(Complex) Fenestration Modeling Tools: Radiance

2017 Building Technologies Office Peer Review

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Eleanor Lee, eslee@lbl.gov
Lawrence Berkeley National Laboratory

Project Summary

Timeline:

Start date: 10/1/2015

Planned end date: 9/30/2018

Key Milestones

1. Validated simulation models for complex fenestration systems, 9/30/17
2. Validated tools and standards for deriving bidirectional scattering distribution function (BSDF) data, 9/30/18
3. Radiance Releases: 4/30/17, 4/30/18

Budget:

Total Project $ to Date:

- DOE: $525K ($350K in last 12 months)
- Cost Share: $150K

Total Project $:

- DOE: $1050K
- Cost Share: $300K
  (California Energy Commission)

Key Partners:

Attachments Energy Rating Council (**AERC**), National Fenestration Rating Council (**NFRC**), European Solar-Shading Organization, (**ES-SO**)	**Bartenbach** Lichtlabor GmbH, Lucerne University of Applied Sciences and Arts (**HSLU**), École Polytechnique Fédérale de Lausanne (**EPFL**)
Pennsylvania State University (**PSU**), National Renewable Energy Laboratory (**NREL**), Massachusetts Inst. of Technology (**MIT**), Loughborough Univ. (**LU**)	International Energy Agency (**IEA**) Solar Heating and Cooling Programme (**SHC**), Task 50+, Fraunhofer-Institut für Bauphysik IBP, ISE and other participating countries

Project Outcome:

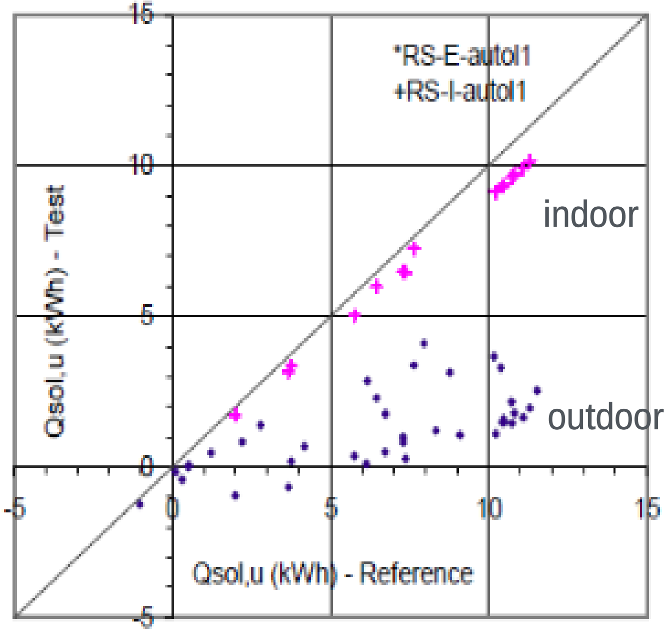
1) Develop validated simulation models and procedures for characterizing solar-optical/ daylighting properties and energy impacts of optically-complex fenestration systems.

2) Implement validated simulation models in software tools for use in product development, building design, and code compliance.

Motivation

Significant energy-savings potential but lack of computationally-efficient tools to evaluate optically-complex fenestration systems (CFS)

Example results from field test
Between 6 types of exterior shades:
78-94% reduction in window heat gains
-**25% to 36%** reduction in lighting energy use
compared to low-e glazing with indoor shade



78-94%
reduction in window heat gains with outdoor shading

E.S. Lee et al., High Performance Building Façade Solutions, Final project report, California Energy Commission, CEC 500-06-041 (2009), Table 6.

Purpose and Objectives

Problem Statement:

- Optically-complex fenestration systems (CFS) have the technical potential to save nearly 1.8 Quads[1] annually or about $74B in HVAC and lighting energy use in 2030.
- Shading and daylighting “attachments” shape energy and comfort performance in perimeter zones: the most highly-valued real estate in the entire building.
- With no standard mechanisms for assessing performance, energy and cost savings cannot be fully realized due to lack of guidance for new product development and selection. → Objective: Develop standard models for assessing CFS.

Target Market and Audience:

- Market: All existing and new windows for commercial and most residential buildings.
- Audience: Window covering manufacturers, building owners, architects and engineers, code officials, utilities, state and federal policy decisionmakers.

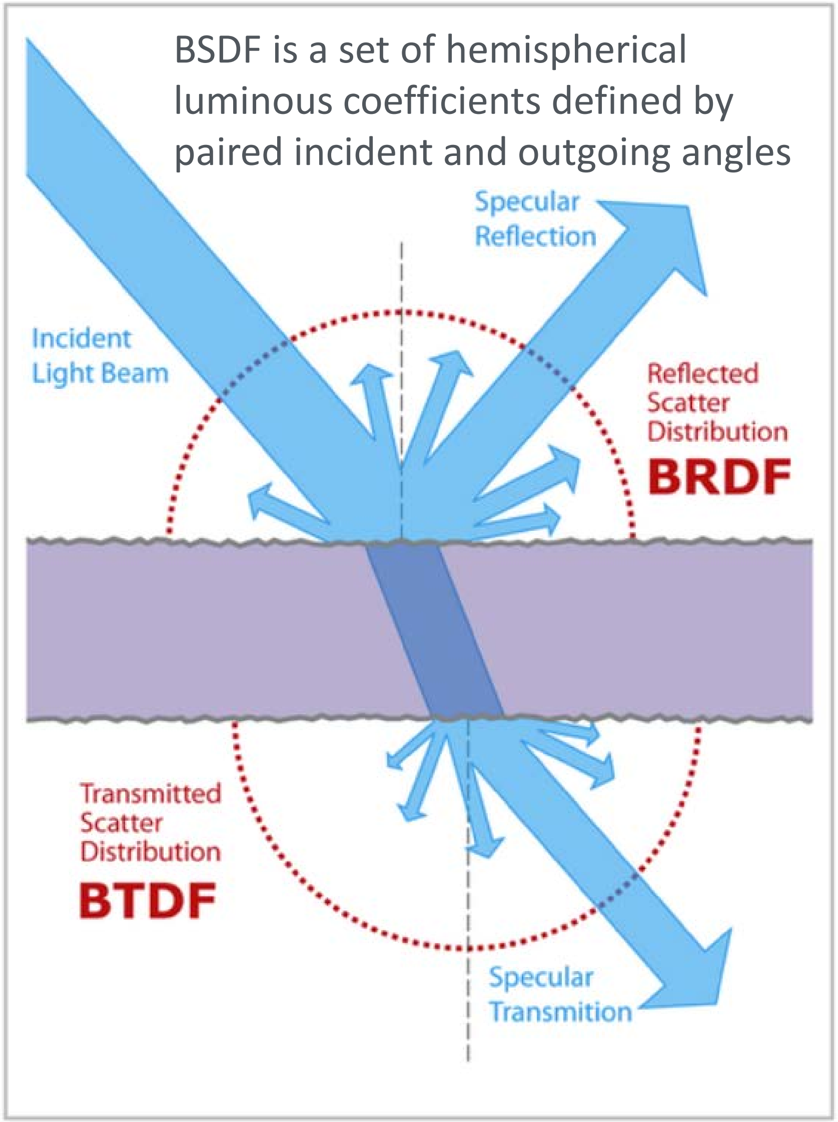
Impact of Project:

