Two lectures on scatterometry

- the appearance of materials
- simple detectors
  - radiometry / photometry
- angular dependence
  - goniometry
- polarization
  - polarimetry / ellipsometry
- spectral characterization
  - colorimetry / spectroradiometry

© 1997 Marc Levoy

Sources for figures

- Richard S. Hunter and Richard W. Harold, The measurement of appearance, second edition, JohnWiley, 1987.
- John Stover, Scatterometers, in Handbook of Optics, M. Bass ed., McGraw-Hill, 1995, vol. II, section 26.
- John T. Neu and Martin Bressler, Design considerations for multipurpose bidirectional reflectometers, Proc. SPIE, vol. 1530, 1991.
- Tod F. Schiff, Mary W. Knighton, Daniel, J. Wilson, Fred M. Cady, John C. Stover, Design review of a high accuracy UV to near IR scatterometer, Proc. SPIE, vol. 1995, 1993.
- Ross McCluney, Introduction to radiometry and photometry, Artech House, 1994.

© 1997 Marc Levoy

Interaction of light with matter

- microscopic view
  - reflection
  - absorption
  - transmission
- macroscopic view
  - specular (smooth surface) reflection
  - diffuse (rough surface) reflection
  - sub-surface scattering
- other effects
  - polarization
  - fluorescence
  - phosphorescence
  - emission

© 1997 Marc Levoy

The appearance of manufactured materials

- milling, finishing
  - anisotropic reflection models (Kajiya, 1985), (Poulin and Fournier, 1990), (Ward, 1993)
- painting, lacquering
  - scattering in diffuse laminar materials (Kubelka-Munk, 1931)
  - subsurface light transport (Hanrahan and Krueger, 1993)
- weathering, patination
  - layers and operators on them (Dorsey and Hanrahan, 1996)
    - » coat, erode, fill, polish, offset
- erosion, deposition, staining
  - flow of water across a surface (Dorsey, Pederson, and Hanrahan, 1996)

© 1997 Marc Levoy

Hunter's taxonomy of appearance measurements

- attribute being measured
  - spectral
  - geometric (goniometric)
- involvement of human observer
  - physical
  - psychophysical
- type of source
  - illuminant (light source)
  - object (surface)
  - aperture (light field)
- primary light transport mode
  - diffuse reflection + gloss
  - specular reflection + haze
  - diffuse transmission + image
  - image + transmission haze
- location of measurement device
  - laboratory setting
  - industrial or field

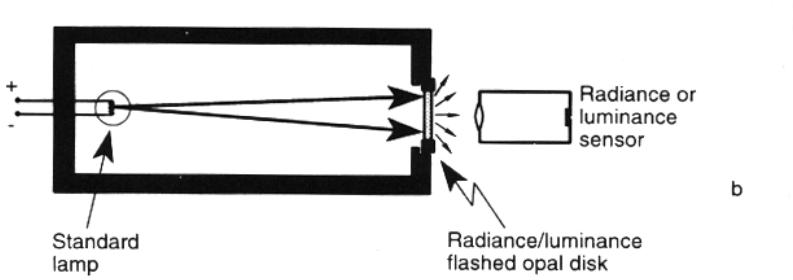
© 1997 Marc Levoy

Levoy's taxonomy of measurement devices

- simple detectors
  - measuring radiance and irradiance
  - radiometers versus photometers
- goniometric characterization
  - integrating spheres
  - gonioreflectometers and goniotransmittometers
  - glossimeters, hazemeters, and other exotica
- polarization characterization
  - polarimeters
- spectral characterization
  - monochromators
  - colorimeters
  - spectroradiometers and spectrophotometers

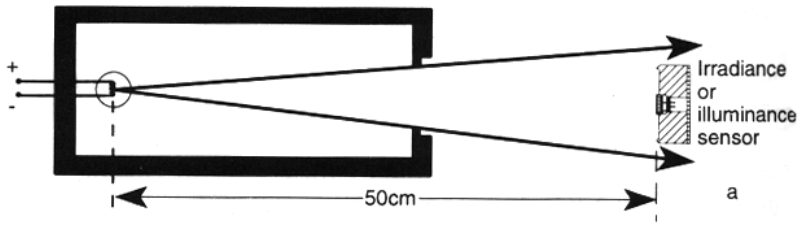
© 1997 Marc Levoy

Measuring radiance and irradiance



measuring the light leaving a surface (radiance)

$$L(\omega) \qquad \left[\frac{W}{m^2\, sr}\right]$$



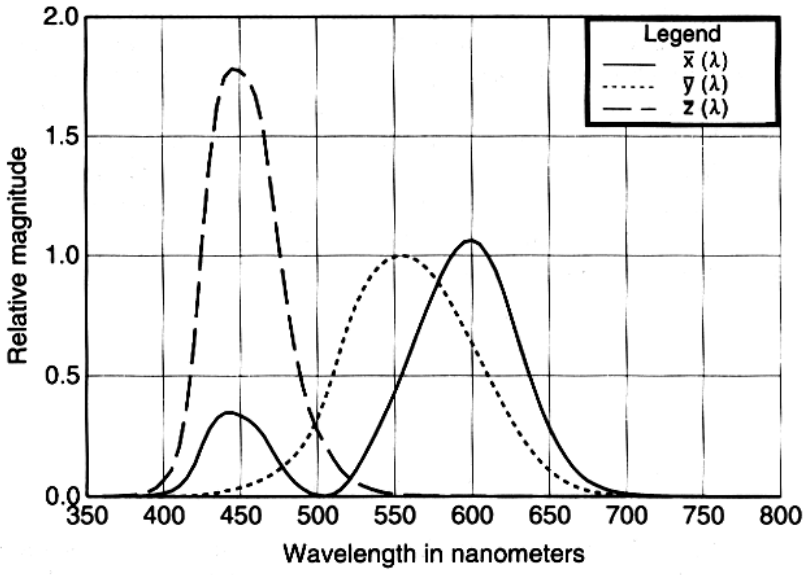
measuring the light incident on a surface (irradiance)

