# Flux-O-Meter

## Making luminous flux measurements more accessible

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Lighting Research Center

# Luminous Flux, Lumens, Total Light Output... Who cares?

- Lighting practitioners use illuminance (lux, footcandles) and luminance ($cd/m^2$, footlamberts)
- Luminaires are characterized by intensity, intensity distributions, luminance and efficiency (a relative measure)
- Flux measurements are usually confined to
  - National labs
  - Lamp Manufacturers

# Current fixture photometry

- Standard photometric reports do not reveal system efficacy
- Traditional fixture photometry is based on relative light output
  - Numbers scaled to rated lamp light output
  - The industry relies on lamp manufacturers to provide luminous flux data
  - Luminous flux is for operation at standard, bare lamp conditions
- Luminaire efficiency does not fully take into account thermal, positional and ballast effects (system issues)

- The current practice suffices if we don’t care about total system efficacy.

# Energy codes and labeling programs

- People drafting energy-use standards would like to specify end-user efficiency (lm/watt), but are unable due to measurement complications.
- The market for inexpensive, residential grade lighting products cannot bear the cost of adapting existing photometric testing for absolute measurements
- Manufacturers often do not have access to inexpensive photometric testing which makes energy efficient design difficult.
- Luminous flux measurement is key to the issue of generating and controlling light *efficiently*

# Luminaire Efficacy Rating (LER)

- Earlier effort to rate system efficacy without measuring fixture flux
  - NEMA LE 5-2001 Procedure for Determining Luminaire Efficacy Ratings for Fluorescent Luminaires
- Works well for well characterized systems
  - e.g. T8 linear fluorescent lamp systems
- Insufficient data available for CFL and lower volume/specialty lamps and ballasts
  - Standard covers only 5 types of "high volume" luminaires
- Gets complicated for universal ballasts, different operating positions and temperatures, atypical luminaire configurations, etc.
- Errors from –23% to +86% for CFL luminaires
  - NLPIP Specifier Reports: Energy-Efficient Ceiling Mounted Residential Luminaires (1999)

Must measure flux to determine true system efficacy

# Traditional Flux Measurements
## Integrating Spheres

- Very sensitive to departures from ideal
- Substitution method is the practical means of use
- Requires calibrated flux standards – expensive, delicate, limited lifetime
- Requires frequent calibration and maintenance
- Must be much larger than the objects placed inside

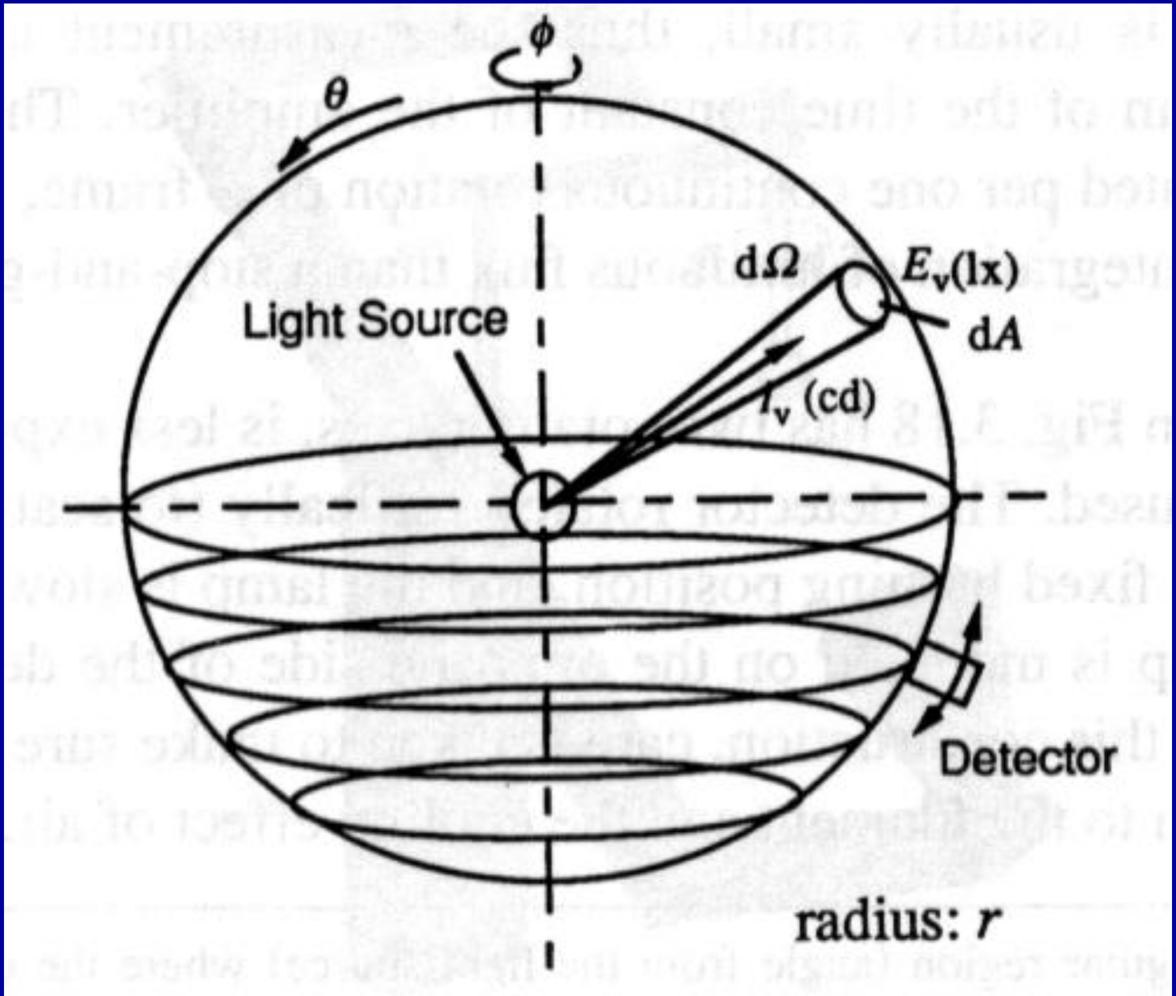
# Traditional Flux Measurements
## Goniometers

