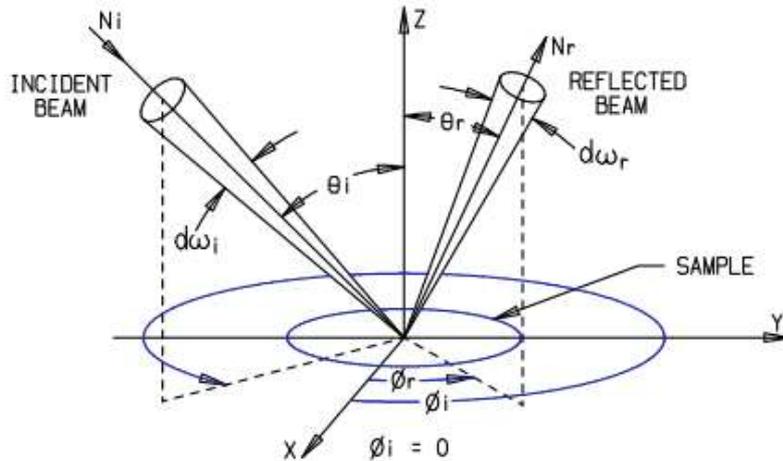# Advanced Analytical and Experimental Techniques for Characterizing the Optical Scattering of Surfaces

James C. Jafolla, Martin Szczesniak and Michael Beecroft

Surface Optics Corporation

Bidirectional Reflectance Distribution Function (BRDF)

$\hat{n}$ = Outward Surface Normal Unit Vector

θ_i = Incident Zenith Angle

θ_r = Reflected Zenith Angle

ϕ = Reflected Azimuth Angle

BRDF: $\rho'(\theta_i, \theta_r, \phi)$

$$\frac{\delta N_r(\theta_r, \phi)}{N_i(\theta_i)} = \rho'(\theta_i, \theta_r, \varphi)\cos\theta_i\,\delta\Omega_i$$
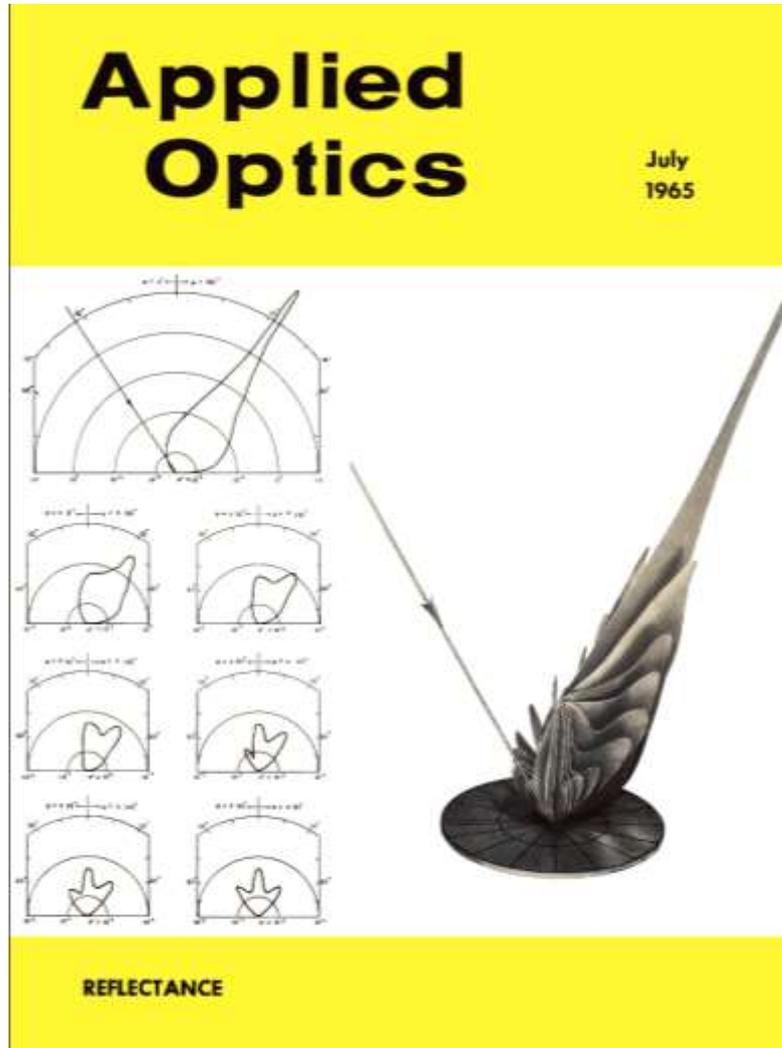
DHR: $\rho_D(\theta_i)$

$$\frac{N_r}{N_i(\theta_i)} = \iint \rho'(\theta_i, \theta_r, \varphi)\cos\theta_r\,\sin\theta_r\,d\theta_r\,d\phi$$
$$= \rho_D(\theta_i)$$

(These apply to isotropic surfaces; also, $\phi \equiv \phi_r - \phi_i$ here.)

$\pi\rho' = \rho_D$ For Lambertian Diffuse Surface

Pictorial Representation of BRDF

F. Nicodemus, "Directional Reflectance and Emissivity of an Opaque Surface", *Appl. Opt.*, **4**, 767-773, 1965.
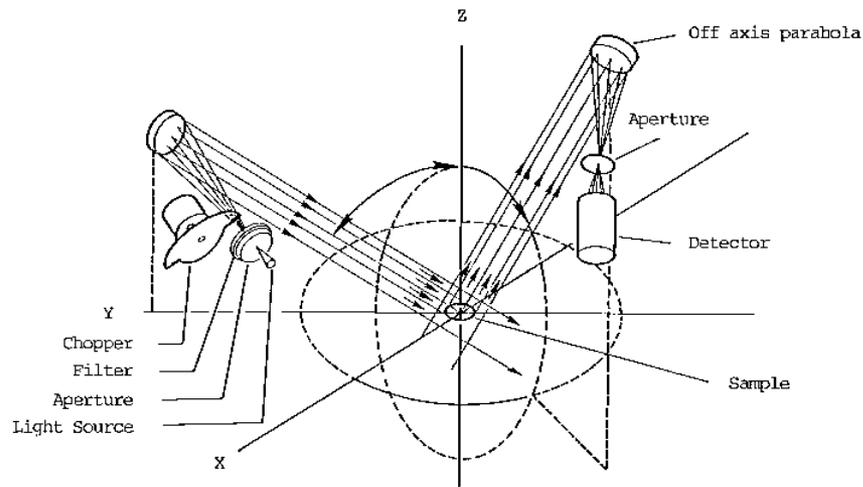
BRDF Measurements

