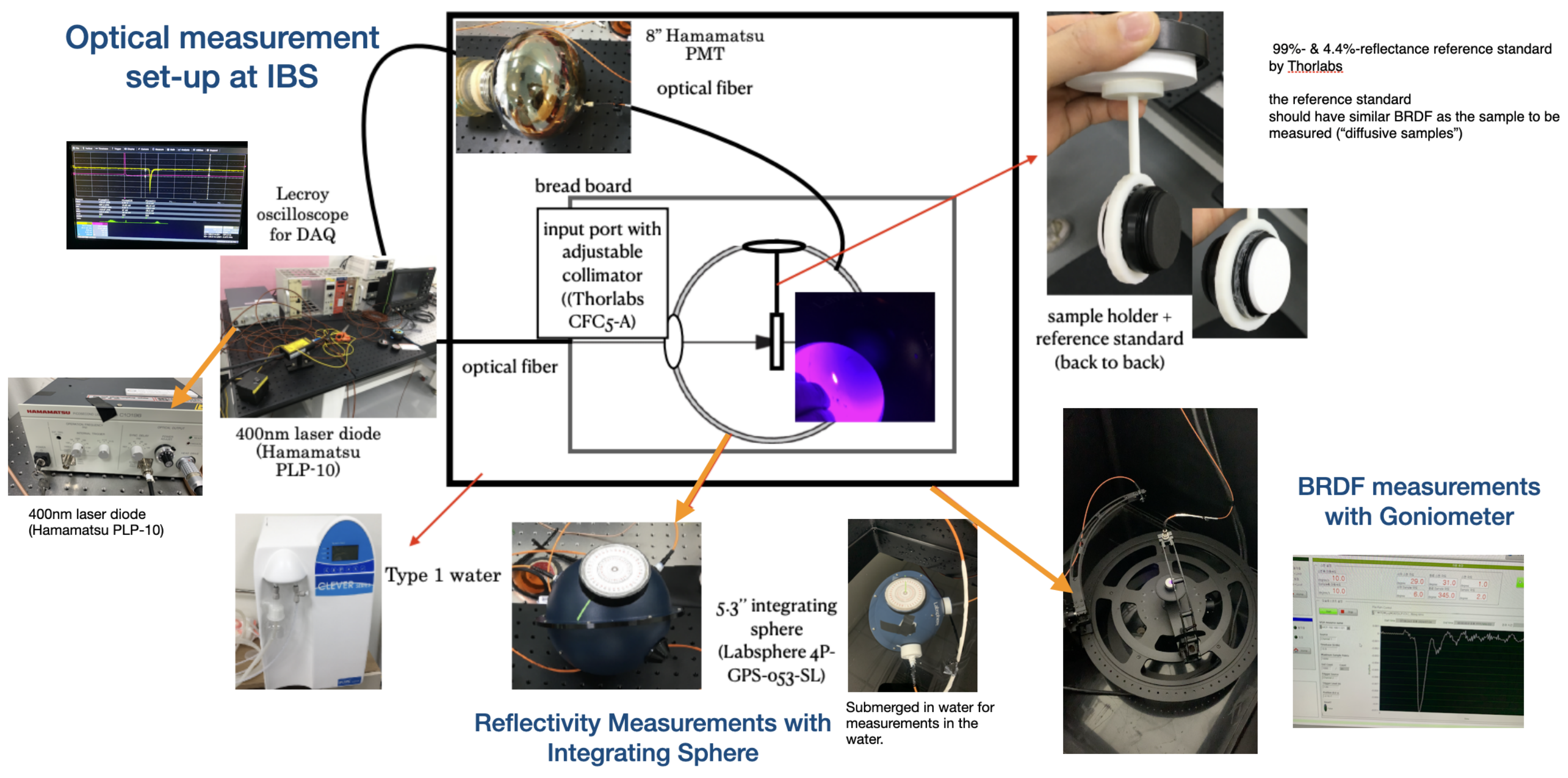
Multi-Photo Multiplier Tube (mPMT) module

The black sheet during the installation phase in the WCTE detector at CERN. We carried out a detailed study of the optical properties of the black sheet at IBS, Korea. Image Courtesy : WCTE collaboration.