- Requires large test distance, large spaces, high ceilings
- Sensitive to stray light (need dark room)
- Typically optimized for precise angular measurements
- Scan times can take several hours depending on accuracy and system design
- Expensive due to large size and precise movement
- Only a few facilities have one

# Alternate Method
## High density illuminance sampling all around fixture

- Measure the illuminance at many points around an imaginary sphere enclosing the source
- Integrate over area
- Concept is not new, but advances in instrumentation makes the method inexpensive and practical

# Integrating illuminance over area



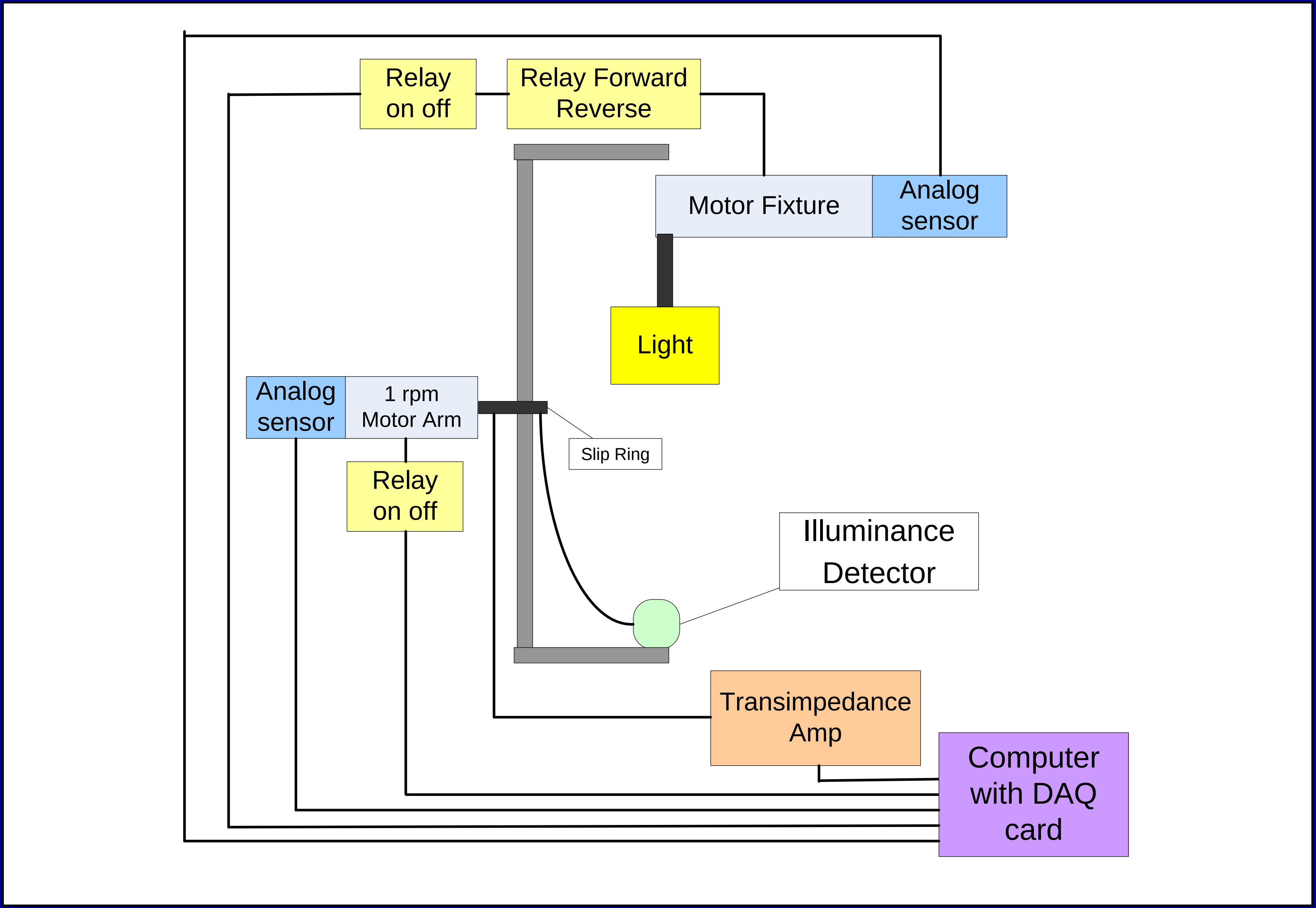

$$Flux = \int_{sphere} E dA$$

Source: C.DeCusatis, Handbook of Applied Photometry, Springer-Verlag 1998

# Design objectives

- Inexpensive (< $10,000)
  - Use off-the-shelf components
  - Avoid precise motion control (steppers, servo motors, etc.)
  - Use a minimum of space
- Quick measurement (a few minutes per sample)
  - Avoid stopping and starting
- Easy to calibrate and maintain