BRDF Measurements Involve Mapping the Light Scattered into the Hemisphere

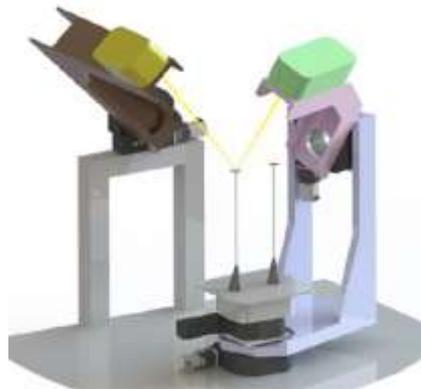Calibration to Known Diffuse Standards

Normalized to HDR Measurements

Goniometers Map the BRDF by Positioning Source and Detector in the Hemisphere

New Reflectometers Capture Image of Scattered Light

SOC-200/210 Bidirectional Reflectometers

- Broad-Band Sources, 0.3 - 14 μm
  - Quartz Halogen
  - Silicon Carbide Glower
  - Laser Diodes Optional
- Detectors
  - Si, InGaAs, MCT
- Wavelength Selection Using Narrow Band Filters
- Full Hemispherical Coverage (Four Axes Automation)
- Polarized (Mueller Matrix) BRDF
- Noise Floor ~10^{-3} sr^{-1}
- Sample Size
  - Nominal 1" Diameter
  - Can Measure Powders & Liquids

SOC-600 HHDR

Hand-Held Instrument
## Simultaneous HDR and BRDF Measurements

- Measures BRDF of A Sample at Over 30,000 Reflected Angles

- Reflectance Angles, With $0°$ ● $\square_r$ ● $\sim 90°$, and $-10°$ ● $\nearrow_\square$ ● $190°$

- Incident Angles From $0°$ to $85°$

- 3 -5 and 8 - 12 ◯m

- Computes In-Band DR From BRDF

- Frame Rates Up To 60 Per-Second

- Accuracy up to $\sim 10^{-6}$ sr^{-1}

# Angular Imaging Collects Scatter From Half-Hemisphere

Ellipsoidal Mirror Gathers Scattered Light From Slightly More Than Half-Hemisphere and Directs It To Second Focus

Collimating Mirror Past Second Focus Maps Angular Distribution to Spatial Distribution on Focal-Plane Array
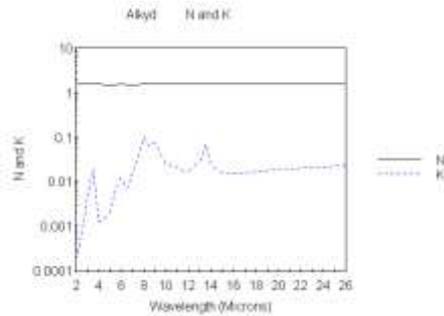

*Angular Imaging Concept Patented By Keith Davis at Boeing
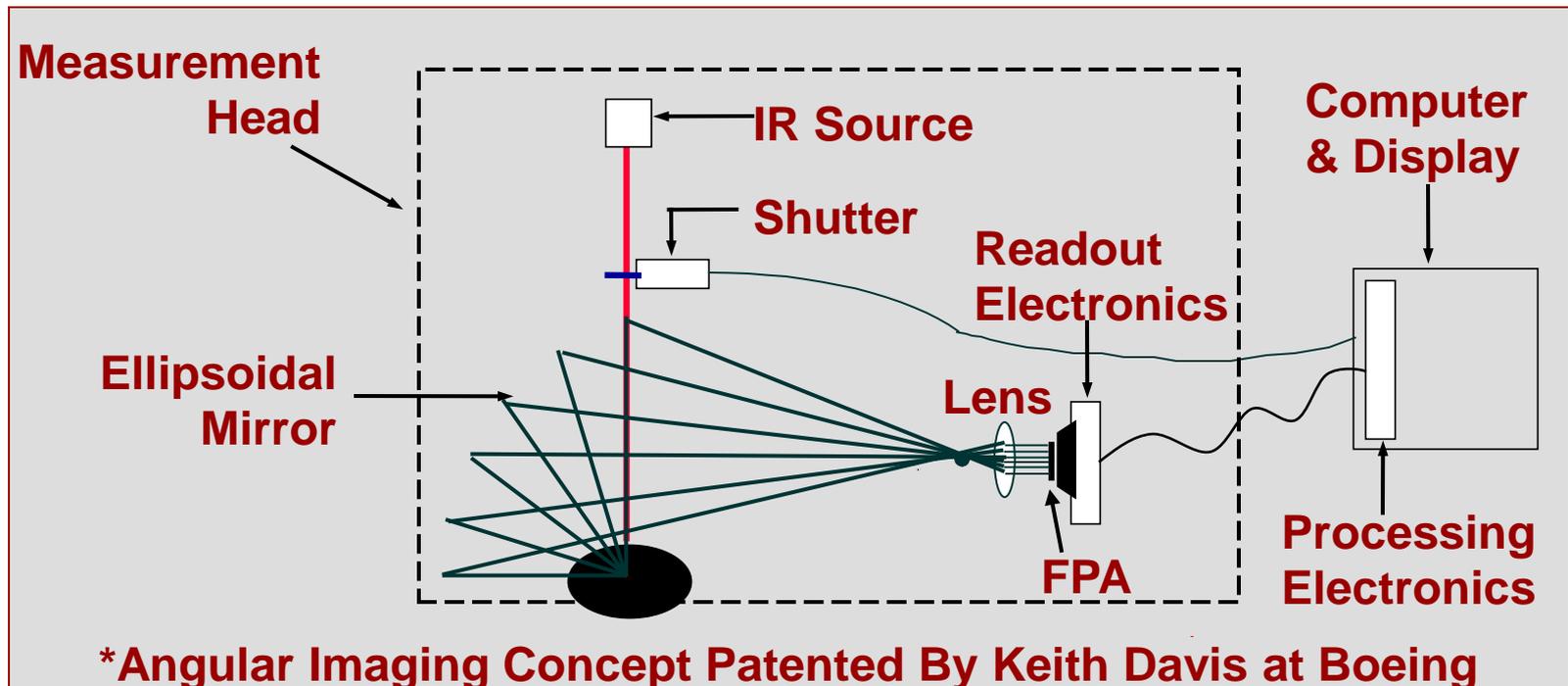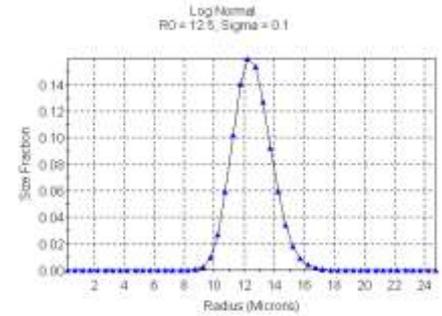
Gray Paint Measured at 50□ Incidence 3-5 □M
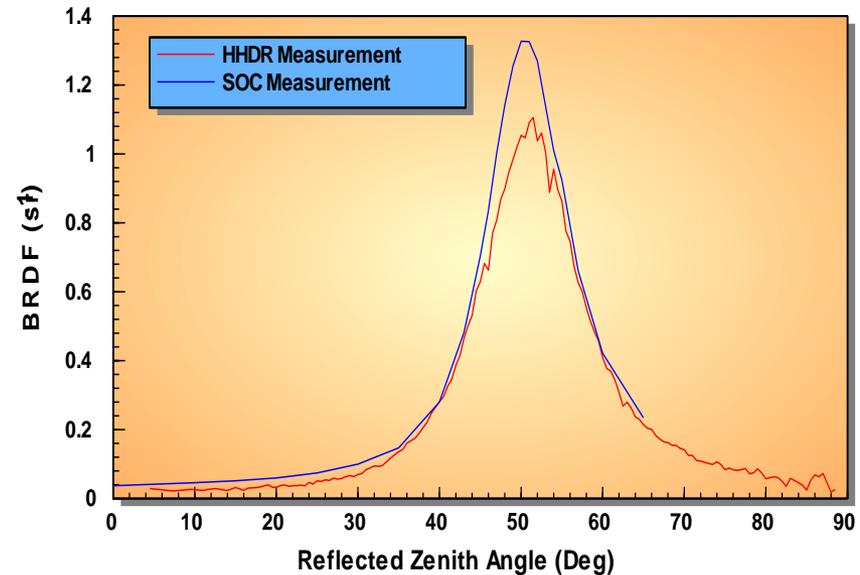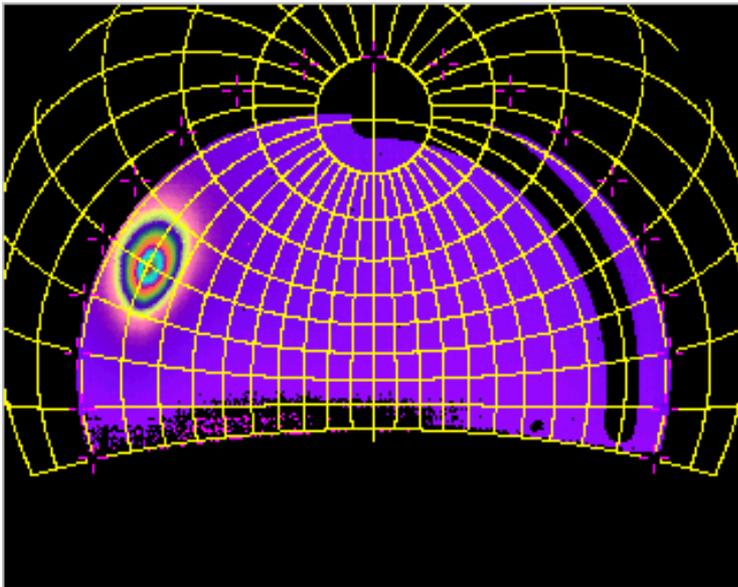
- HHDR Reported HDR: 0.133