$$E(\omega) = \int_{2\pi} L(\omega) \cos\theta \, d\omega \qquad \left[\frac{W}{m^2}\right]$$

(from McCluney)

© 1997 Marc Levoy

Radiometers versus photometers



$$L_v = 683 \int_{380}^{770} L_\lambda \; V(\lambda) \, d\lambda \qquad \left[\frac{lm}{m^2 \, sr} \right]$$

$$V(\lambda) = \bar{y}(\lambda)$$

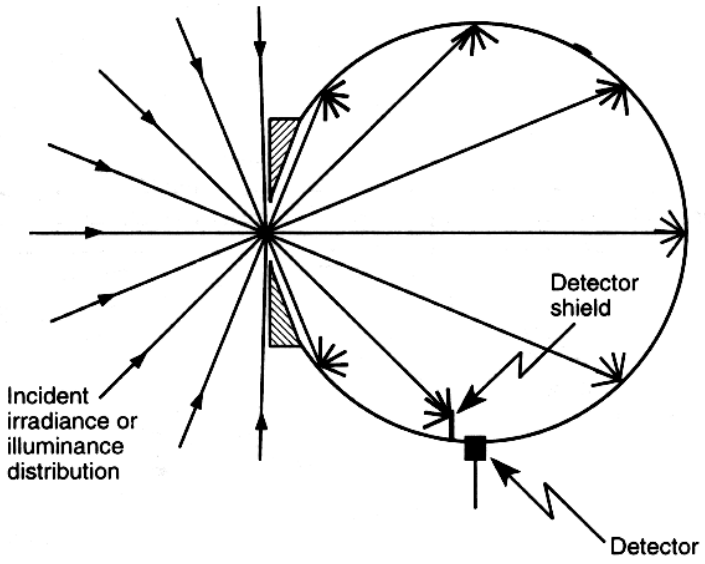
(from McCluney)

© 1997 Marc Levoy

Measuring irradiance using an integrating sphere

$$F_{A_i A_j} = \frac{1}{A_i} \iint_{A_i\ A_j} \frac{\cos\theta_i \cos\theta_j}{\pi r^2}\, dA_j\, dA_i$$

The form factor between any two patches on the inside surface of a sphere is the same.



The response to an incident irradiance at any angle will be the same.

(from McCluney)

© 1997 Marc Levoy

The bidirectional reflectance distribution function (BRDF)

$$f_r(x, \omega_i \rightarrow \omega_r) = \frac{dL_r(\omega_i, \omega_r)}{dE(\omega_i)} \qquad \left[\frac{1}{sr}\right]$$

- properties
  - superposition
  - reciprocity
- dimensionality

– isotropic	3D	θ_i , θ_r , ϕ_i - ϕ_r
– anisotropic	4D	ϕ_i , ϕ_r
– spatially varying	6D	x , y
– spectrally varying	7D	λ
– fluorescence	8D	λ_i , λ_r
– phosphorescence	9D	t_i - t_r
– subsurface scattering	11D	x_i,y_i , x_r,y_r

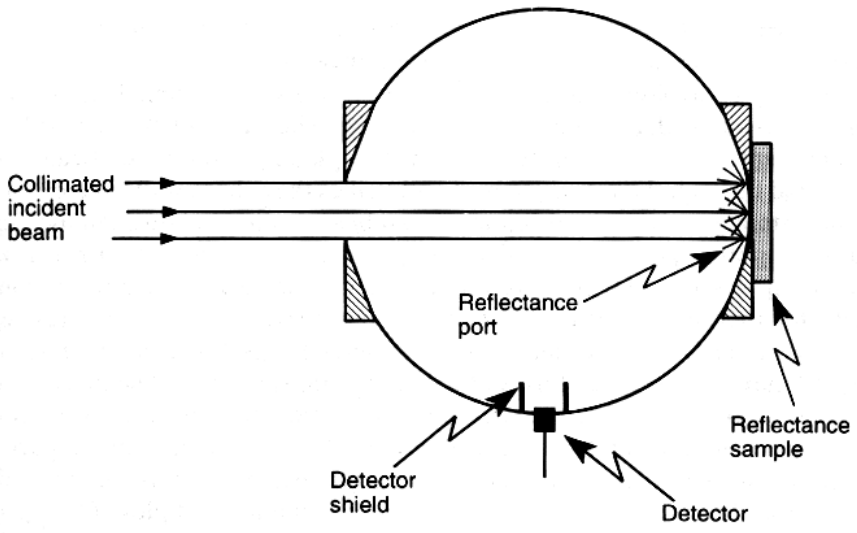
  - polarization adds 2x or 4x but not another “dimension”