# Apparatus schematic

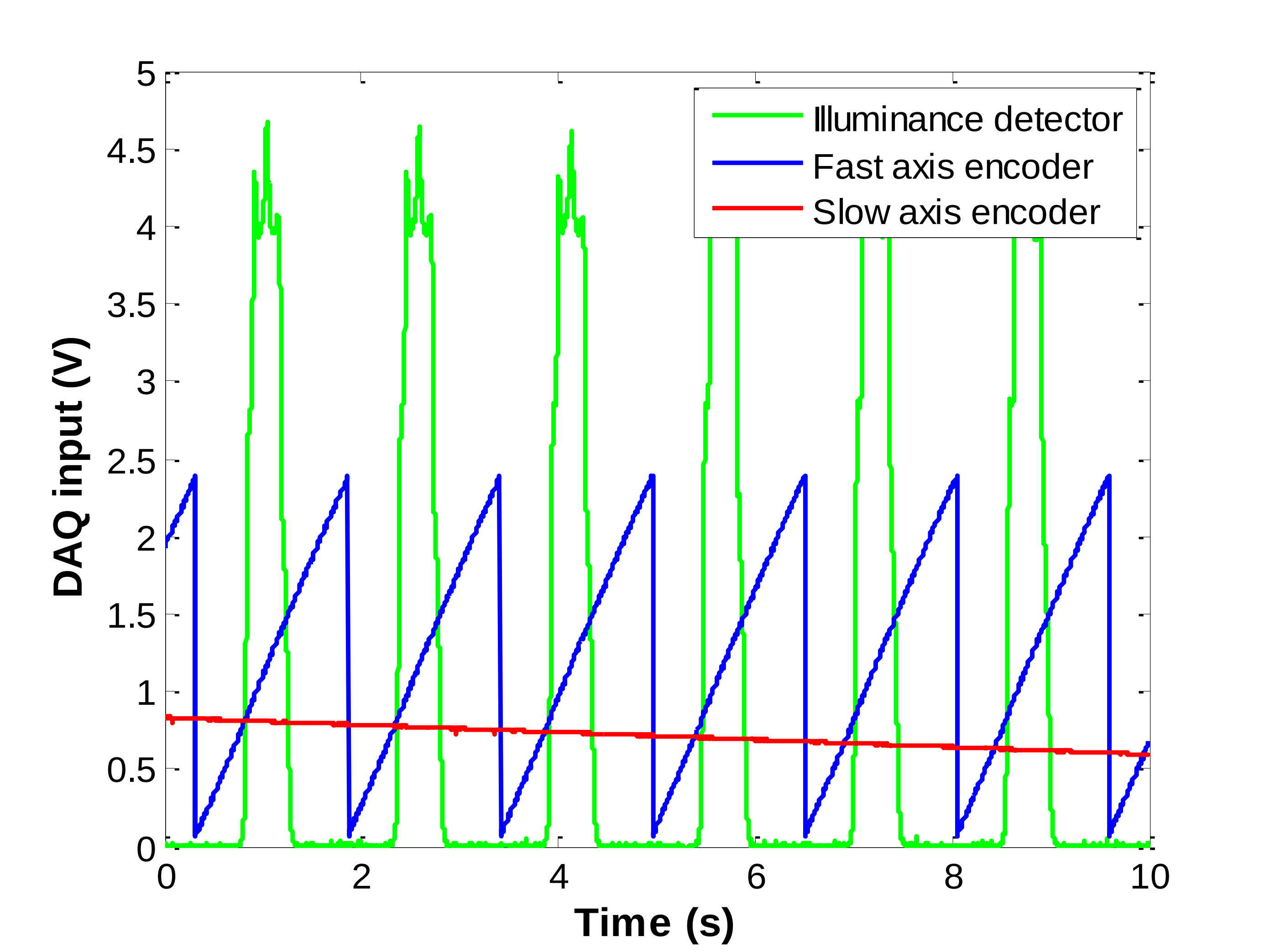


# Apparatus

- Low-cost approach
  - Exploits rapid sampling, low-cost, 12-bit computer data acquisition boards
  - Inexpensive motion control
    - Analog encoders (rotary variable resistors)
    - Continuous motion (no feedback motion control)
  - Inexpensive, robust calibration based on illuminance meter and distance
  - Cost: < $3000 plus computer and software
    - Higher cost for photocell with more accurate color correction

- Accommodates large fixtures and complete lighting systems
  - UL fixture for IC-rated thermal testing