- SOC Measured HDR: 0.148

  – Averaged uniformly across 3-5 band

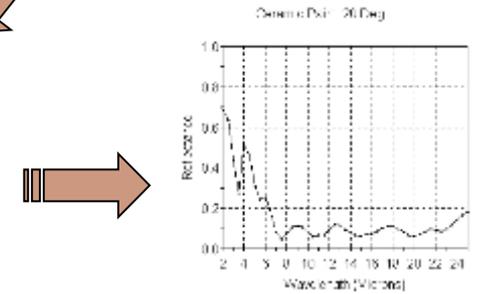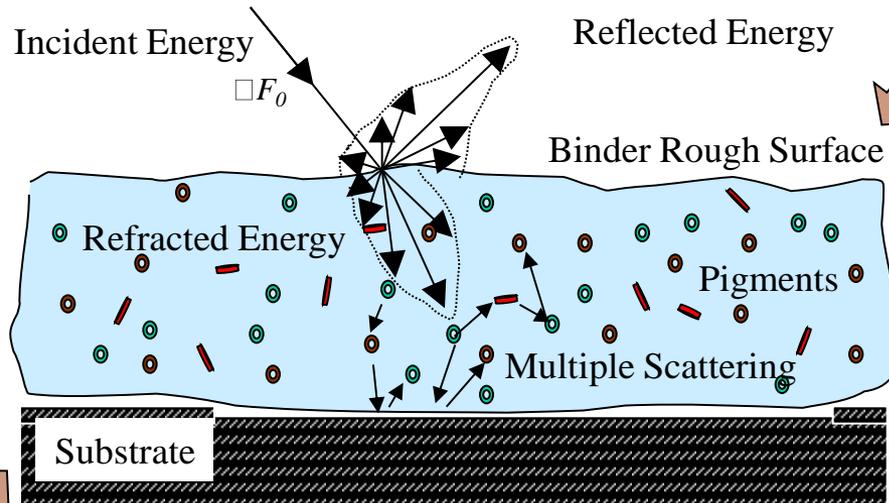 – HDR Changes from 0.060 at 3 □m to 0.19 at 5 □m

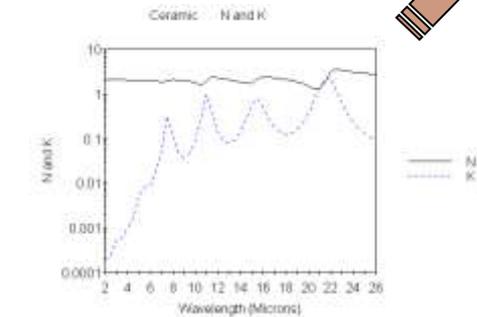# Optical Phenomenology of Composite Materials

Binder Optical Constants

Pigment Size Distribution

Incident Energy

F_0

Reflected Energy

Binder Rough Surface

Refracted Energy

Pigments

Multiple Scattering
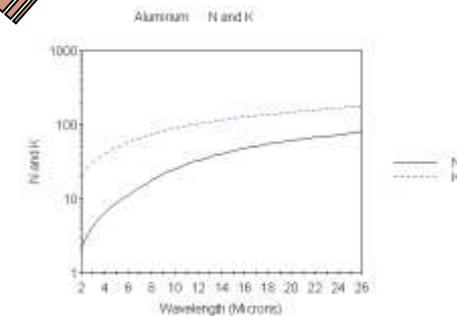
Substrate

Spectral Reflectance

Pigment Optical Constants

Substrate Optical Constants

Analytical Techniques

- Mie/Non-Spherical Techniques for Calculating Pigment Single Scattering

- Multiple Scattering Radiative Transfer Used for Volume Scattering

- Rough Surface Scattering Used for Binder Interface

- Radiative Coupling of Surface and Volume Scattering

# Scattering Coatings Computer Aided Design (ScatCad) Code

- Implements Single Scattering and Multiple Scattering Radiative Transfer Techniques for Engineering Analysis of Pigmented Coatings

- Predicts the Spectral BRDF and HDR Based on the Optical Constants and Micro-Physical Composition of the Coating

- PC Based

- Provides Modules for Optical Constant Analysis

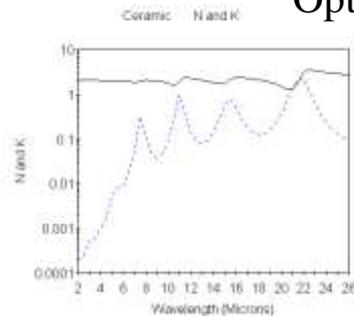- Interfaces to SOC-200/600 BDR and SOC-100/400 HDR Measurement Systems