- Validated algorithms and product databases developed under this project provide the necessary credibility for simulation tools that will be used for emerging technology R&D, design and engineering, and rating and certification programs.
- These tools provide impetus for innovation since products can be compared on an equitable basis. Codes and standards can advocate use of innovative products that meet or exceed specified rating requirements.

[1] Arasteh et al., Zero Energy Windows, ACEEE, 2006.

Approach using BSDFs

Bidirectional scattering distribution functions

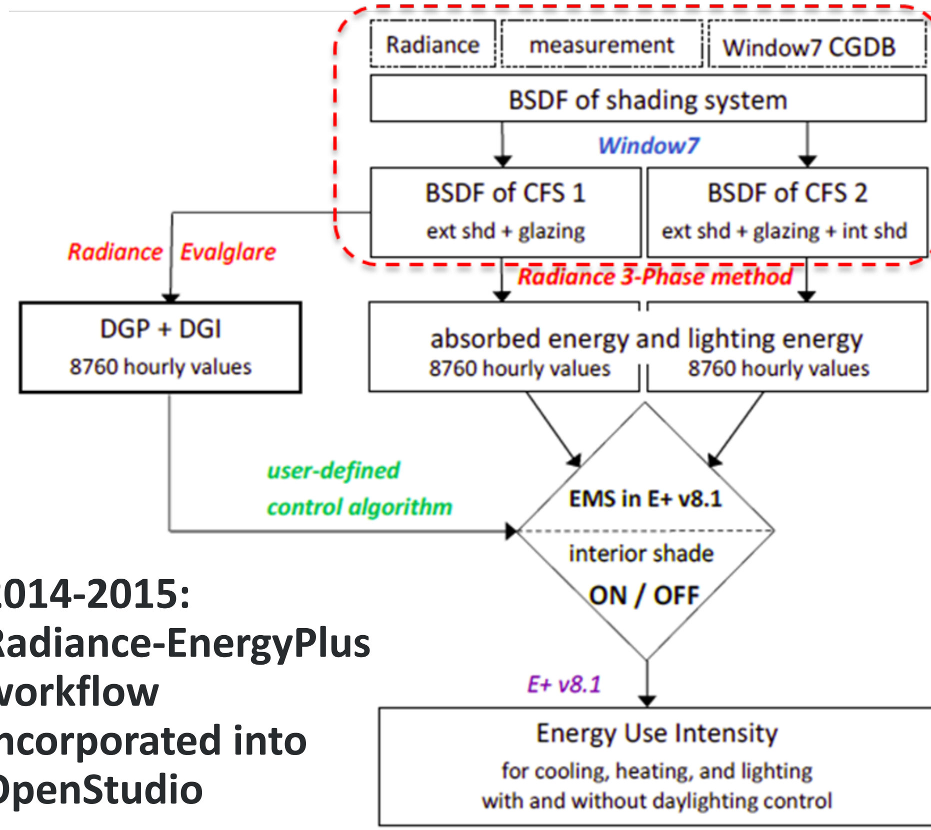


1965: BSDF defined[1]

1993: Klems at LBNL defines matrix approach for computing window heat gains

1995: Klems constructs first scanning goniophotometer

2011-2014: 3-phase models incorporated into WINDOW 7 and EnergyPlus 8.1; enables solar and lighting inputs from Radiance into EnergyPlus[2]



2014-2015: Radiance-EnergyPlus workflow incorporated into OpenStudio

[1] Nicodemus FE. 1965. Directional Reflectance and Emissivity of an Opaque Surface. Appl Opt 4. 767-773.

[2] E.S. Lee et al., High Performance Building Façade Solutions – Phase II, Final project report, California Energy Commission, CEC 500-2015-033 (2014).

Approach

Approach:

- Develop, test, debug, and validate simulation models that enable accurate and rapid evaluation of annual lighting and HVAC energy use, visual and thermal comfort, and indoor environmental quality (IEQ).
- Develop models and standardized measurement protocols for characterizing bidirectional scattering distribution function (BSDF) or angle-dependent solar-optical properties of complex fenestration systems.
- Incorporate open source models in software tools which can then be used for emerging technology R&D, rating/ certification programs, design, and codes and standards.