# How it takes measurements

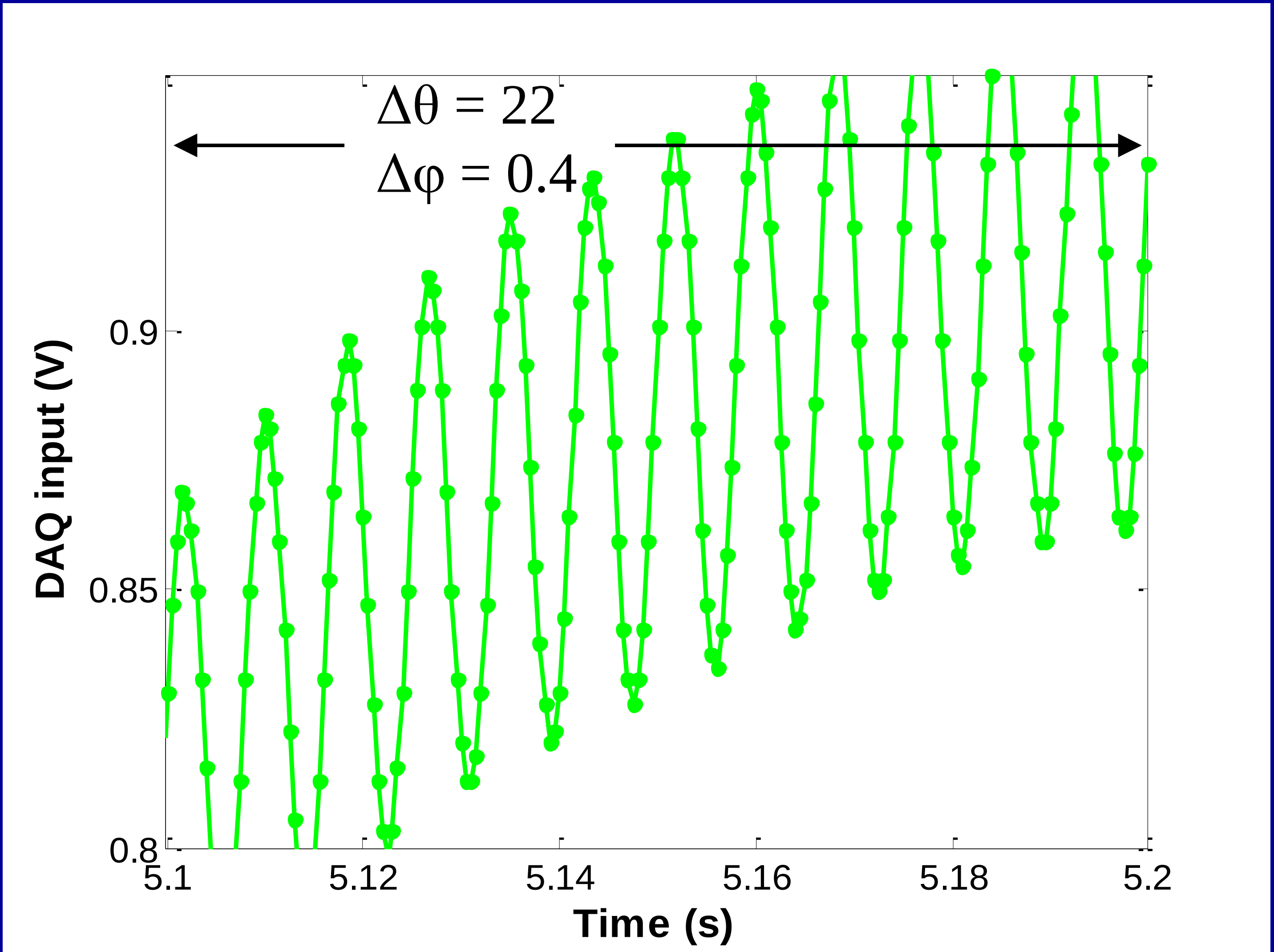


# Rotation speeds

- Fast axis (elevation angles)
  - ~ 1 revolution/s
- Slow axis (azimuthal angles)
  - ~ 0.7 revolutions/minute
- 90 revolutions of the fast axis for every revolution of the slow axis: azimuthal increments of 4

# Modulated Light sources

Incandescent A lamp, 120 Vac, 60 Hz



# Modulated sources

- 120 Hz modulation
- To obtain 10 readings per 8.3 ms period requires 1.25 kHz sample rate
- Arm swing speed = ~4 rad/s (0.6 rev/s)
- Measurement taken every 0.002 rad (0.1 degrees)
- One 120 Hz period spans 1.8 degrees
- This limits the speed of the arm

# Flux calculation algorithm

- Illuminance measurements are not recorded at regular angular increments
  - Not spaced uniformly; higher density at “poles”
  - Angular speeds of axes not precisely controlled
  - Many closely spaced redundant data points
- Need method to assign corresponding surface area (*ΔA*) to measured values in order to perform numerical integration over spherical surface area.