Analysis Based Coatings Design
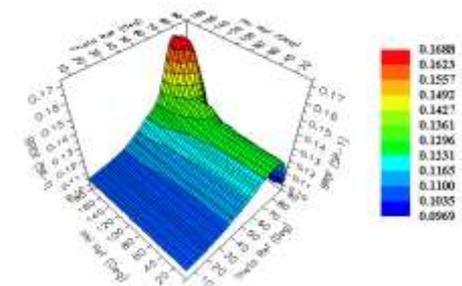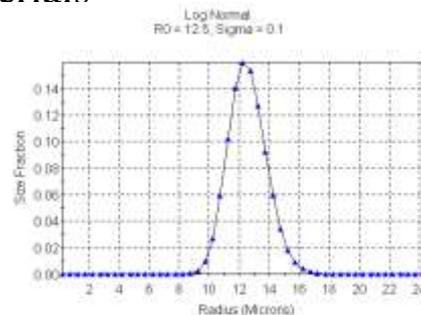

Optical Characterization of Materials

Optical Constants

ScatCad Analysis
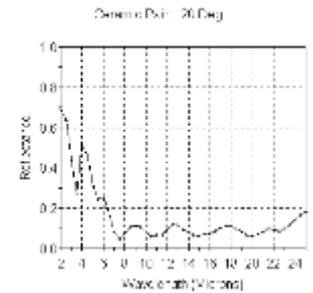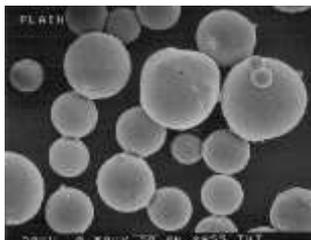
Spectral Directional and Bidirectional Reflectance

Physical Characterization of Materials

Pigment Single Scattering

- Mie Theory for Homogeneous and Layered Spherical Pigments
  - 20 Layer Sphere Algorithm Developed by Weisbrod (MDTI-TM-92-01, McDonnell Douglas, 1992)
- Non-Spherical Single Scattering Techniques
  - Henyey-Greenstein, 2 Parameter Phase Function
  - T-Matrix for Axially Symmetric Particles (Mishchenko, *Appl. Opt.*, **32**, 4652-4666, 1993)
  - Discrete Dipole Approximation for Non-Homogeneous/Irregular Particles (Draine and Flatau, *J. Opt. Soc. Am.*, **11**, 1491-1499, 1994)

Radiative Transfer Analysis

Radiative Transfer Equation

$$\mu \frac{dI(\theta,\phi)}{d\tau} = -I(\theta,\phi) + \frac{\omega_0}{4\pi} \int\limits_{4\pi} p(\theta',\phi',\theta,\phi)I(\theta',\phi')d\omega'$$

$$+ \frac{\omega_0}{4} p(\theta_0,\phi_0,\theta,\phi)F_o e^{-\tau/\mu_0} + (1-\omega_0)B(T).$$
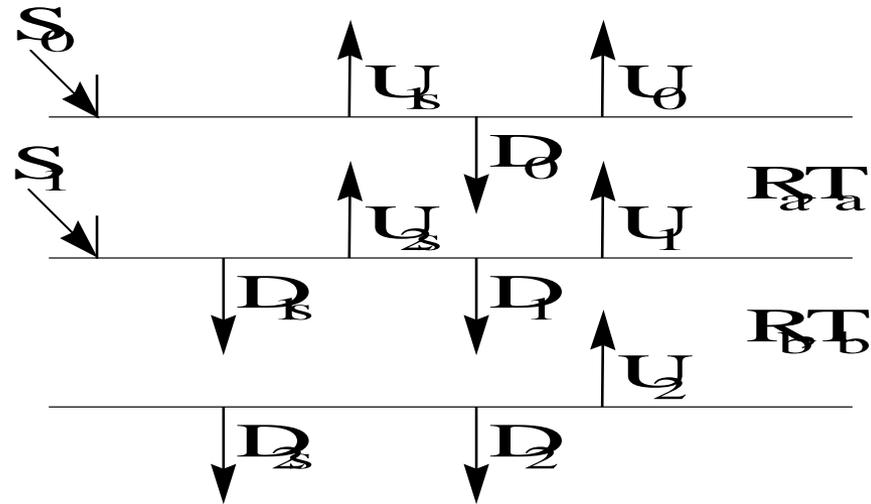
Where

♦ $\square$ is the single scattering albedo

$p(\square',\nearrow',\square\,\text{⟡}\,\nearrow) = p(\cos\text{♋})$ is the phase function

F_o is the incident source radiation

$B(T)$ is the thermal emission

$\bigcirc = \cos\square$

HDR Analysis

- Extension of Kubelka-Munk Two-Flux Analysis
- Uses Three-Flux Approximation to Radiative Transfer Equation
  - Provides Rapid Spectral Calculations for Design Optimization
- Considers Multiple Paint Layers Over Substrate
  - Surface Scattering Not Included
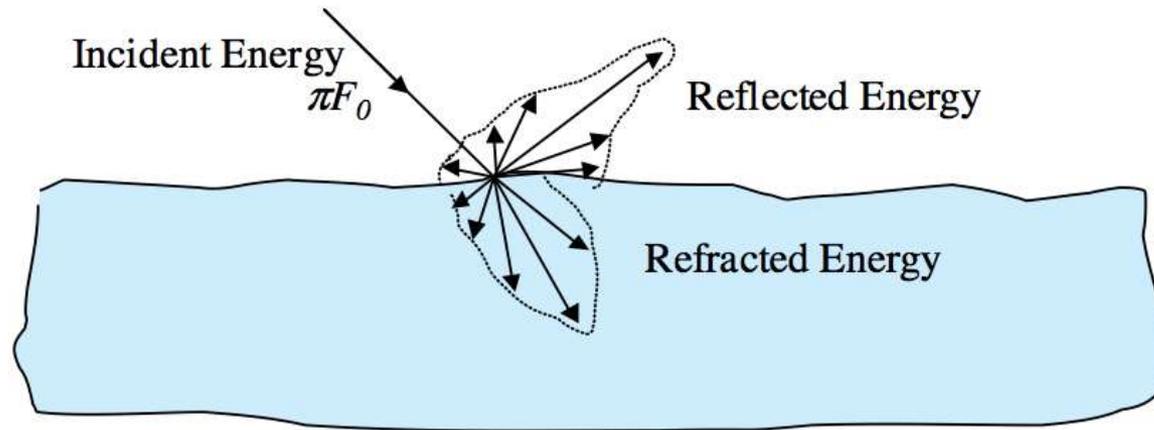- Binder Absorption Treated as Additional Pigment Absorption

$$mean\ free\ path = l_m = 1/(N\pi r^2) \qquad \Delta C_{abs} = 4\pi l_m k_b/\lambda$$