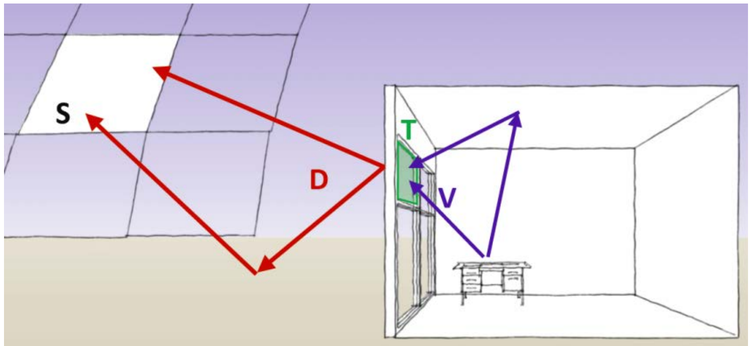
Key Issues:

- Address errors that can occur due to imprecise representation of the **direct solar component** given averaging over large solid angles using a matrix algebraic approach
- Generate accurate, **high-resolution BSDF input data** needed for product database and CFS modeling tools at minimal cost

Distinctive Characteristics:

- World-class laboratory and testbed facilities for product characterization and validation of simulation algorithms
- Active industry engagement and participation with AERC, IEA-SHG Annex 50+, third-party developers, ASHRAE 90.1-2013, Title-24, LEED

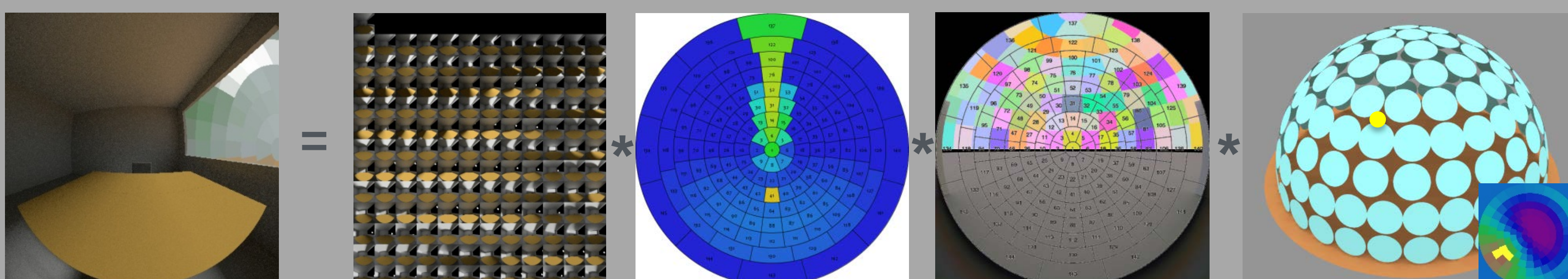
The original 3-phase matrix approach was designed to predict solar heat gains of complex fenestration systems (CFS)[1]



Three-phase method

$$I_{3ph} = VTDS$$

145x145 Klems basis/ matrix resolution

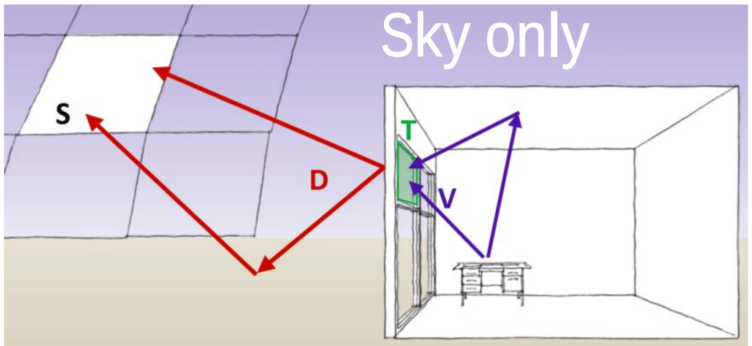


result | **V = view matrix** | **T = BSDF** | **D = daylight matrix** | **S = sky distribution**

[1] Klems, Joseph H.. "A New Method for Predicting the Solar Heat Gain of Complex Fenestration Systems I. Overview and Derivation of the Matrix Layer Calculation." ASHRAE Transactions 100, Part 1 (1993).

Evaluations requiring accurate modeling of the spatial distribution of direct sunlight should use the 5-phase method

(e.g., daylight, discomfort glare, thermal comfort, low-energy cooling strategies, etc.)



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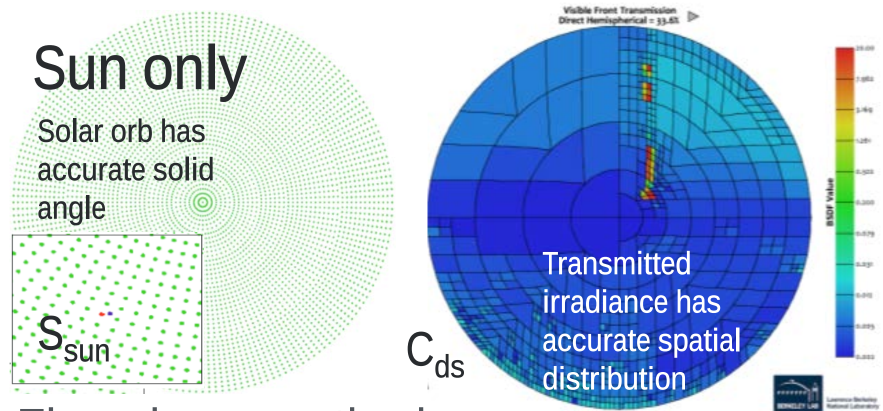