© 1997 Marc Levoy

Measuring total integrated reflectance

$$\rho(\omega_i \rightarrow 2\pi) = \int_{2\pi} f_r\,(\omega_i \rightarrow \omega_r)\cos\theta_r\; d\omega_r$$

directional-hemispherical reflectance

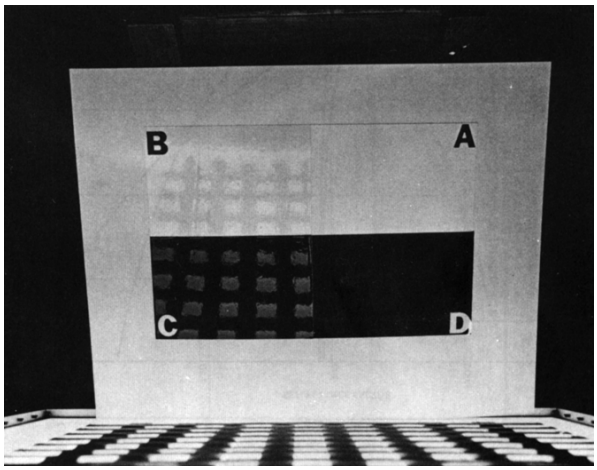


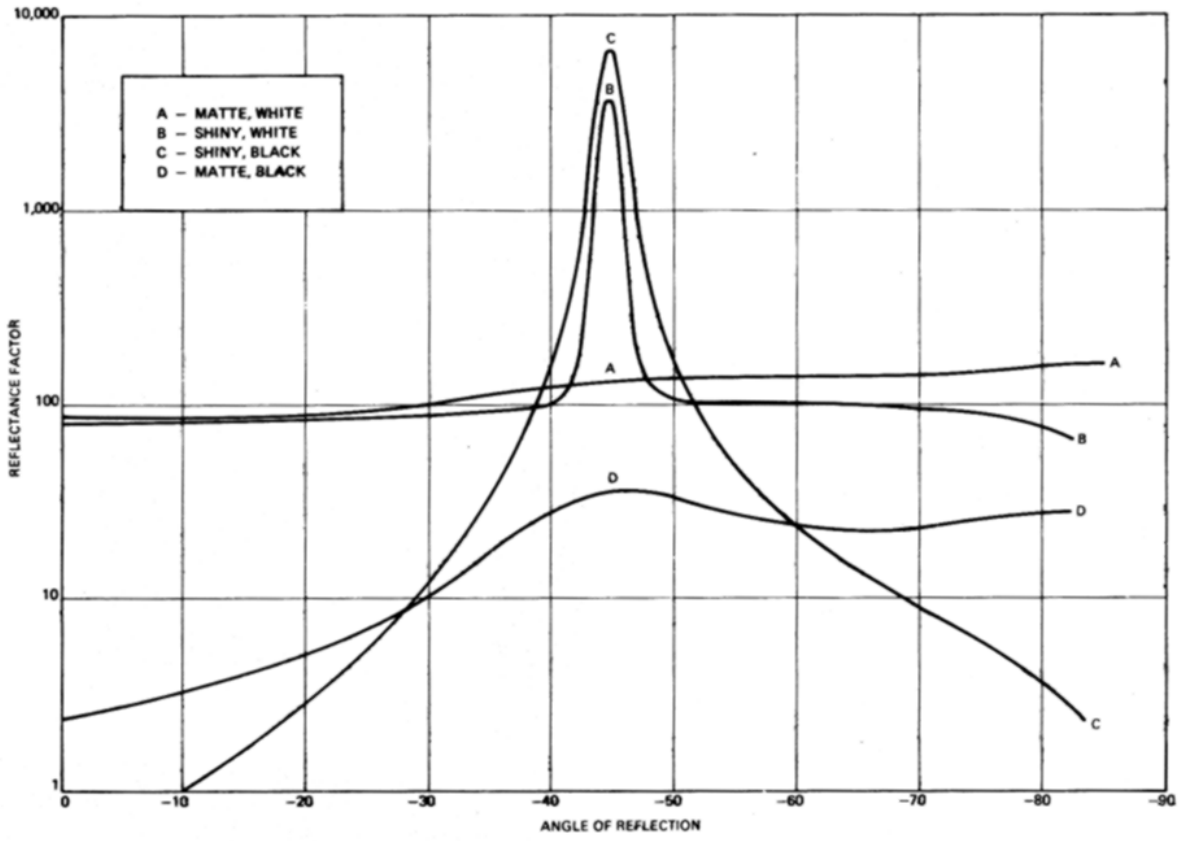
measurement using an integrating sphere

(from McCluney)