BRDF Analysis - Adding/Doubling

$$R = R_1 + R_2 + R_3 + \cdots$$

$$U = U_1 + U_2 + U_3 + \cdots$$
$$D = D_1 + D_2 + D_3 + \cdots$$

$$T = T_1 + T_2 + T_3 + \cdots$$
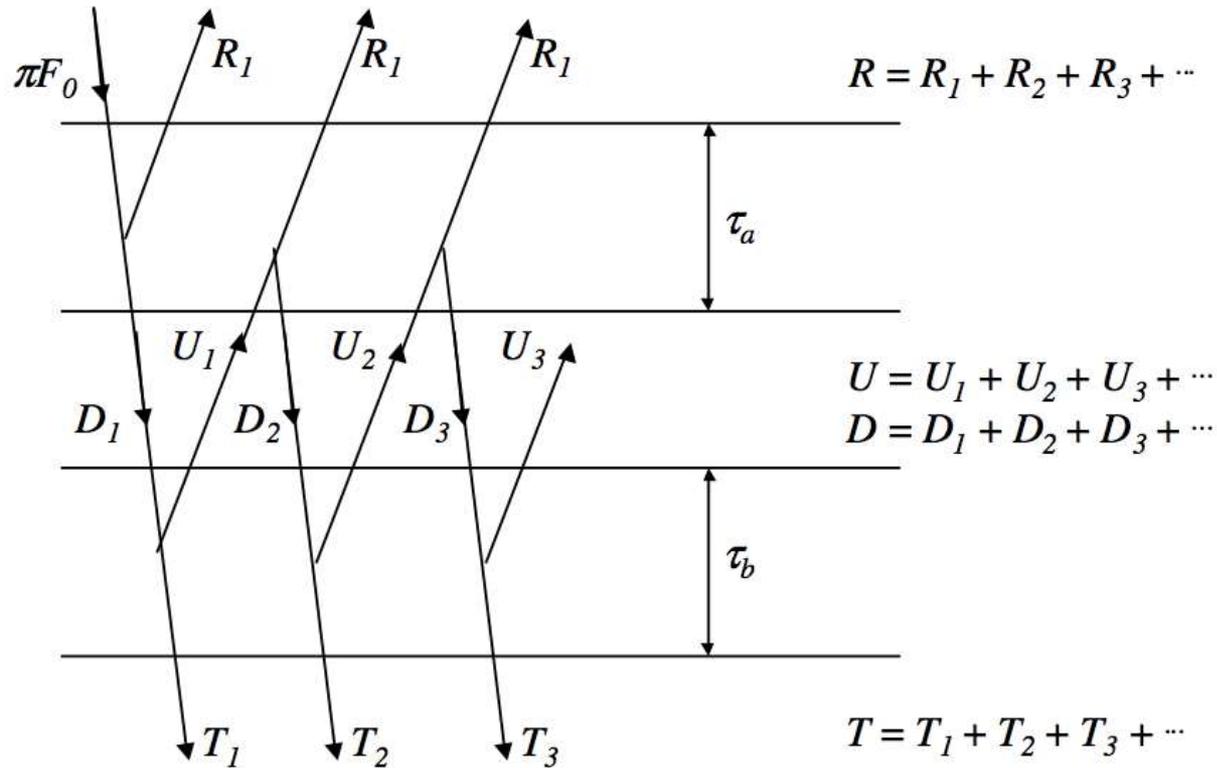
Rough Surface Scattering

Slightly Rough Surfaces
- Rice perturbation model
- Roughness is isotropic
- Surface slopes are small
- RMS roughness height $< \lambda/2\pi$

Very Rough Surfaces
- Tangent-plane approximation
- Roughness is isotropic
- Surface curvature $\ll 1$
- Correlation length $\ll$ Sample Length
- No multiple scattering
- No shadowing

Model Versus Measurement
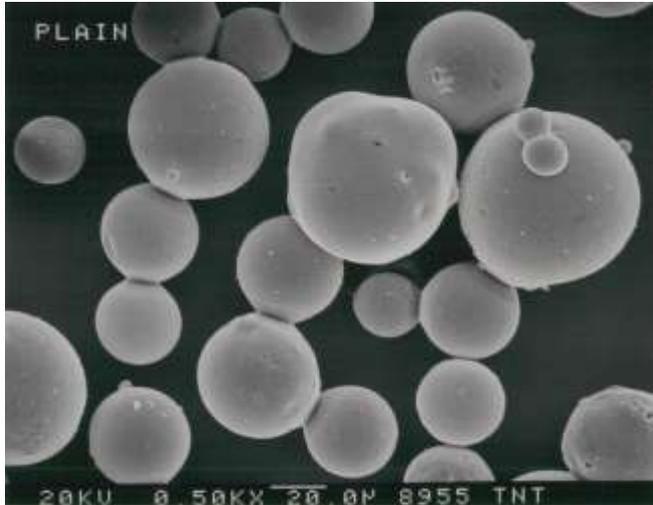
Ceramic (Fly-Ash) Pigment
10 - 70 micron diameter
Log-Normal Size distribution
Mean Diameter 41 microns