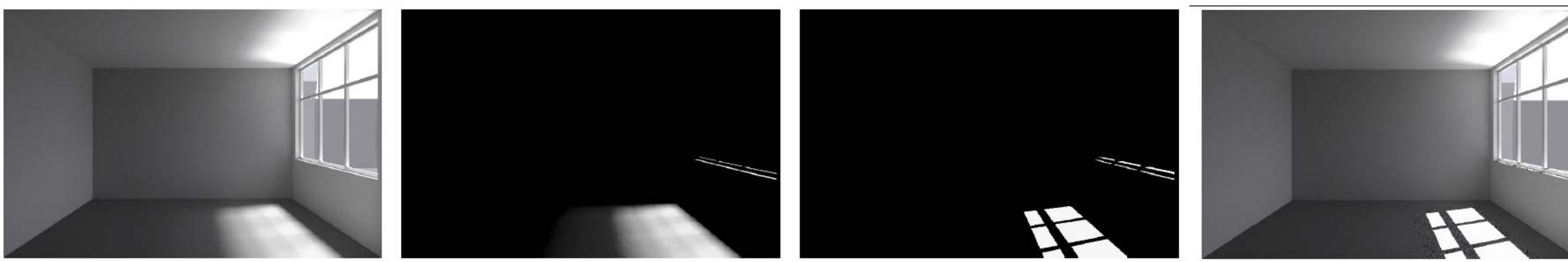
Three-phase method

$$I_{3ph} = VTDS$$

Five-phase method

$$I_{5ph} = VTDS - V_dTD_dS_{ds} + C_{ds}S_{sun}$$

145xN resolution



E_{3ph} $- E_{ds\text{-}3ph}$ $+ E_{ds}$ $= E_{5p}$

3-phase method:

Direct sun contribution is averaged over large solid angle

5-phase method:

Direct sun contribution is properly depicted

McNeil, A., 2013, The Five-Phase Method for Simulating Complex Fenestration with Radiance, LBNL Radiance tutorial.

Validation using full-scale field measured data

Validation of 5-phase method

- FLEXLAB full-scale field study over 6 months, 5 systems
- Inputs: Goniophotometric measurements of sample systems, high-dynamic range (HDR) sky luminance
  Outputs: daylight illuminance, field-of-view luminance

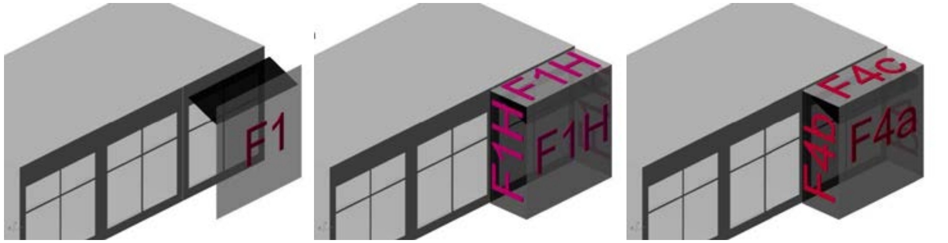
Validation of 6-phase method for non-coplanar (NCP) systems

- Advanced Windows Testbed field study over 6 months with drop-arm awning
- FLEXLAB test of tubular daylight device
- Outputs: solar irradiance, illuminance, field-of-view luminance

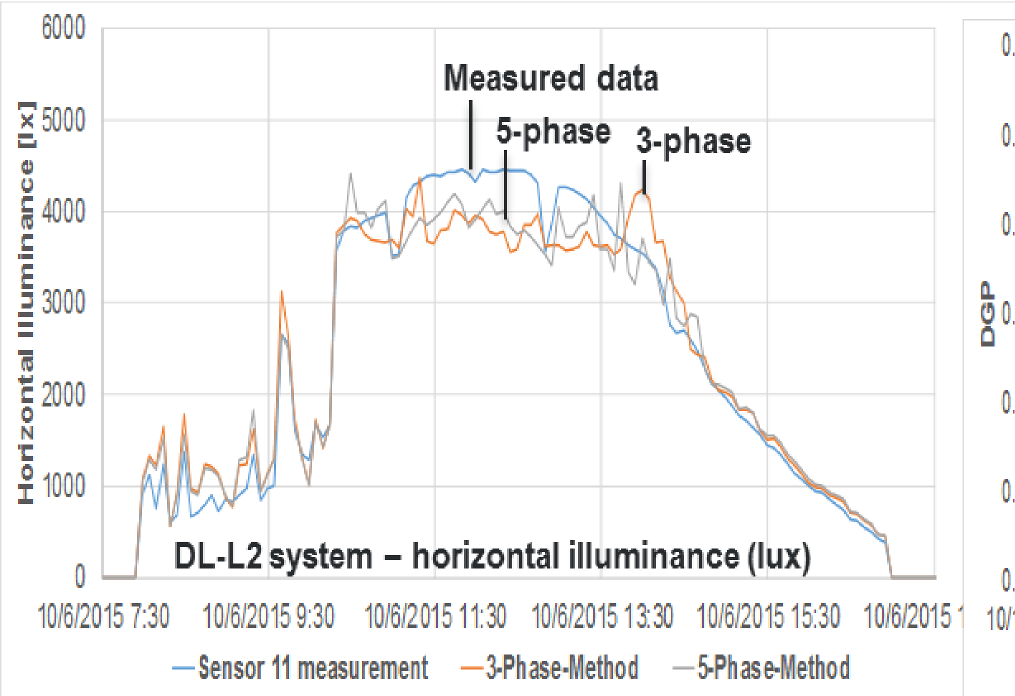
Synergistic: Pacific Gas & Electric, California Energy Commission EPIC program