© 1997 Marc Levoy

Examples of specular and total reflectance



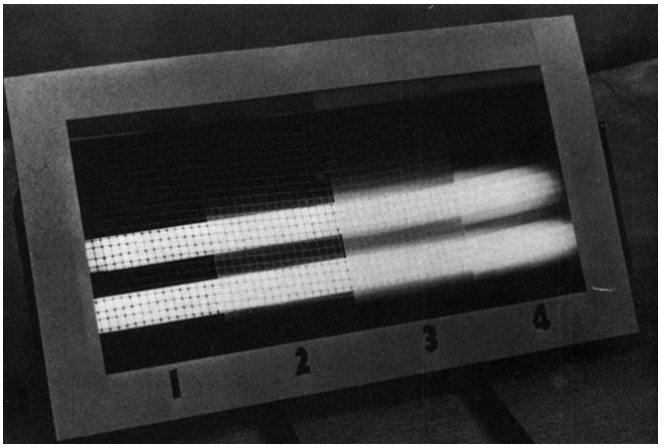


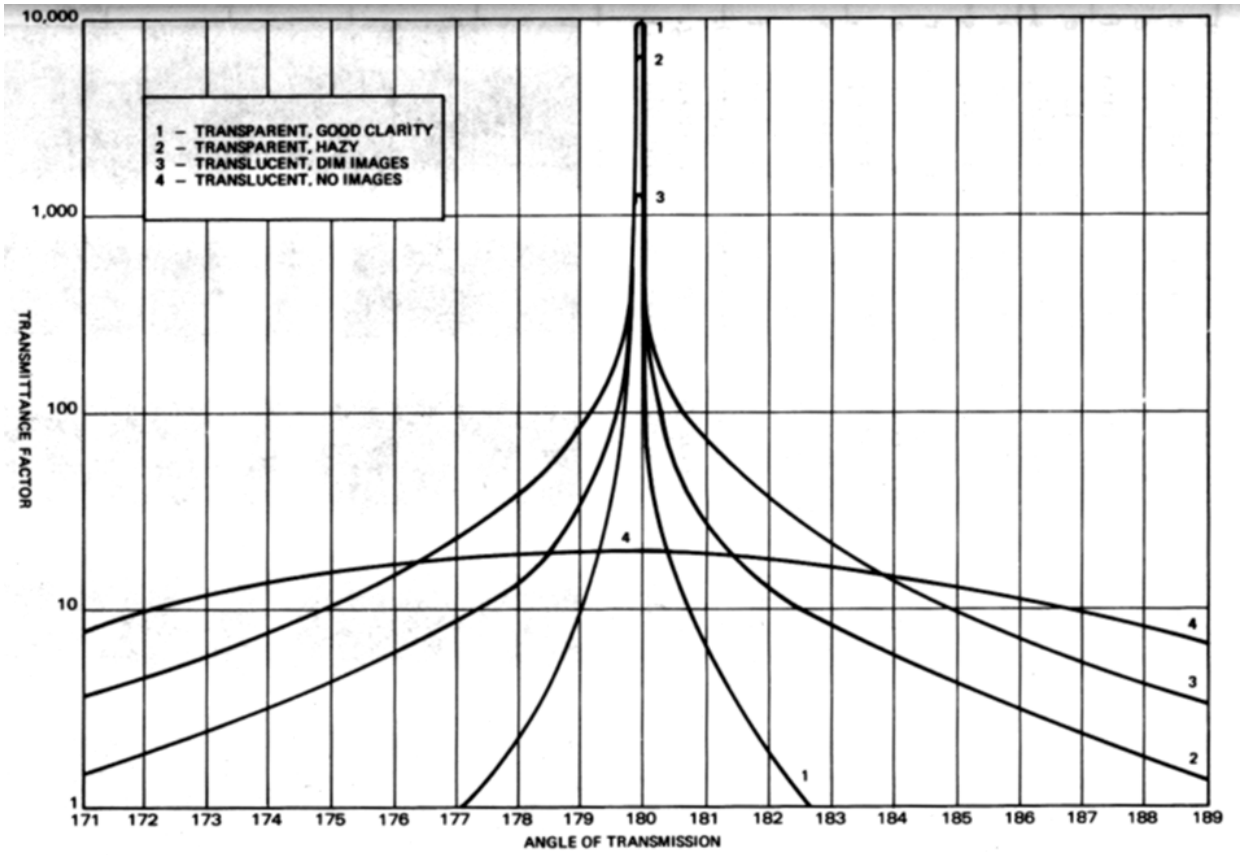
four paper samples

(from Hunter)

© 1997 Marc Levoy

Examples of clarity of specular transmission





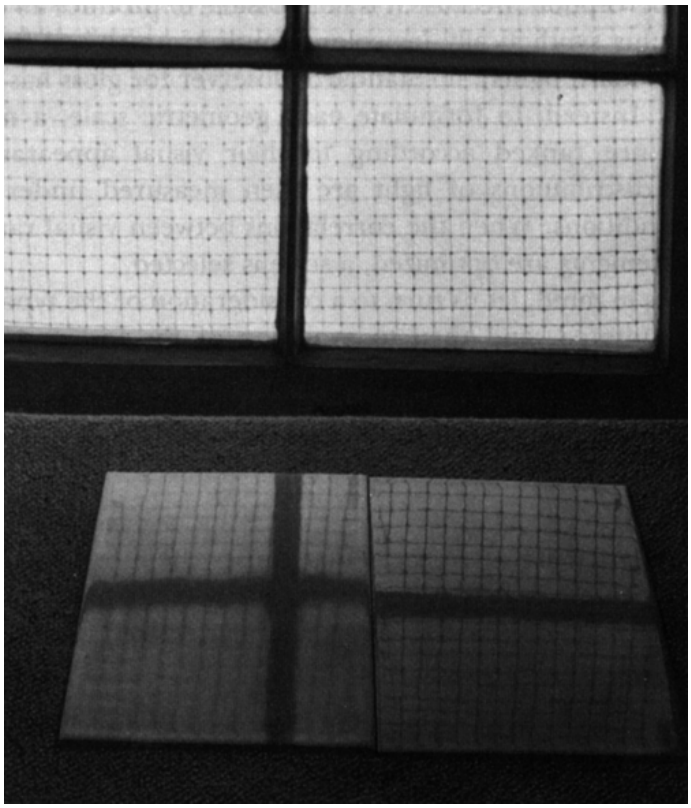
1 degree

four plastic sheets

(from Hunter)