Light reflection types available in Geant4, Specular spike (i.e., perfect mirror), specular lobe, and diffuse (Lambertian). A ground surface is composed of micro-facets where α is the angle between a micro-facet normal and the average surface normal. [Image source : Cuplov et al. DOI: 10.1117/1.JBO.19.2.026004]

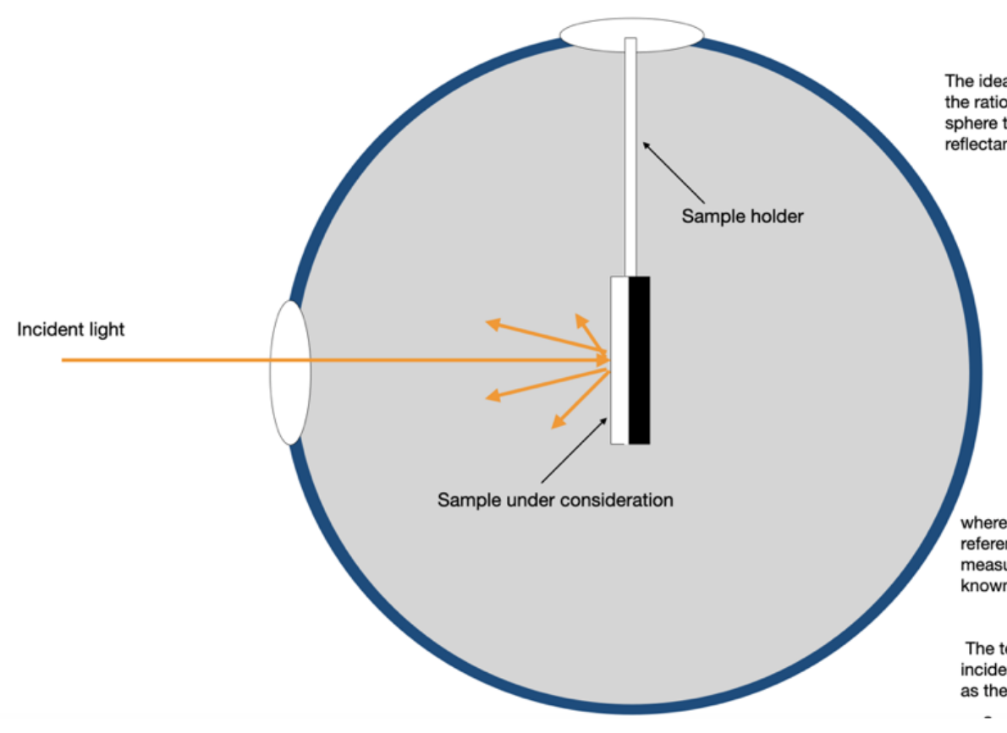
The methodology



99%- & 4.4%-reflectance reference standard by Thorlabs

the reference standard should have similar BRDF as the sample to be measured ("diffusive samples")

We use an integrating sphere as a primary tool to estimate the absolute reflectance, and a water-proof 2-dimensional goniometer for BRDF measurement.



The ideal measurement relationship is for the ratio of radiance produced inside the sphere to be equal to the ratio of the reflectance for each material.

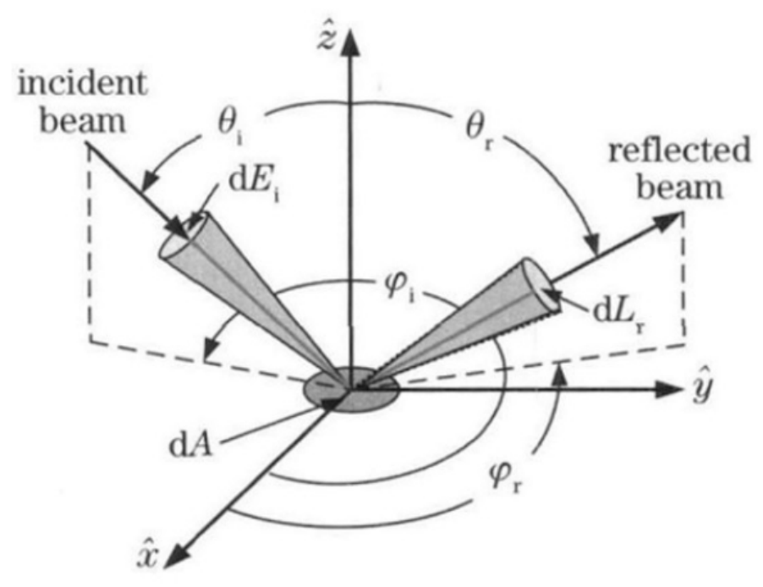
$$\frac{L_s}{L_r} = \frac{\rho_s}{\rho_r}$$

where; ρ_r : the reflectance of the reference material The sample measurement quantity, ρ_s is properly known as the reflectance factor.

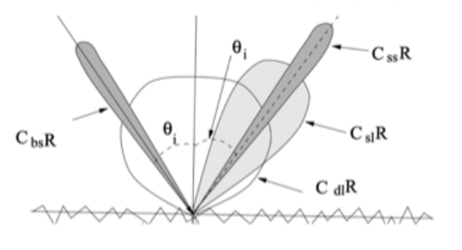
The term refers to the fact that the incident flux was not directly measured as the reference.