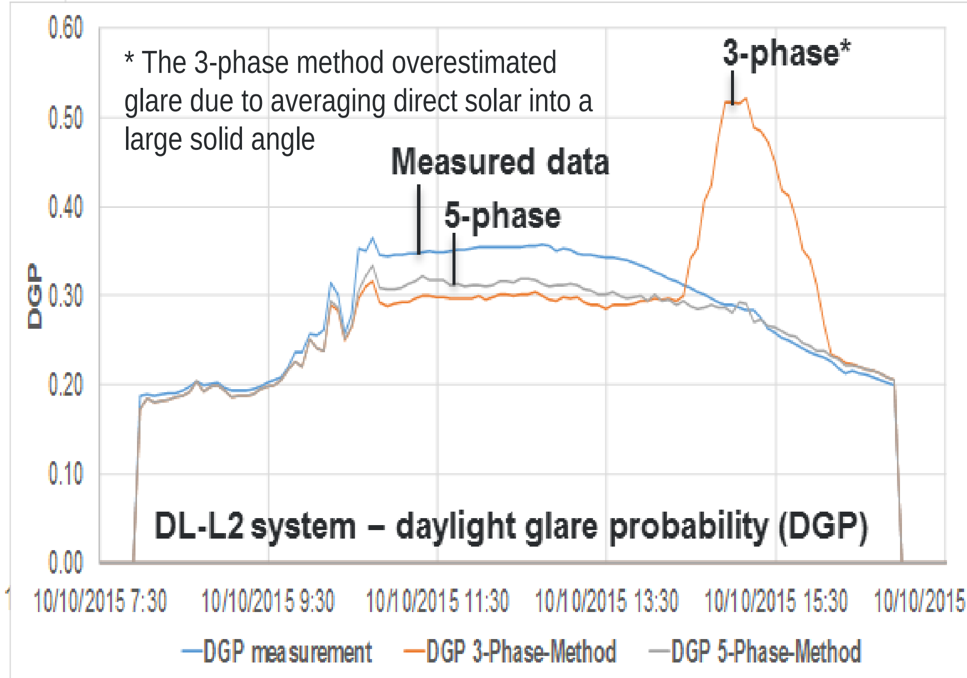
In-kind: 3M, Serralux, Lucent Optics, Draper, Embedia, MechoShade, GlenRaven, Smart Louver, Enlighted, Terrestrial Light

Non-coplanar models map incident solar flux to a fourth "F" matrix at the window plane

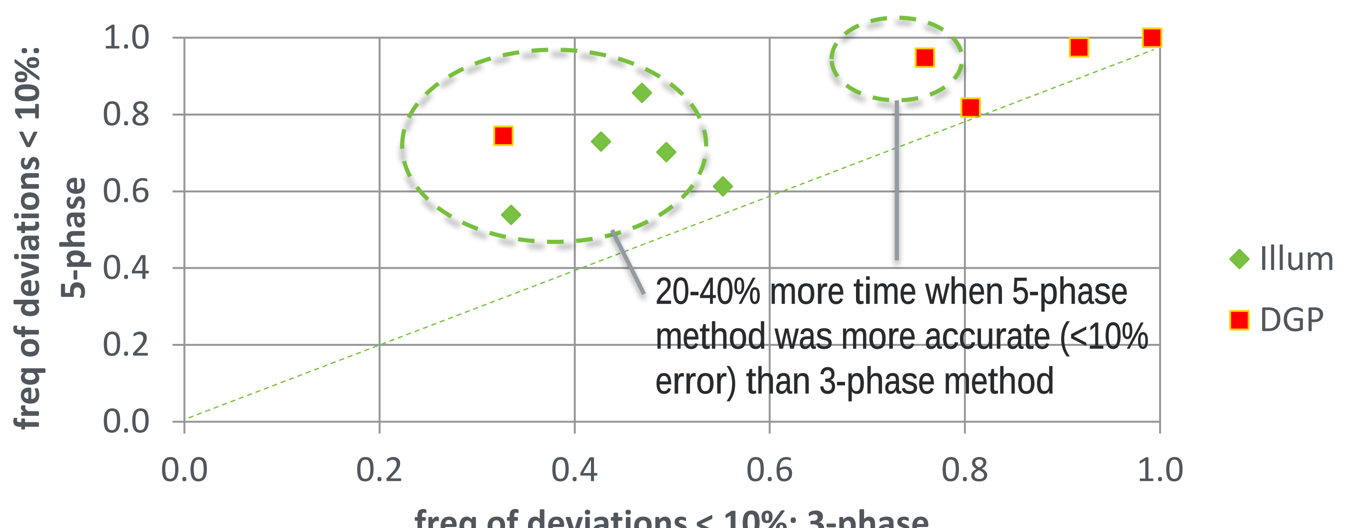


Validation (results to date): 5-phase method yields significantly greater accuracy than the 3-phase method