© 1997 Marc Levoy

Examples of clarity of specular reflection

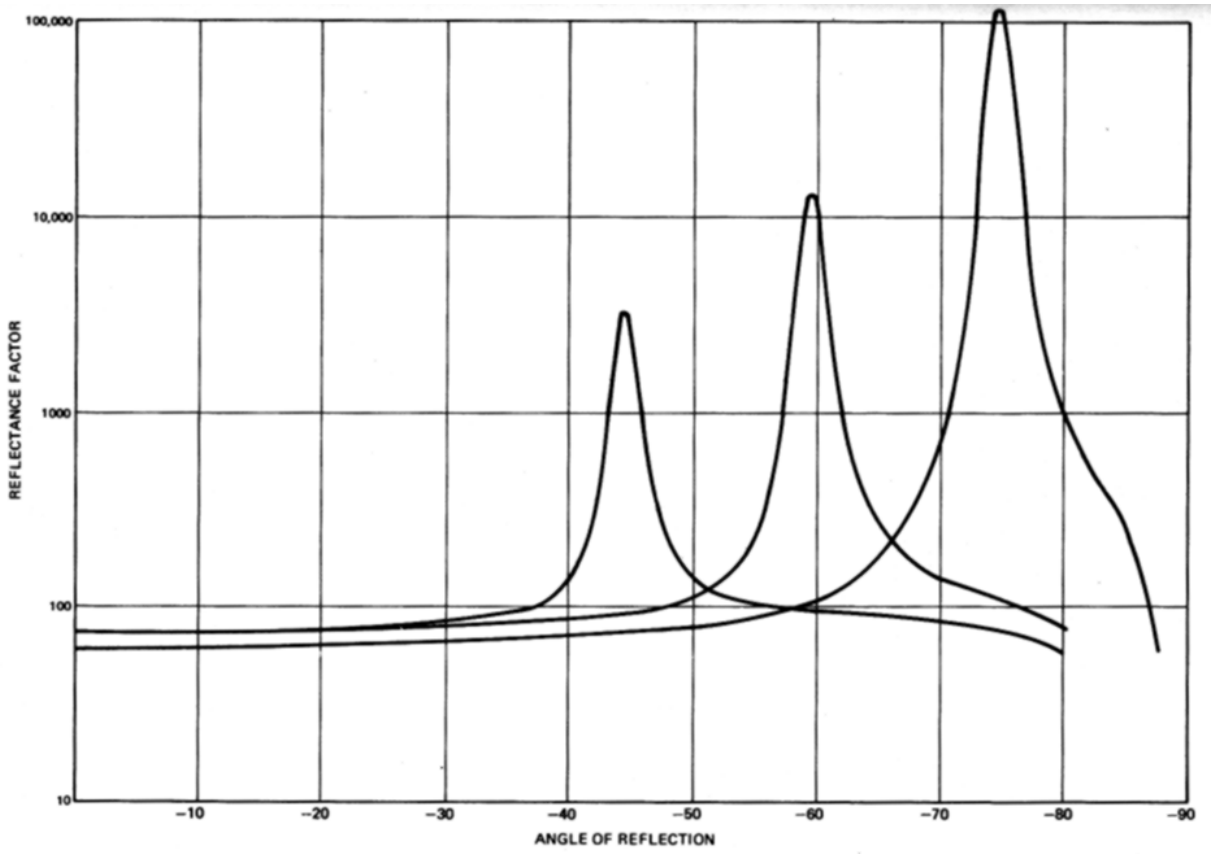


white porcelain enameled panels
specular reflections differ only in innermost 0.5 degree

(from Hunter)

© 1997 Marc Levoy

Examples of reflectance for different angles of incidence

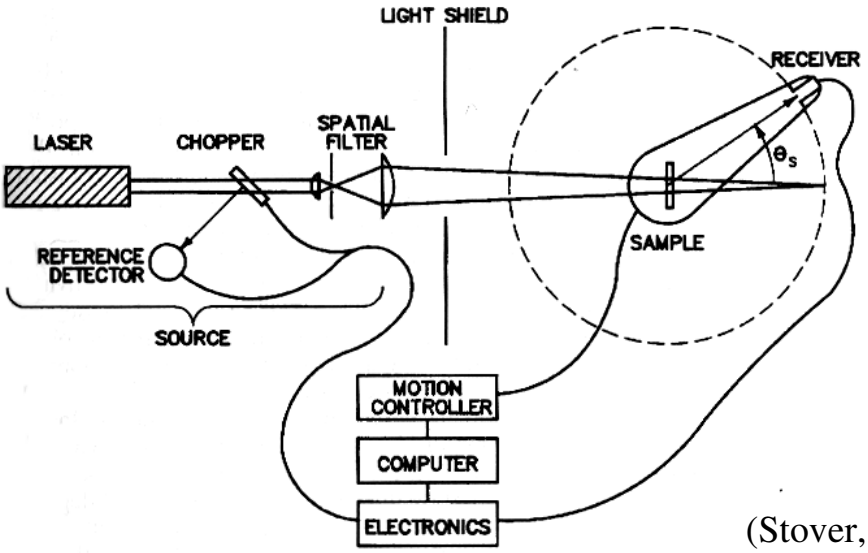


paper sample
light incident at 45, 60, and 75 degrees

(from Hunter)