Source: Labsphere manual

For extracting the BRDF profile of the sample material and its implementation in the Geant4 simulation toolkit, we follow the prescription in Nokia et al., https://doi.org/10.1364/OE.19.004199



$$\mathrm{BRDF}(\theta_d, \phi_d, \theta_i, \phi_i) = \frac{L(\theta_d, \phi_d)}{E_0(\theta_i, \phi_i)} \quad [\mathrm{sr}^{-1}]$$



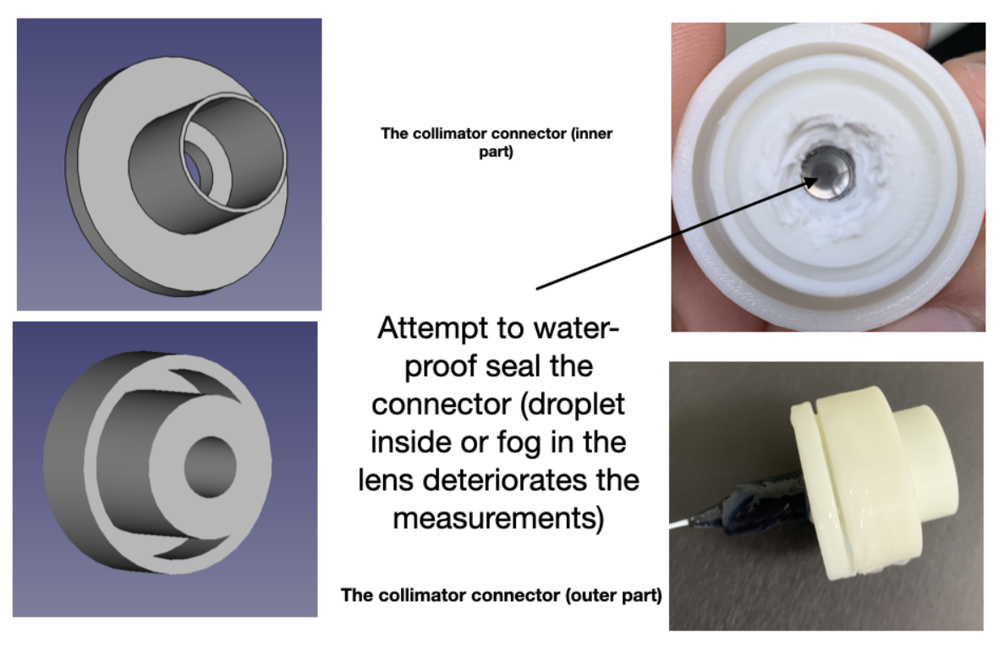
$$\begin{aligned} J_U(\theta_i, \theta_r, \phi_r) \approx\ & R(\theta_r', n_1, n_2)[C_{sl}\, g(\alpha_r; 0, \sigma_\alpha) \\ & + C_{ss}\delta(\theta_i - \theta_r)\delta(\phi_r) + C_{bs}\delta(\theta_i + \theta_r)\delta(\phi_r) \\ & + C_{dl} cos(\theta_r)] \\ & + T(\theta_t', n_1, n_2) g(\alpha_t; 0, \sigma_\alpha), \end{aligned}$$

$$C_{sl} + C_{ss} + C_{bs} + C_{dl} = 1$$

Source: Geant4 Manual, and references therein

Challeges & Mitigation

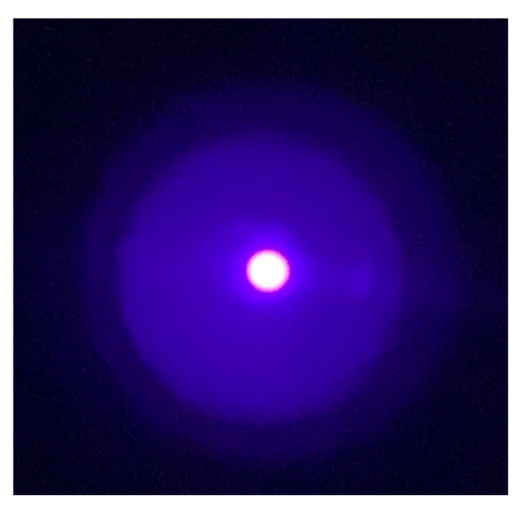
Major challenge has been designing a watertight optical coupling without losing collimation substantially, several iterations tried.