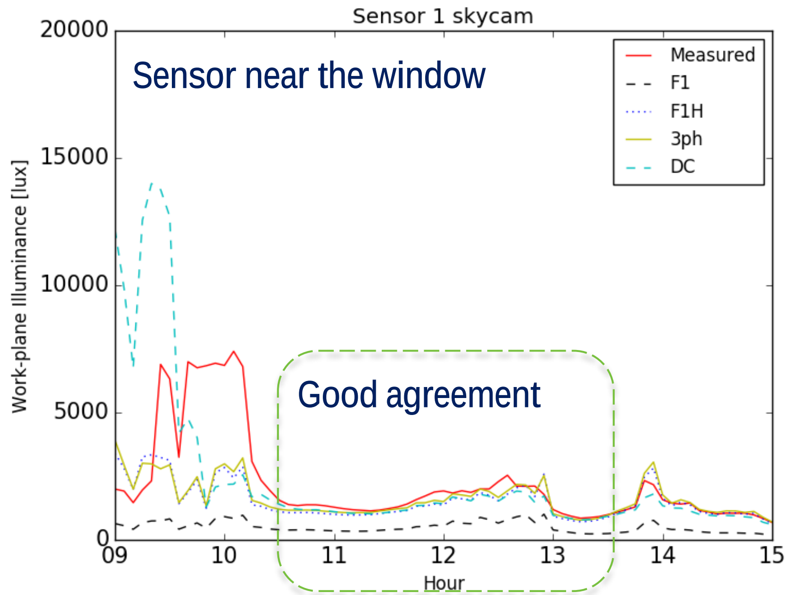


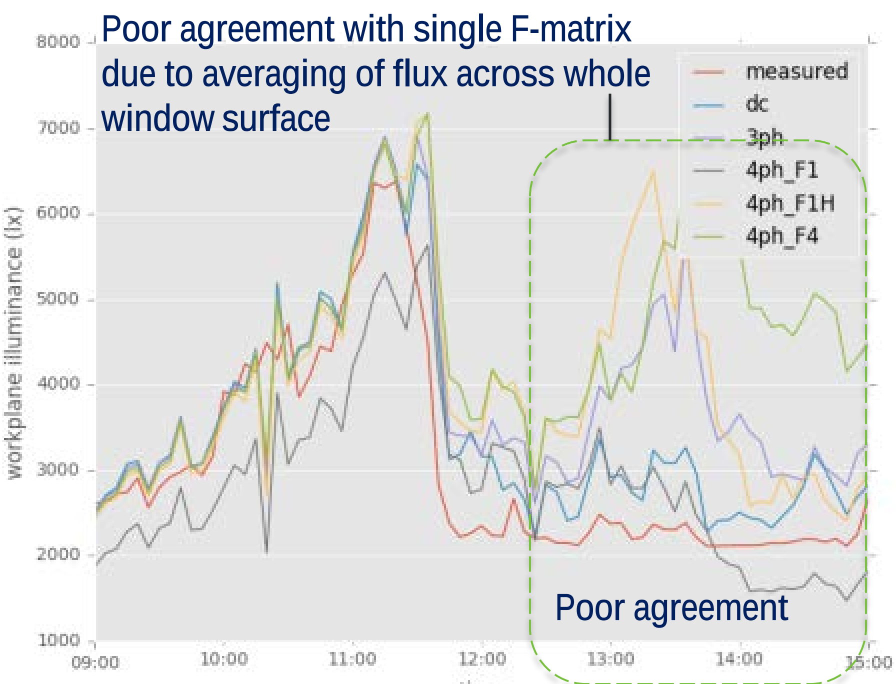
Frequency (% of measured period) of deviations in horizontal illuminance and DGP between simulation results and measurements (Δ%) for equinox period, various CFS technologies

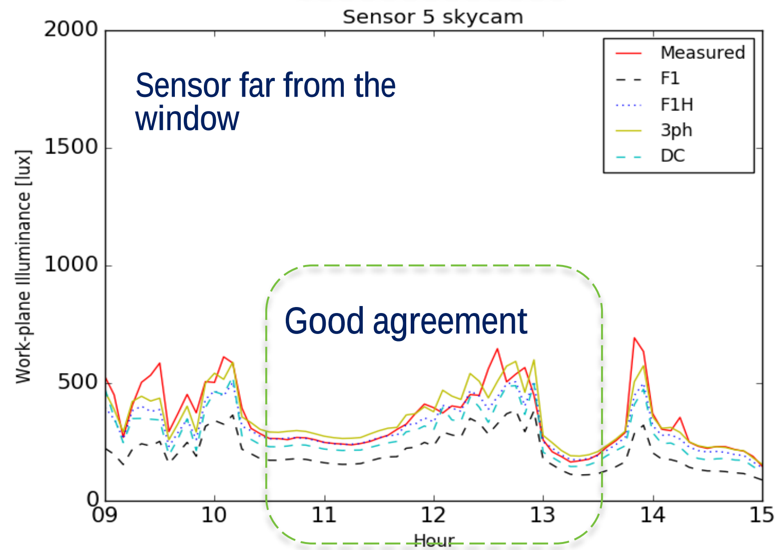


Validation (to date): Non-coplanar model may require subdivision of the window if the direct solar contribution is not separately computed

F-matrices for horizontally subdivided window yields good agreement between simulated and measured data for sensors both near and far from the window



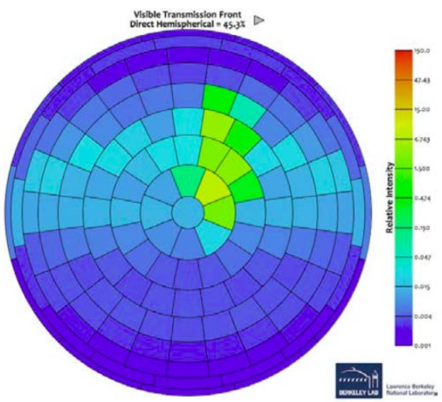




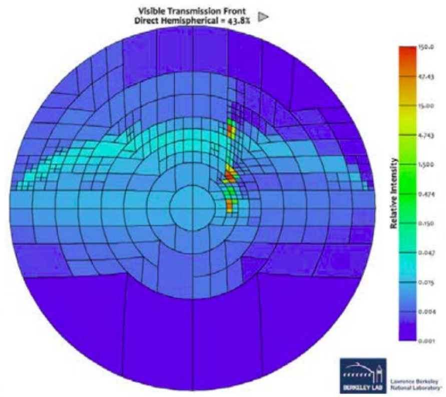
Conclusion: Use 5-phase method to improve accuracy

BSDF Input data

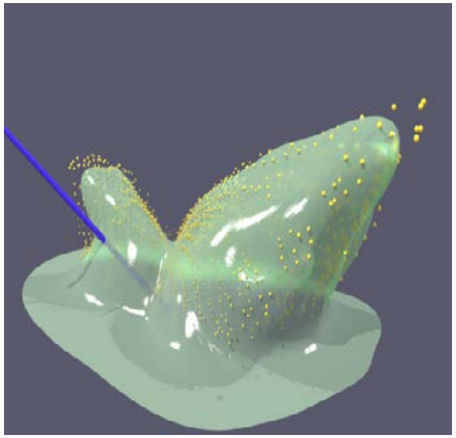
Significant differences between 3- and 5-phase methods



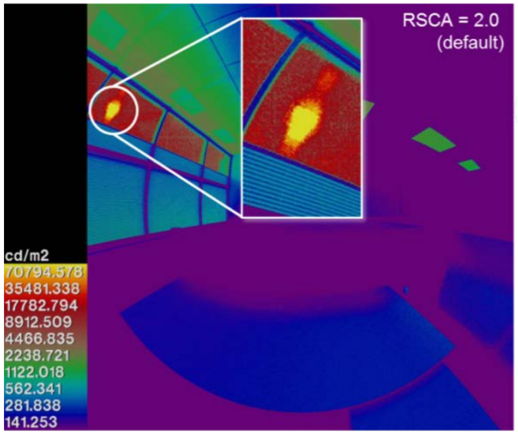
3-phase input data
Fixed resolution
Large solid angles



