Pitfalls in Optical Testing

Commonly Made Mistakes and What to Watch Out For
Managing Unreal Expectations For Testing
Sometimes Physics Gets In The Way

- Customer Expectations Can Be Unrealistic
  - Unattainable Accuracy
  - Unavailable Traceability
  - Oversimplification of Complexity of Measurement
  - Limitations on simulating the application in the test setup
Example: Focal Length

- What is it?
- Distance from rear principal plane to focal plane (Effective Focal Length, EFL)

Smith, Modern Optical Engineering
Example: Focal Length

- How is it measured?
- Three common methods:

- Nodal Bench

- Double Slit (Focal Ratio)

Magnification \( (x' \tan \theta) \)

EFL = \( x' / \tan(\theta) \), where \( x' \) is the image height at angle \( \theta \)
Example: Focal Length

Question:
- “Why can’t I get a NIST traceable focal length measurement?”

Answer:
- Error sources can be established and estimated as described
- NIST Tech Note 1297 provides direction
- Refer to OSA Webinar Last Month:
Example: Focal Length

Question:
- “How do lens aberrations affect results?”

Answers:
- Lens aberrations do matter
Example: Focal Length

- Consider a 50 mm F/1.2 LWIR Lens
Example 1: Focal Length

- ZEMAX tells me the Paraxial EFL is 49.993 mm
What Gives?!

- Measured EFL result is 50.322 mm

  - Measured by recording image height ($x'$) at off axis angle, $\theta$, of 0.5 degrees

  $EFL = \frac{x'}{\tan(\theta)}$

- Difference between measured EFL and predicted EFL is
  
  50.322 - 49.993 = 0.329 mm or approximately 0.6%!
It’s a ‘perfect’ lens...

- Lens is Diffraction Limited and has very little distortion at 0.5 Degrees Off Axis.
The effect of off axis centroid

- Look at Centroid Locations
- Aberrations Cause Shift of Off Axis Centroid Location, Relative to Chief Ray
That Feels Better...

- Calculate EFL from Centroid location at 0.5 Degrees
- Result is 50.293 mm
- Now, the difference between measured EFL and predicted EFL is $50.322 - 50.293 = 0.029$ mm or approximately 0.05%!
Accurate EFL Measurements – Not Easy

- Focal length from chief ray location is different than focal length from centroid location.
- This difference degrades the accuracy of focal length measurements.
- Severely abberated images can cause significant differences between chief ray and centroid locations.
- Remember, this affects distortion measurements too!

These are real images!!!
Example 2: Non-Circular Apertures

- Consider a lens with a 3-leaf Iris Aperture
- What’s the F/# of this lens?
Example 2: Non-Circular Apertures

- **F/# = EFL/Ent. Pupil Diameter**

- What is Entrance Pupil Diameter?

- Lens diffraction limited performance (related to F/#) will be different in different directions

   Closeup of the Aperture
Example 3: What is “White Light”?

![Graph showing the spectrum of white light and solar spectrum. The graph compares the light intensity across different wavelengths, with a blue line indicating the 400-700 Band and an orange line showing the Solar Spectrum (5500 K).]
Example 3: How do I approximate “White Light”?

- Metrology Instrument Response = Source x Camera
What is “White Light”

- Could use Mercury-Xenon arc lamp source.
What is “White Light”

- Could use “White” Phosphor LED

www.trainweb.org

www.candlepowerforums.com
Conclusions

❖ Best case scenario: Use same source and sensor in the test setup that will be used in lens application

❖ Or, use source/camera combination with well characterized spectral response; Use this response to predict lens performance

❖ Or make monochromatic measurements at several wavelengths
Takeaway: Manage expectations by clearly stating the goals of the measurements and the constraints of the metrology setup
Questions?
Correlating and Comparing MTF Measurements with Interferometric Measurements
Optical systems can be evaluated in two ways:

- Measure transmitted wavefront with an interferometer
- Record the line spread function at the image plane and calculate the MTF
MTF vs. Interferometry

- Interferometers measure the transmitted or reflected wavefront.
- MTF is derived from acquisition and Fourier transform of the point spread function.
What to watch for...

- How do these results differ?
- How do these differences affect how these results correlate?
Major Differences

MTF
- Polychromatic
- Generally Measured in Two Orthogonal Directions at Image Plane
- Includes effects from Stray Light & Ghosting

Interferometry
- Generally Monochromatic
- Provides 2D Map of Wavefront Topography
- Does Not include effects from Stray Light & Ghosting
What are Stray Light and Ghosts?

Unintended light in an optical system, causing overall decrease in contrast.