The collimator connector (inner part)

Attempt to water-proof seal the connector (droplet inside or fog in the lens deteriorates the measurements)

The collimator connector (outer part)

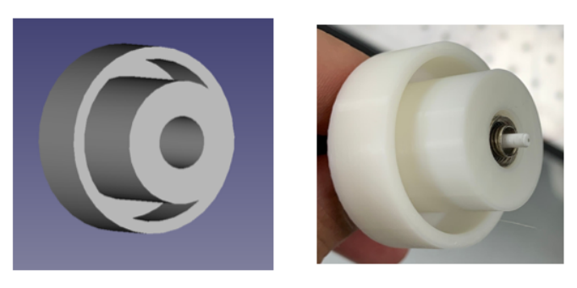


reducing the 'halo' of the incident photon beam by baffles

several combination of Thorlab collimators and connectors tried.

Collimator-1 : [CFC11P-A, f= 11 mm, FC/PC]
Collimator-2: [CFC8-A, f= 7.5 mm, FC/PC]
Collimator-3: [CFC5-A, f=4.6 mm, FC/PC]

The collimator connector (inner and outer parts connected together). The collimator is inside and sealant has been applied at appropriate points.

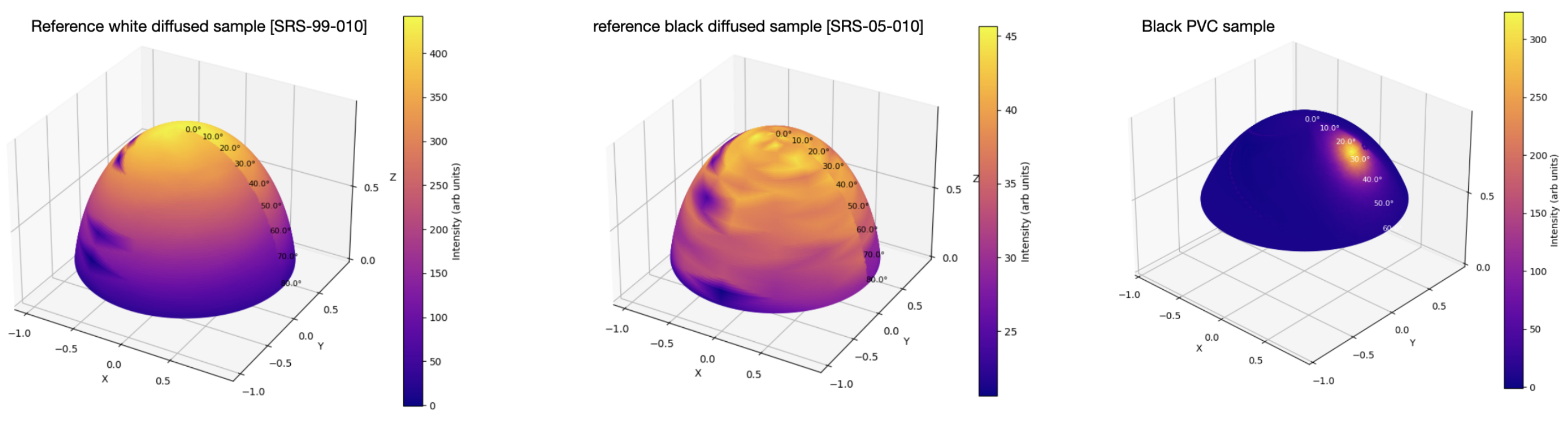


The connector holding the optical fibre that carries the output from the integrating sphere to the 8 inch PMT was 3D printed. It is not waterproof, as that is not the requirement for this component

Different kind of sealants tried to waterproof the system

Results & Outlook

The total reflectivity of a 'comparison mode' is simply the ratio of the mean of pulse area for the sample (black) and the reference standard (white) The reflectance of the black reference standard shows 20 % higher value than the known value (4.4%), probably due to remaining halo component. The overall reflectivity for PVC shows around 5 % in air and lesser in water The reflectivity values in the water are consistently lower than the corresponding values in the air. The results shown here are preliminary and the measurements need to be repeated several times to quantify the statistical and the systematic error.



3D surface intensity maps showing the measurements using a goniometer (in the air) for a standard reference white, reference black, and our PVC sample under consideration. The incident light is at 30° for all the cases, data taking spanned over θ=[0,80], and φ=[0,360] (scanning with 5° x 30° grid size takes around 11 hours, each bin represents a mean of 1000 pulses). For easy visualization, the data points have been interpolated to generate this 3D map (hence the slight jumps at the azimuthal angle = 0). We can visually see the diffused angular reflection for the reference samples, as expected. The specular reflection in the case of the PVC sample is visible. The total (summed) output intensity in each case is proportional to their reflectivity as measured independently by an integrating sphere.

Industrial Applications

Applications of Extracted BRDF include

- Surface Characterization : analyzing material reflectance properties for coatings, optics, and photonic.
- Rendering and Visualization: BRDF models for realistic rendering in computer graphics.
- Optical Design: Input for ray-tracing simulations in optical systems.

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