5-phase input data
Variable resolution
Solid angle size varies



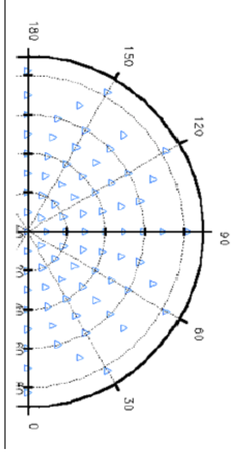
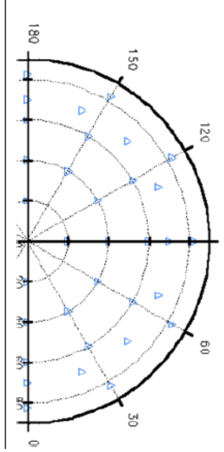
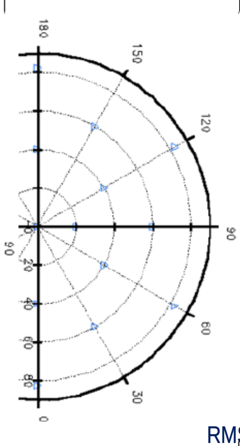
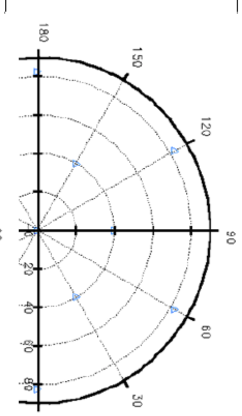
Interpolation of measured scattering values for a single incident direction, shown as blue line. Yellow dots are measurements, and green surface is interpolation using radial basis functions. Earth mover's distance models are used to migrate data between incident directions.



Validation with FLEXLAB data. Smoothing function affects shape of Gaussian lobe, which in turn affects intensity of transmitted solar irradiance/ illuminance.

Characterization: If we take less measurements, will BSDF data still be sufficiently accurate?

Validation outcome:
Interpolation algorithms yield low RMSE and enable reduced measurement requirements (i.e., number of incident angles)

#Angles	88	32	13	7
RMS Error (<75°)	0.114	0.117	0.142	0.744
Incident Directions				

13 instead of 88!

RMSE with peak value of 37

Standards for generating BSDF data

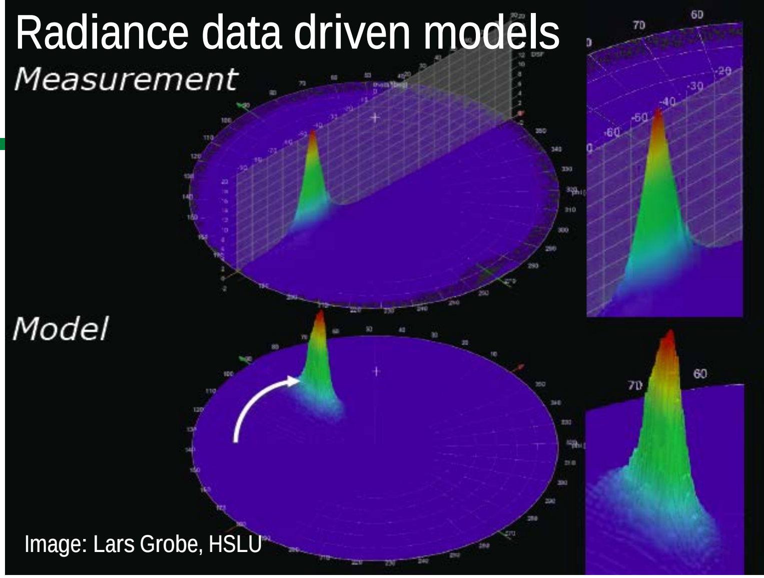
Constraints: Measurement cost, rapid generation of BSDF datasets, 1000s of products (e.g., roller shade fabrics)

145x145 Klems basis (3-phase method):

- Example: Draft AERC protocol for fabric shade: <u>Single</u> spectrophotometer measurement at normal incidence, angle dependent values generated from models assuming isotropic properties

Variable resolution, tensor tree basis (5-phase):

- Investigate use of synthetic models with limited empirical data; validate with detailed goniophotometric measurements
- Collaborate under IEA SHG 50+ to develop and standardize methods for measuring and characterizing high-resolution BSDF properties



Radiance open source models are incorporated into many software tools: All use the 3 phase method*, 5-phase method not yet adopted

* or a variant of the 3-phase method

3DStudioMax	EvalDRC (HSLU)
DALEC	Groundhog
DAYSIM	IDA ICE
DAYSIMps	IES-VE
DIVA for Rhino	LightStanza
Ecotect	Sefaira
EDSL TAS	SPOT

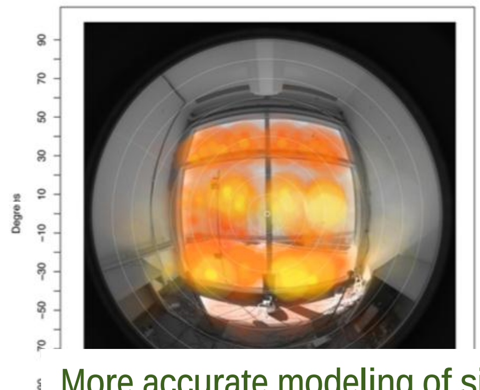
Open Source

WINDOW
EnergyPlus
OpenStudio
Honeybee
Modelica Bldgs Library

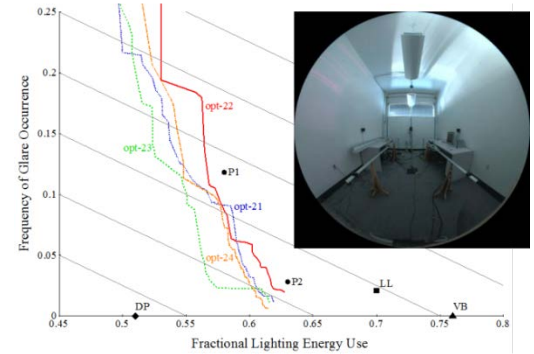
Honeybee-Ladybug: 66,700 downloads as of February 2017