Pigment Modeled as Air Core
and 2 Micron Ceramic Layer
Alkyd Binder
Surface Roughness
Commensurate With Pigment
Dimensions
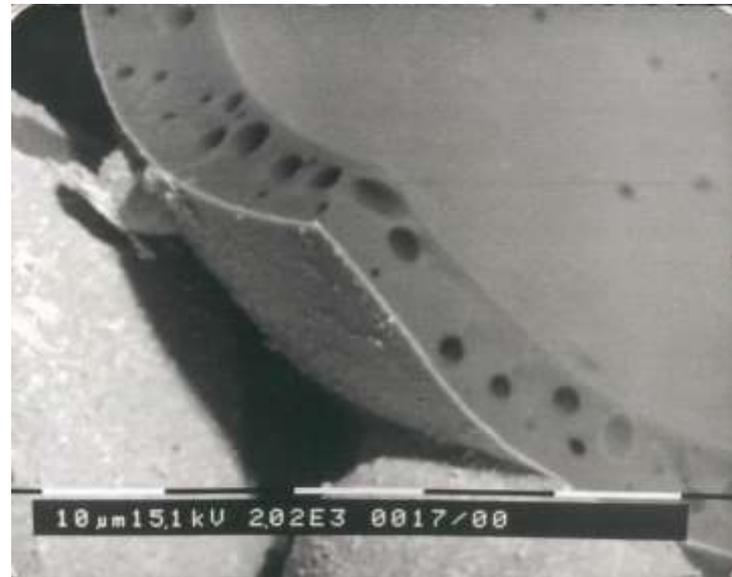
Optical Constant Determination
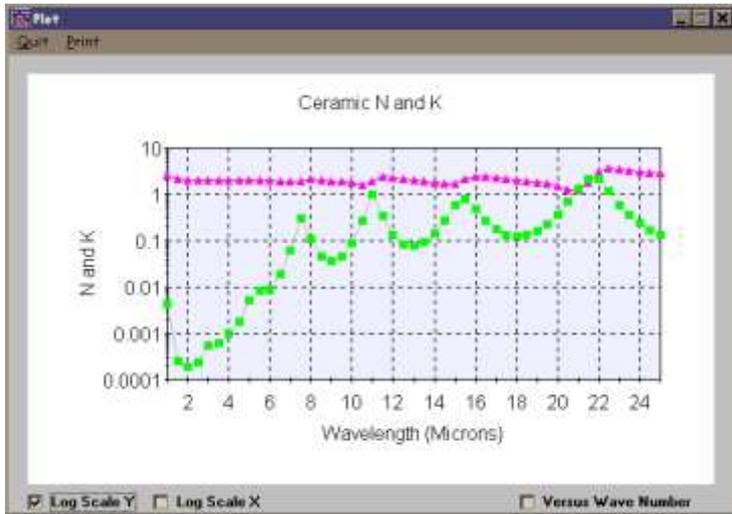
Ceramic Optical Constants Determined From Analysis of HDR Measurement of Micro-Balloon Powder
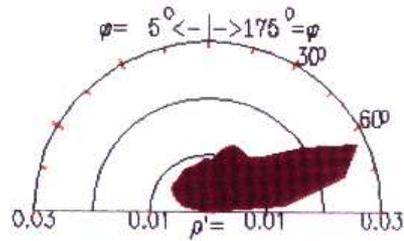
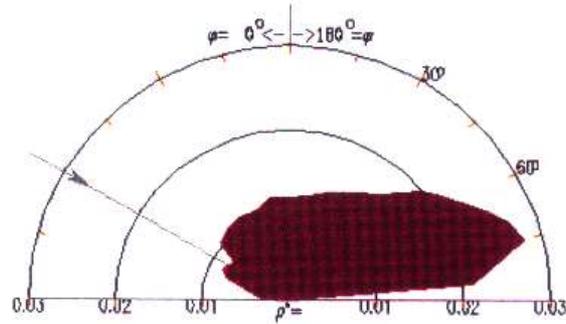Alkyd Optical Constants Determined From Analysis of HDR Measurement of Thin Film Over Al Substrate
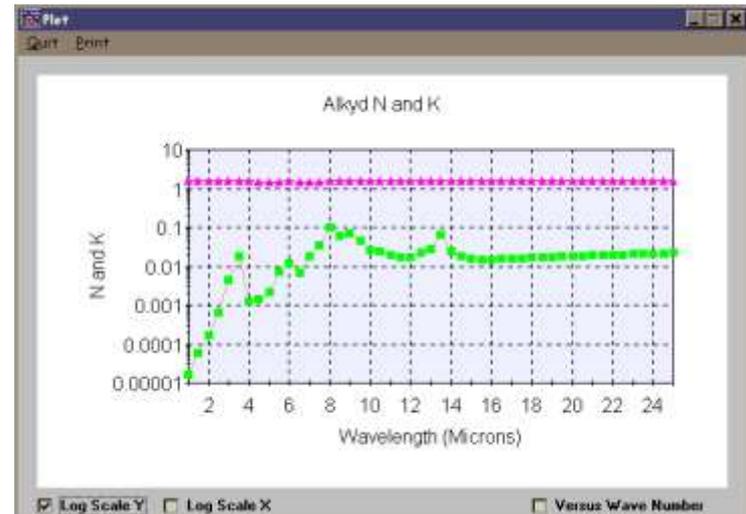
HDR Model Versus Measurements
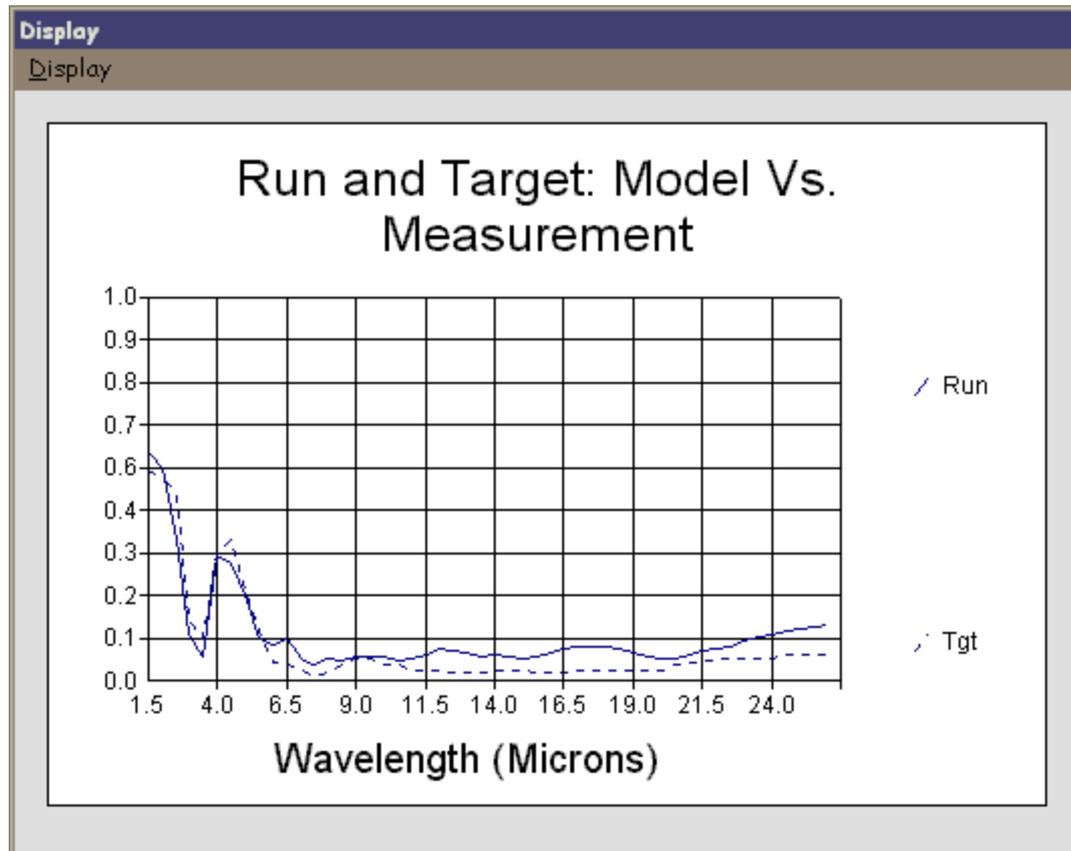
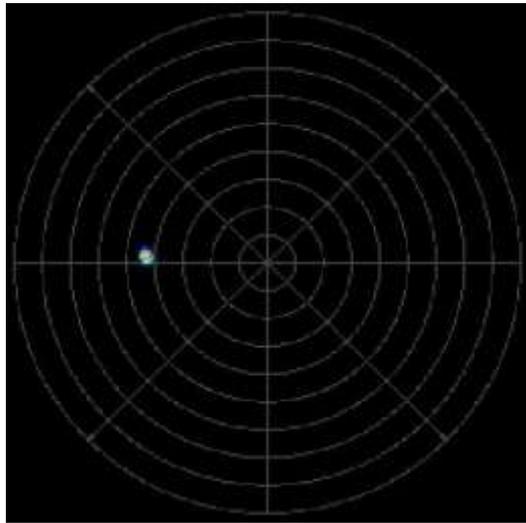# BRDF Model Versus Measurements

ScatCad
Calculation

Measurement

Application: Surface Finish

- BRDF Measurements/Analysis Provides Information on the Surface Finish of Materials