$$\Phi = \sum_i E_i \Delta A_i$$

# Flux calculation algorithm

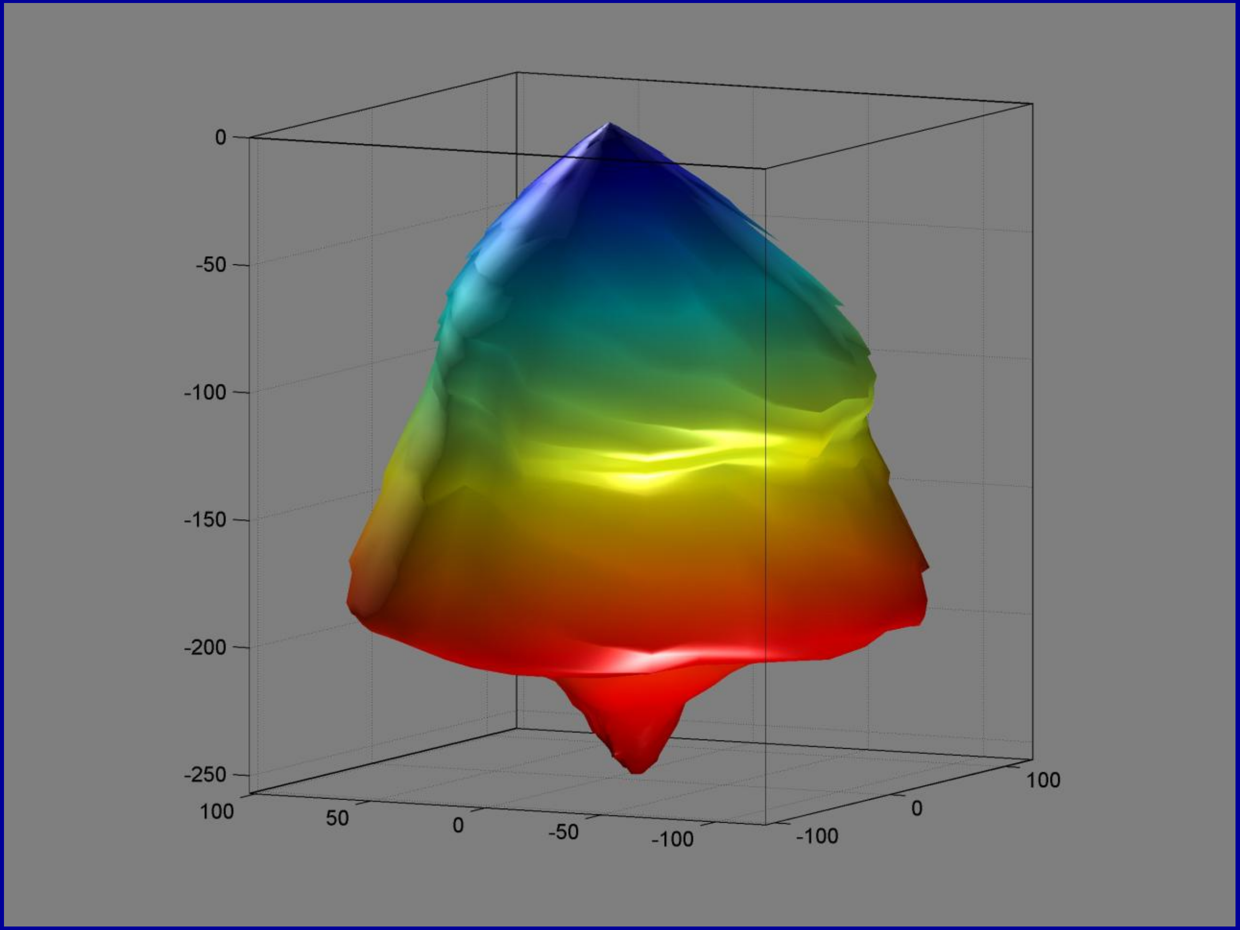
- Interpolation of data into regular grid didn't work well
  - Too time consuming and computationally difficult for large data set (200,000 data points)
  - Redundant (phi, theta) measurement locations
  - Modulated sources create too rough of a surface for interpolation – need to smoothing of illuminance surface
- Could sacrifice high precision of angular data for more stable, average illuminance values
- Used binning method to collect illuminance measurements at nearby locations and reduce data set to average illuminance values over a regular grid spherical coordinates

# Code for calculating flux

```
% Bin measurements into regular grid positions
for i = 1:length(Intensity)
    index1 = floor(theta(i)/dtheta )+1;
    index2 = floor(phi(i)/dphi)+1;
    M(index1,index2) = M(index1,index2) + Intensity(i);
    N(index1,index2) = N(index1,index2) + 1;
end
M = M./N * IntensityCal;

% Integrate intensity over grid positions
flux = zeros(180/dtheta,360/dphi);
for j = 1:360/dphi
    for i = 1:180/dtheta
        theta1 = i*dtheta - dtheta;
        theta2 = i*dtheta;
        phi1 = j*dphi - dphi;
        phi2 = j*dphi;
        deltaOmega = (cos(theta1*pi/180)-cos(theta2*pi/180))*(phi2*pi/180-
phi1*pi/180);
        flux(i,j) = M(i,j)*deltaOmega;
    end
end
totalFlux = sum(sum(flux));
```