Provide guidance on work flow to 3rd-party developers

Case study applications

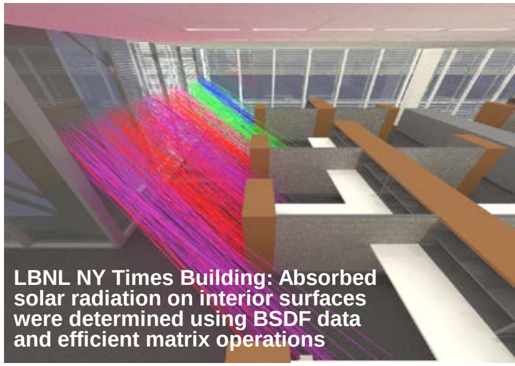


More accurate modeling of size and intensity of glare sources



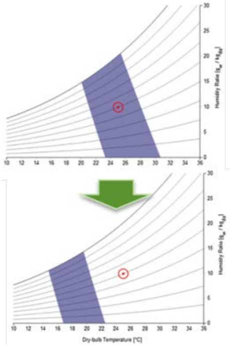
LBNL particle swarm optimization (100,000 designs) for new product R&D (3M, Dow Chemical)

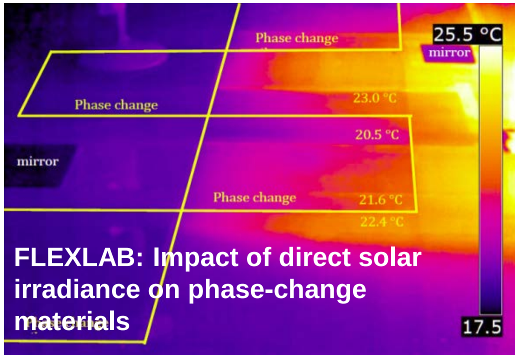
Impact of direct solar irradiance on thermal comfort in Genentech building



LBNL NY Times Building: Absorbed solar radiation on interior surfaces were determined using BSDF data and efficient matrix operations

Thermal comfort: Incident solar radiation from window on >1000 body parts using BSDFs in UCB's SoloCalc





FLEXLAB: Impact of direct solar irradiance on phase-change materials

Progress and Accomplishments

Accomplishments:
- Validated Radiance models (4-, 5-, and 6-phase) using field monitored data from FLEXLAB and Advanced Windows Testbed
- Demonstrated superior accuracy of new models over 3-phase approach
- Significant speed-up of parametric simulations for rapid prototyping of emerging technologies
- Demonstrated need for high-resolution BSDF input data

Market Impact:
- Significant increase in use of Radiance open source software world wide: from about 500 downloads 6 years ago (for point-in-time calculations) to **70,000+** downloads to date (as of 2/2017)

Lessons Learned:
- Automating workflows will be essential for adoption of new models by third-party software developers
- International coordination needed to achieve widespread adoption of BSDF characterization procedures and standards

Project Integration and Collaboration

Project Integration

- AERC – initiated development of attachment rating and certification program for commercial buildings
- Codes/ standards – CA Title-24 2019 CASE energy-efficiency standards advocating use of innovative fenestration systems and attachments
- Industry – rapid prototyping of new technologies; architectural use cases

Partners, Subcontractors, and Collaborators:

- Industry associations: AERC, PAMA, ES-SO
- BSDF standards: IEA-SHC Task 50+
- Open source developers: Anyhere Software, PSU, NREL

Communications:

- Radiance workshops, IBPSA 1997 conference, CIBSE ASHRAE 2017 symposium, IEA-SHC 2016 meetings
- AERC technical committee meetings
- Open source community

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Next Steps and Future Plans

Next Steps: Tools for evaluating annual performance

- Complete validation of models: identify key sources of error, modify/ improve algorithms
- Support incorporation of open source models in software tools
- Impact: Credible, validated simulation tools for use in emerging technology R&D, rating/ certification programs, design, and codes and standards

Future Plans: Product Database

- Develop models and standardized measurement protocols for characterizing CFS products with **high-resolution** BSDFs
- Develop certified product databases that enable comparison of products on an equitable basis for commercial building applications
- Impact: Credible source of input data that enables equitable comparisons of energy and non-energy performance between products

REFERENCE SLIDES

Project Budget

Project Budget: $300K/yr for Radiance and related software development, $50K/yr for maintenance of laboratory and full-scale testbed facilities, FY16-18
Variances: None.
Cost to Date: $525K ($350K in last 12 months)
Additional Funding: synergistic funding: $100K/yr from California Energy Commission EPIC; in-kind technical support from industry partners (equipment, technical expertise); in-kind access to monitored data from PG&E FLEXLAB study

Budget History					
10/1/15– FY 2016 (past)		FY 2017 (current)		FY 2018 – 9/30/18 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$350K	$100K	$350K	$100K	$350K	$100K

Project Plan and Schedule

- **Project Period**: 10/1/15 to 9/30/18
- **Schedule and Milestones**
  - Phase I goniophotometric and field test measurements completed, 3/31/16
  - Phase I field validation completed, 9/30/16
  - Phase II goniophotometric and field test measurements completed, 3/30/17
  - Phase II field validation completed, 9/30/17
- **Explanation for slipped milestones and slips in schedule**
  - Delay in receipt of DOE funding
- **Go/no-go decision points**
  - Go/ No-go: Average monthly agreement better than 20%, 6/30/16, 6/30/17
- **Current and future work**
  - Validation of 5-phase method for solstice condition
  - Develop methods for generating high-resolution BSDFs for Phase I products
  - Collaborate with third-party developers to implement 5-phase methods in software tools

Milestone/Deliverable (Originally Planned)

Milestone/Deliverable (Actual)

	FY2016				FY2017				FY2018			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Phase I goniophotometer, field test completed												
Current/Future Work												
Phase I field validation completed												
Phase II goniophotometer, field test completed												
Phase II field validation completed												
Methods for generating high-res BSDFs defined												
Phase III field validation completed												