© 1997 Marc Levoy

Typical scatterometer (BRDF + BTDF = BSDF)

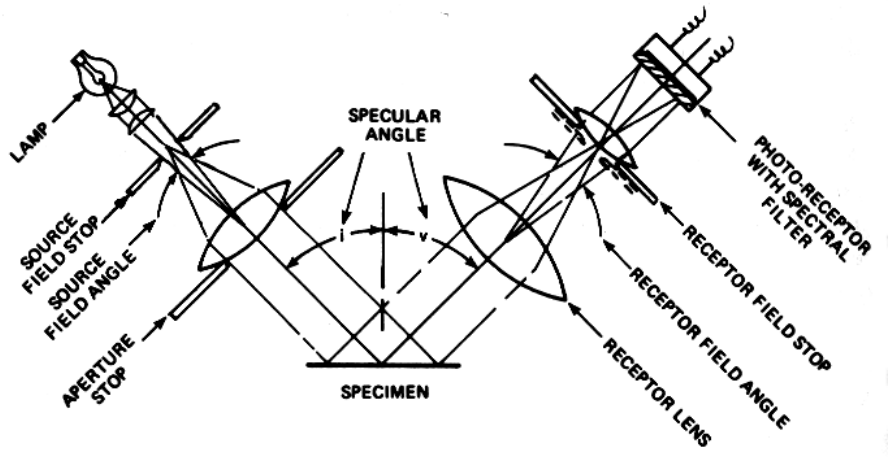


(Stover, fig 2)

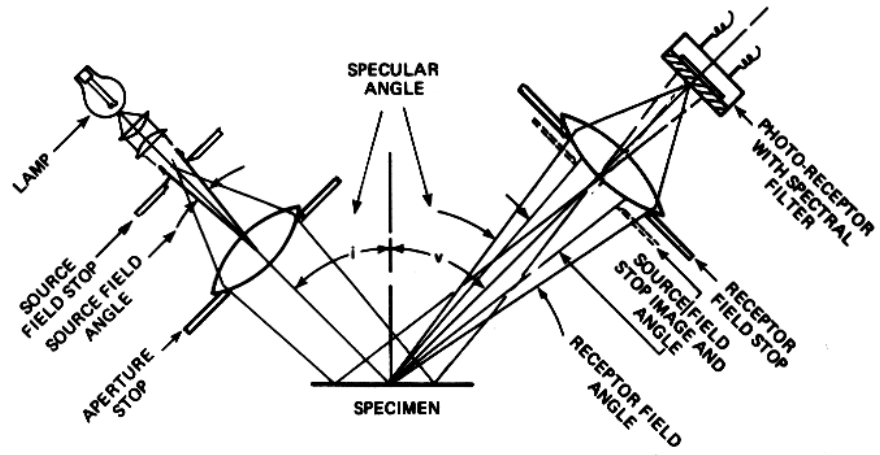
- illumination
  - coherent vrs. incoherent
- detection
  - photovoltaic, photoconductive, CCD
  - collimated versus converging beam
- other issues
  - retroreflection
  - spectral characterization
  - polarization

© 1997 Marc Levoy

Collimated versus converging beam



collimated (parallel)-beam reflectometer



converging-beam reflectometer

(from Hunter)

© 1997 Marc Levoy

Performance issues

- measures of sensor performance
  - sensitivity
  - dynamic range
    - » 10^{6} sr^{-1} in specular direction for HeNe laser source
    - » 10^{-4} sr^{-1} to 10^{-10} sr^{-1} for low-scatter surfaces
    - » 12 orders of magnitude!
  - linearity
  - noise
- systematic errors
  - positioning accuracy
  - source power fluctuations
  - scatter within instrument
  - convolution effects due to finite receiver aperture
  - laser speckle