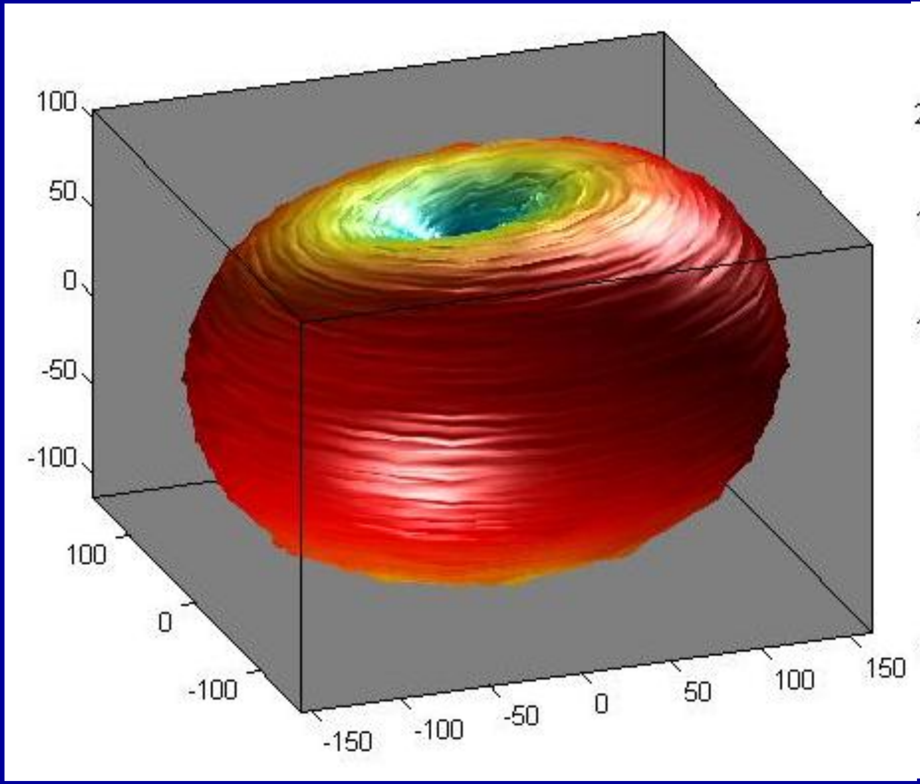
# 3D Illuminance Plot of LED Fixture



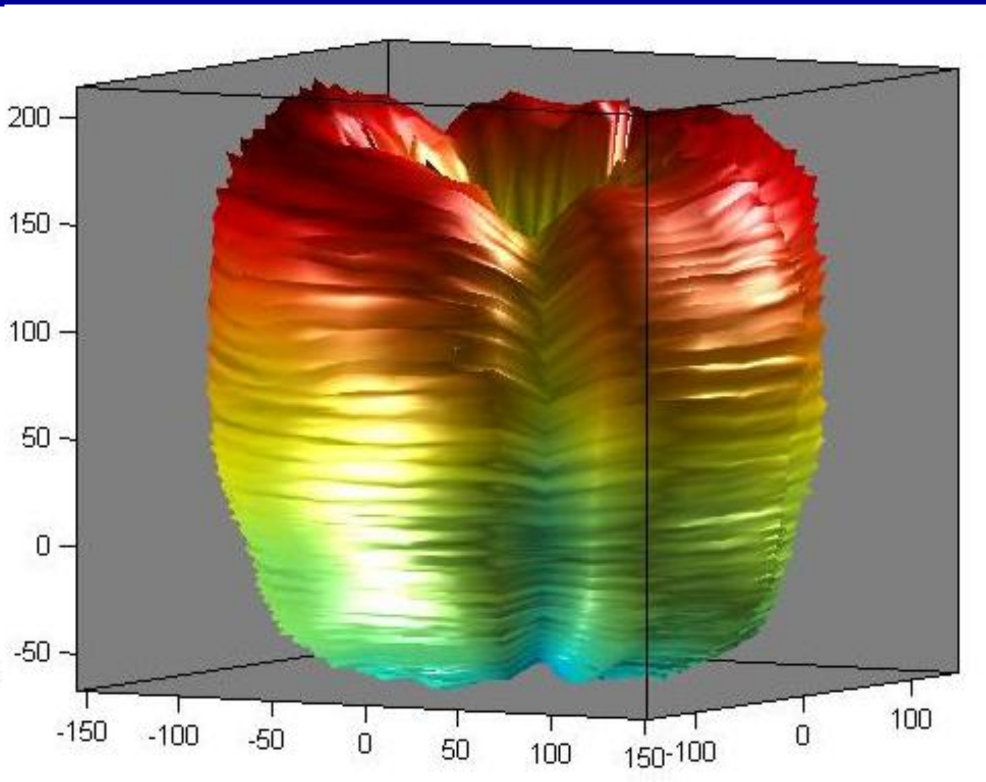

False-color coded according to illuminance (intensity)