- Shape of the BRDF is Directly Related to Surface Roughness for Opaque Bulk Materials

- BRDF of Composite Materials (e.g., Paints) Includes Volume and Surface Scattering Contributions

- Comparison of BRDF Measurements of "Clean" to "Scratched" Samples Should be Able to Quantify Roughness Statistics

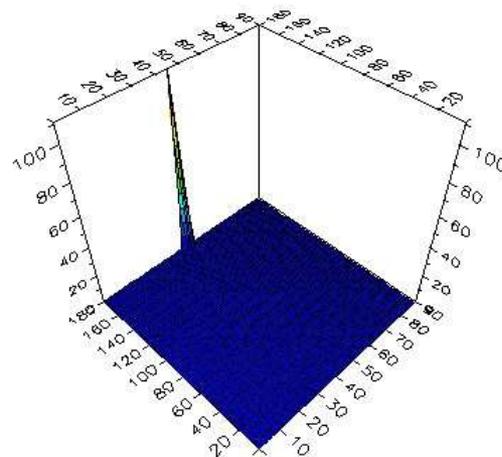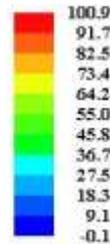- Results Run for Gold and Aluminum Samples

Shiny Aluminum

Surface Roughness

BRDF Measurements
3-5 μm, 45 Deg

Shiny Disk, 45d, 3-5 um.col
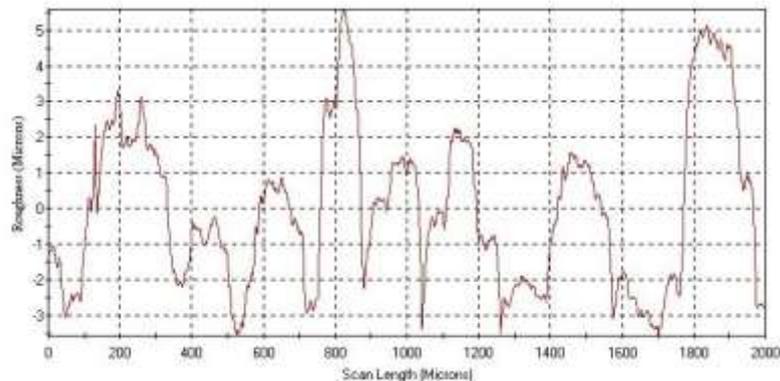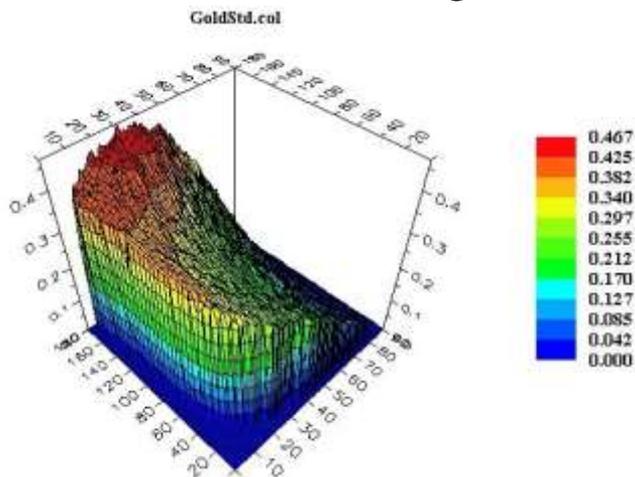
BRDF Calculations
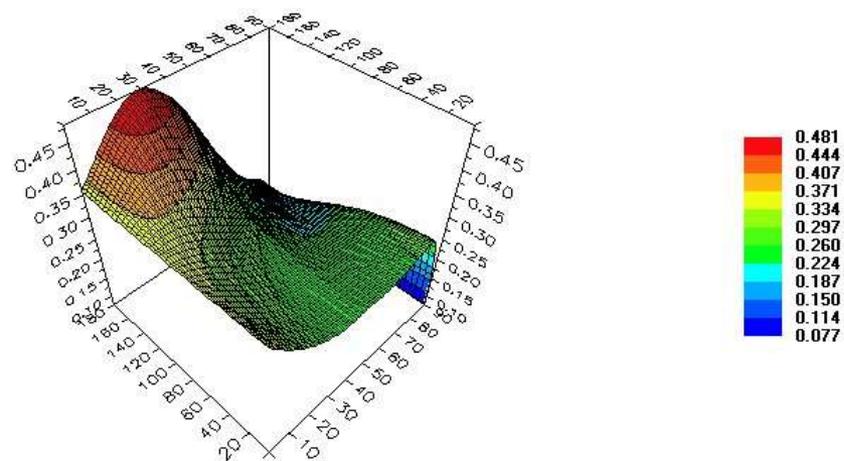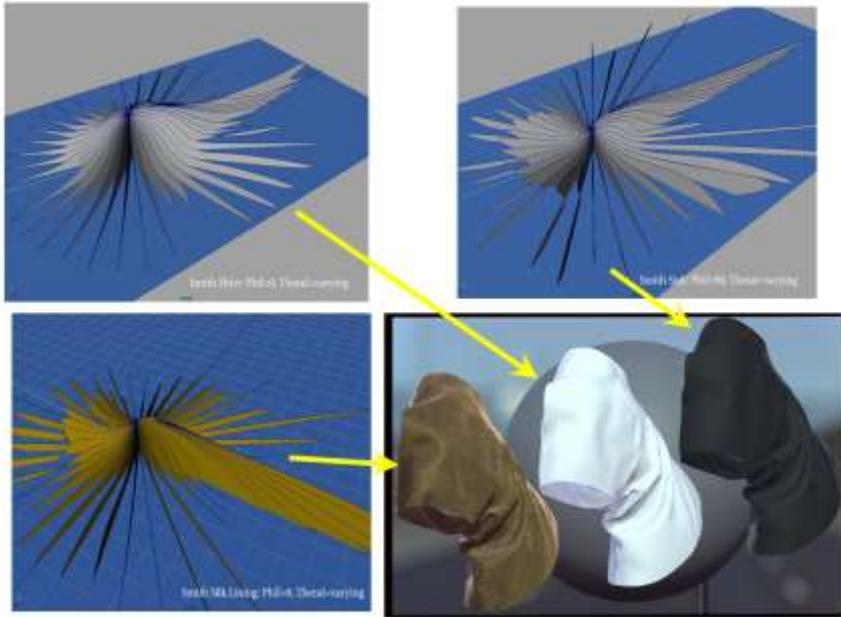
Roughened Gold
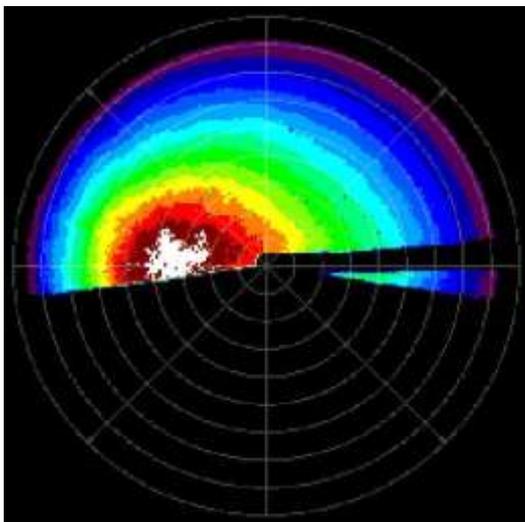
Surface Roughness