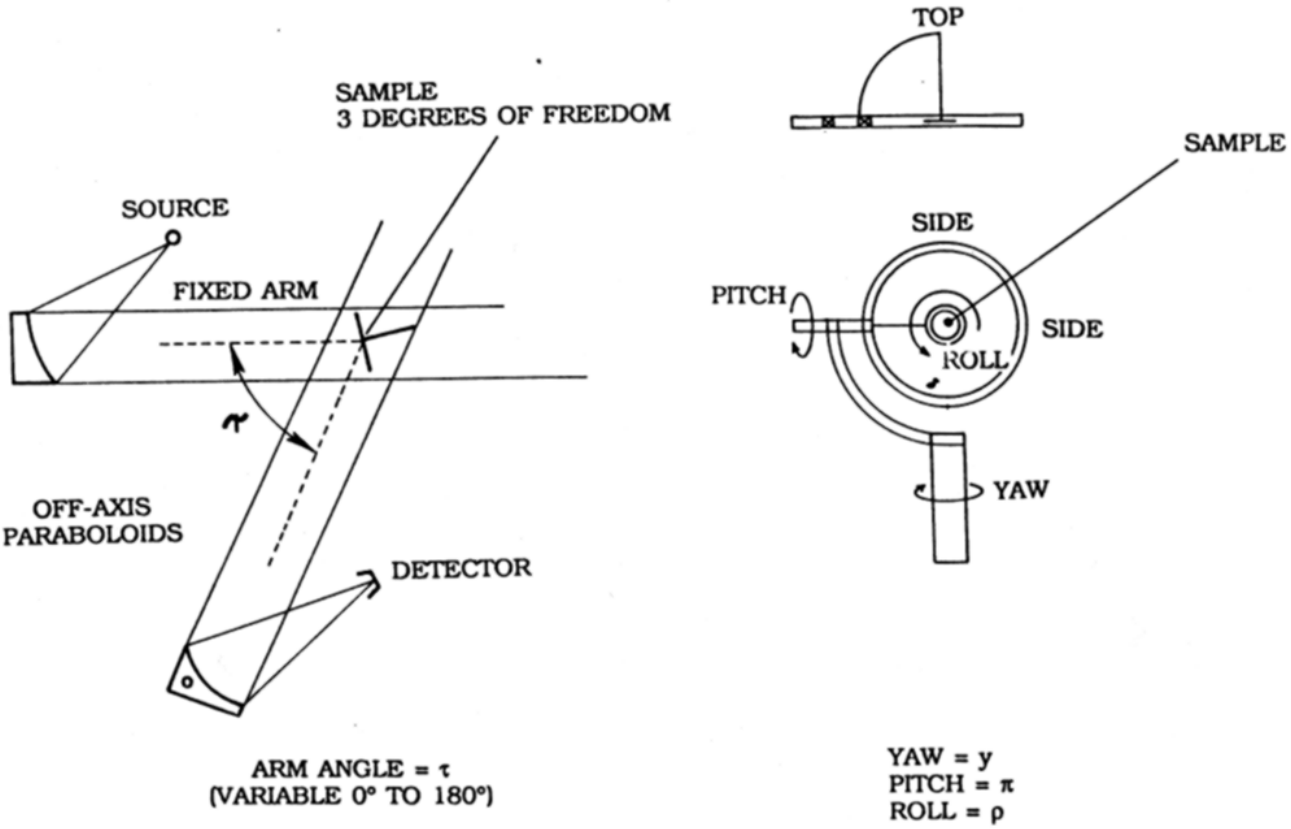
© 1997 Marc Levoy

Geometric design

- degrees of freedom
  - 7 (spatially varying) - 1 fixed = 6
- fixed versus moving parts
  - fixed source, sample, or receiver
- detector dimensionality
  - point, multiple point, line, area
- source dimensionality
  - all existing systems are single source
- automation
  - motorized versus manual goniometer
  - motorized versus manual x,y positioning
- acquisition time
  - stop-motion versus on-the-fly

© 1997 Marc Levoy

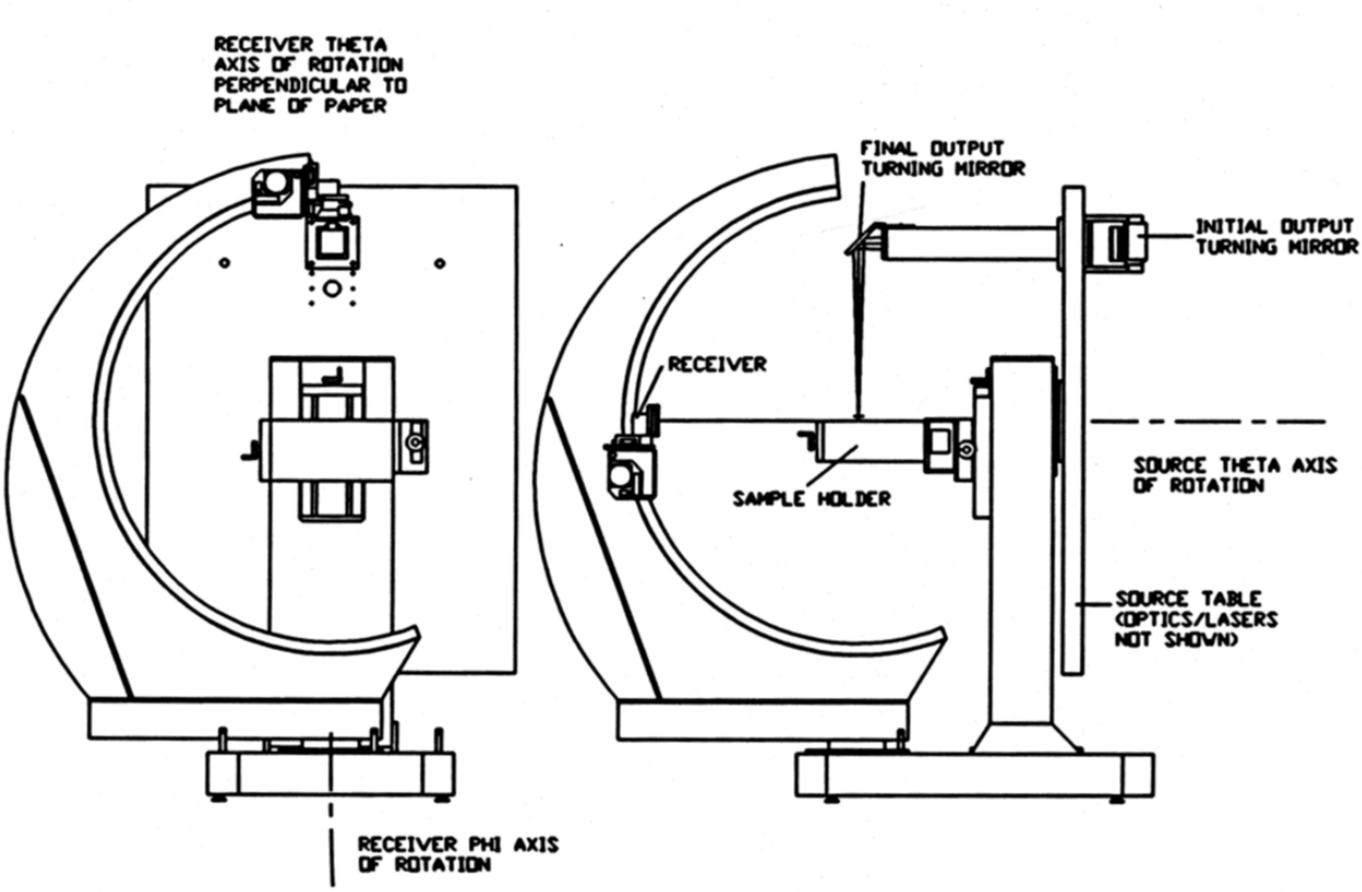
fixed source,
3-DOF sample,
1-DOF detector