Blue = low Red = high

# 3D illuminance plots of A19 incandescent lamps

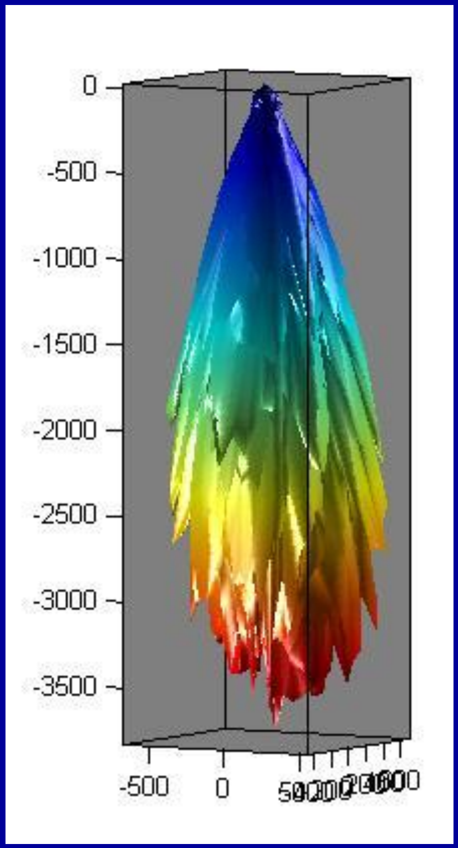



Frosted A-lamp

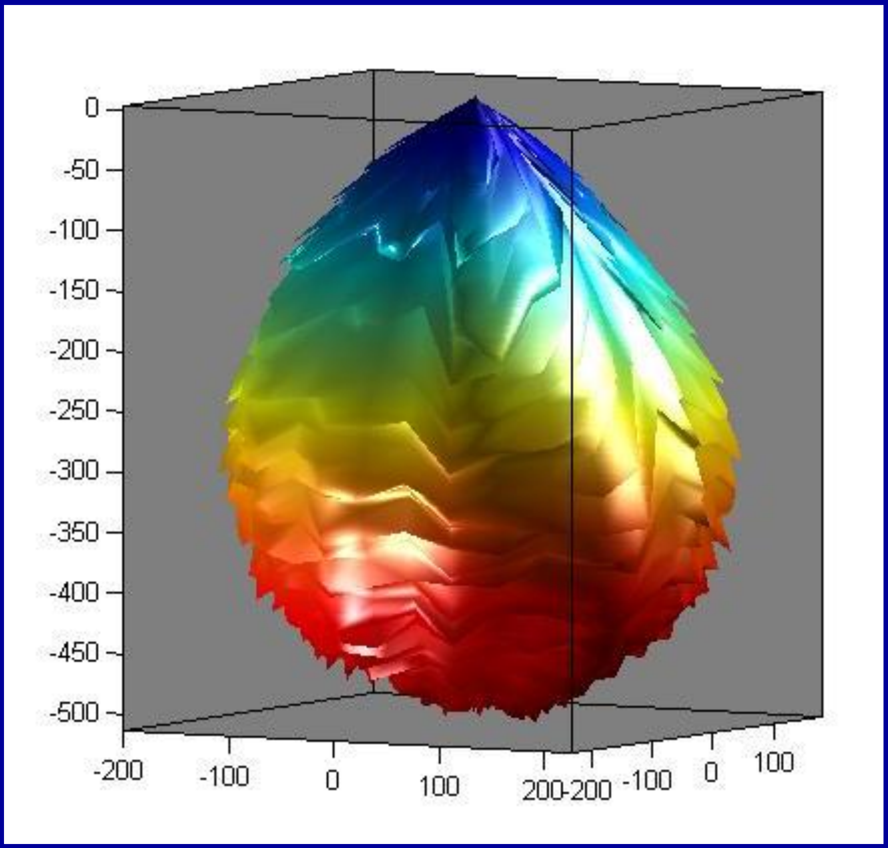



Clear A-lamp, vertical filament

# 3D illuminance plots of directional sources

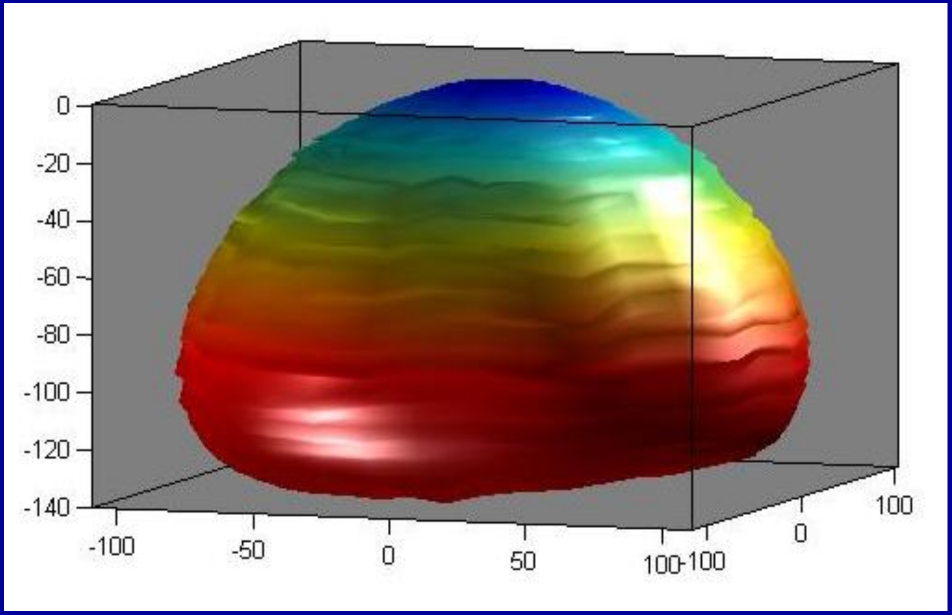



Incandescent PAR 36

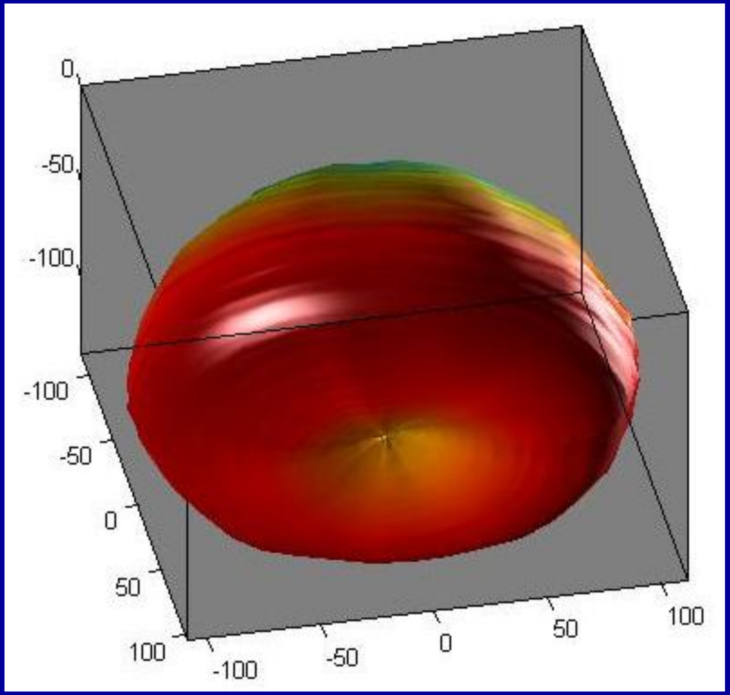



LED downlight fixture

# 3D illuminance plots of CFL down light




Side view




Bottom view

# Comparison with integrating sphere

| | | Lamp Type | | |
|---|---|---|---|---|
| | 60W A-19 Soft-white | 100W A-19 Frosted | 100W A-19 Clear | 50W PAR 30 Lamp |
| | | | | |
| Sphere (lm) | 811 | 1692 | 1647 | 655.1 |
| | | | | |
| Flux-O-Meter (lm) | 828 | 1730 | 1690 | 655.5 |
| | | | | |
| Difference (%) | 2.1 | 2.2 | 2.6 | 0.1 |

Stray light likely accounts for the 2% larger readings for the Flux-O-meter for omni-directional light sources. Stray light is minimized for directional light sources (e.g. PAR lamp).

# Comparison with commercial goniometer system using CFL fixtures

| | 20W Circline (bare lamp) | Fixture #1 | Fixture #2 | Fixture #3 |
|---|---|---|---|---|
| | | | | |
| Goniometer (lm) | 1232 | 818 | 1132 | 640 |
| | | | | |
| Flux-O-Meter (lm) | 1272 | 872 | 1190 | 673 |
| | | | | |
| Difference (%) | 3.2 | 6.4 | 5.0 | 5.0 |

Which measurement is correct?

The measurement differences shown here likely result from the sample changing due to temperature, repositioning, etc, and are not indicative of the accuracy of the Fluxometer.

# Comparison with Integrating Sphere

| | | Lamp Type | |
|---|---|---|---|
| | CFL, integral ballast | White LED parabolic fixture | RGB LED Downlight |
| | | | |
| Sphere (lm) | 1163.6 | 690.9 | 308.1 |
| | | | |
| Flux-O-Meter (lm) | 1182.2 | 686.6 | 316.2 |
| | | | |
| Difference (%) | -1.6 | 0.6 | -2.6 |