BRDF Measurements
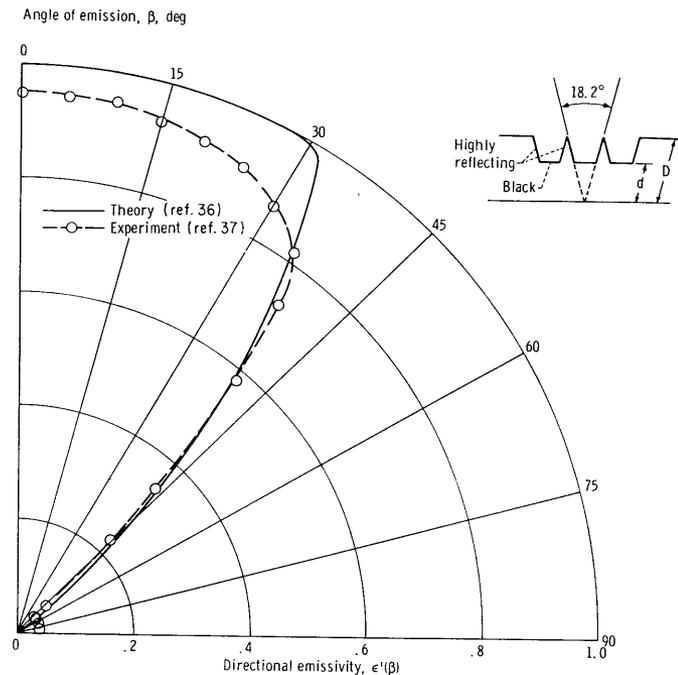3-5 ▢m, 45 Deg

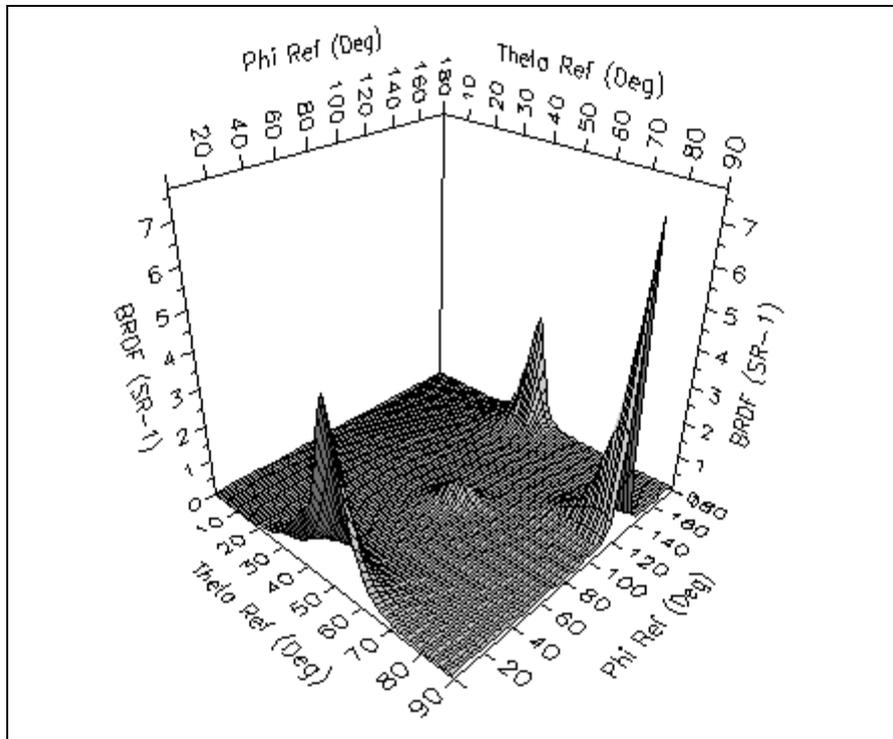BRDF Calculations

Application: Non-Isotropic Surfaces

• Many Real-World Materials Exhibit Surface Structure (e.g., Cloth, Bark)

• Provides Challenges For BRDF Measurement And Representation

• Engineering Applications for Thermal Design

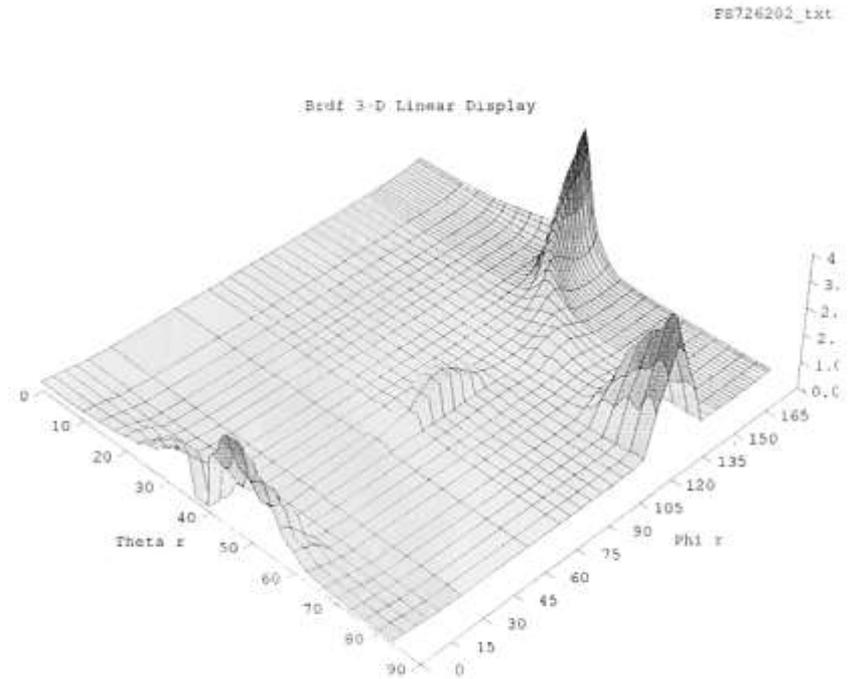• Ref. Seigel R. and Howell J., *Thermal Radiation Heat Transfer*, McGraw-Hill, 817pp, 1972

Model/Measurement Comparison

ScatCad Prediction   Measurement

Computer rendered character from a science fiction movie.

photo   rendered

Summary

- Optical Measurements and Phenomenological Models Can Provide Qualitative/Quantitative Insight Into the Optical Properties of Coatings and Surfaces

- ScatCad is a Phenomenological Model for Engineering BRDF and HDR Analysis of Composite Materials

- Interfaces to SOC-210/600 BDR and SOC-100/410 HDR Measurement Systems

- Includes Tools for Optical Constant Analysis and Design Optimization

- Allows "Virtual Prototyping" for Development of Paints and Diffuse Reflectance Standards