(Neu and Bressler, Figure 4)

© 1997 Marc Levoy

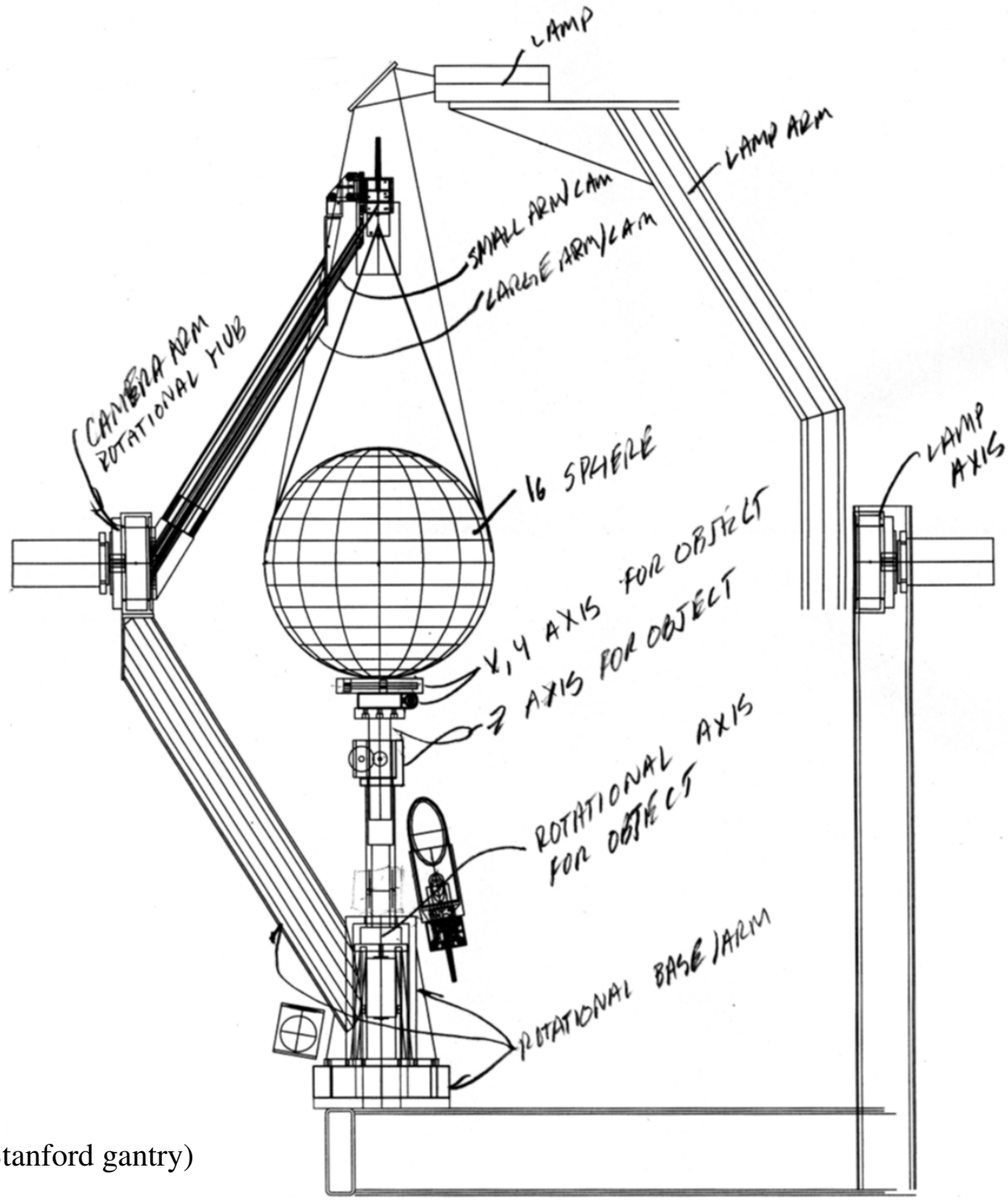
1-DOF source,
1-DOF sample,
2-DOF detector



(Schiff et al., figure 1)

© 1997 Marc Levoy

1-DOF source,
1-DOF sample,
2-DOF detector



(Stanford gantry)

© 1997 Marc Levoy