When temperature and stabilization times are tightly controlled comparisons between different measurement techniques agree much better.

# Benefits / Limitations

- No minimum distance requirements
- No flux standards (Calibration is based on illuminance and distance)
- Not sensitive to positioning of source
- Not sensitive to source size, color, shape
- Slight sensitivity to distribution (beam vs. blob) due to stray light
- Provides intensity distribution data for some small fixtures

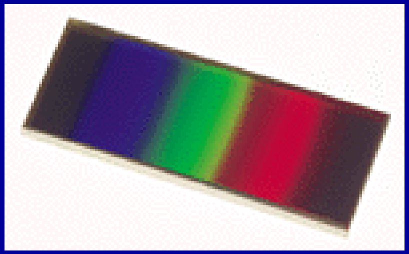
- Short measuring distance prohibits calculating intensity distribution for many sources
- Sensitive to stray light (requires black surroundings)
- Mounting support blocks small solid angle (not an issue for directional light sources)
- Wind drafts from rotating arm affect temperature stability (slower rotation speed or more aerodynamic profile is needed)

# Adding color capabilities

- Add a variable narrow bandwidth sensor to the swinging arm
- Measure spectral flux for each wavelength setting
- High resolution angular information is preserved for each narrow band spectral measurement
  - Enables analysis of color uniformity as well as integrated color properties as had with sphere measurements

# Narrow bandwidth spectral sensor

- Linear variable interference filter
  - Schott Veril
  - 400 – 700 nm
  - 10 – 18 nm half bandwidth



- Wireless Bluetooth radio link controlls stepper motor  to adjust slit position
- Sensor output to DAQ card via slip rings

# Color Sensor Issues

- Light collection is very limited
  - Angle dependency limits measurements to small, point source like fixtures
  - Diffuser required for larger fixtures reduces signal strength
    - Limited to high flux fixtures
- Time required for full spectrum scan
  - 5 nm sampling interval, 400 – 700 nm
  - Measurement time = 90 minutes