Secondary images generally caused by reflections between lens surfaces and/or sensor cover glass.
Because Interferometers measure transmitted wavefront at the pupil, they do not “see” the light from stray light and ghosting at the image plane.

Since MTF is derived from all of the light falling at and near a specific field point in the image plane, MTF results will be degraded by stray light and ghosts.

“Strehl Can Tell” the difference....
Chromatic Aberrations

- Most interferometers use laser sources; measurements are performed at the laser wavelength

- MTF measurements can be polychromatic; allows characterization of chromatic aberrations
Questions?
Validating and Calibrating Test Equipment
What are Calibration & Validation?

- **Calibration**
  - Comparison of measurements to a known standard (usually traceable)

- **Validation/Verification**
  - Check that a metrology system is operating correctly and meets specifications
Optical Metrology Equipment

- NIST Provides Calibration Service for Some Optical Parameters are NIST Traceable
  - Optical Radiation
    - Luminous Intensity and Color Temperature
    - Photometers, Illuminance & Luminance Meters
    - Spectral Transmittance & Reflectance
    - Radiometric Measurements
    - Laser Power, Optical Fiber Power, etc.

- Some parameters are not NIST Traceable - accuracy is estimated from uncertainties of error sources
  - Effective Focal Length (EFL)
  - Modulation Transfer Function (MTF)
Example: Validation of EFL

Reference Lens: Plano-Convex Singlet EFL depends on only two parameters - Radius of Curvature and Index of Refraction

Picture of RL-400

- Calibrated radius of curvature
- Index of refraction measured with Abbe refractometer.
Example: Validation of MTF

- Audit Lens is designed to have diffraction-limited performance on axis over a specific spectral band. Multi-element design with higher numerical aperture than Reference Lens.

- For example, the Optikos AL-300 LWIR Audit Lens.
Validation of MTF

- MTF specification can be calculated from wavelength and F-number.

![Graph showing Modulus of the OTF vs. Spatial Frequency in cycles per mm]

<table>
<thead>
<tr>
<th>Polychromatic Diffraction MTF</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL-300 LWIR Audit Lens, Rev 1</td>
</tr>
<tr>
<td>5/20/2013</td>
</tr>
<tr>
<td>Data for 8.0000 to 12.0000 μm.</td>
</tr>
<tr>
<td>Surface: Image</td>
</tr>
</tbody>
</table>

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Pitfalls of the Measurement

- Need accurate measurement of the lens entrance pupil diameter and EFL – these affect F-number

- Need accurate characterization of source and detector spectral weighting. These affect polychromatic diffraction limit.

- Alignment of the lens to the optical bench axis is critical
Alignment Matters!

- Lens alignment is critical to obtaining accurate MTF results

- The Optikos OG-1200 source provides both visible and infrared illumination; it also has a convenient crosshair alignment target
Uncertainty of MTF Validation

- Uncertainties associated with
  - Audit Lens Construction (Radii, Material Indexes, Etc.)
  - Measurement Parameters (Spectrum, Focus)
  - Collimator Errors (Focus, object size, etc.)
  - Test System Errors (Spatial Frequency, Signal Processing)
  - Refer to "The Optical Transfer Function of Imaging Systems: - Tom Williams, 1999"
  - Typical uncertainty of Audit Lens MTF measurements is on the order +/-2%

- It is NOT advisable to add a "fudge factor" to correct for differences between the theoretical and measured MTF!
Questions?
Collimators, Fold Mirrors, and Chromatic Aberration Considerations
What is a Collimator?

- Many optical systems are designed for objects at infinity
- A collimator is part of a metrology system that projects an infinitely distant object (ideally, a perfectly planar wavefront) into the lens under test
- In practice, residual aberrations in a collimator must be considered
Types of Collimators

- Reflective using off axis parabolic mirrors (OAP)
- Refractive using collimating lens
Refractive vs. Reflective Collimators

Refractive

- Chromatic aberrations need to be considered
- Generally less expensive
- Generally can be used only over discrete spectral bands
- Can be used without folding
- Lens under test can be close to collimator – more compact system layout
- Maximum apertures limited
- Off axis performance may be corrected

Reflective

- Truly wavelength independent
- Generally more expensive
- Can be used over multiple wavebands
- Generally require fold (or central obscuration)
- Fold requires some distance between collimator and lens under test – larger system layout
- Large beam diameters possible
- Off axis performance is set by OAP geometry
Residual Collimator Aberrations

- Axial aberrations are scaled by magnification squared (axial color, astigmatism), where

\[ \text{Magnification} = \frac{EFL_{\text{Test Lens}}}{EFL_{\text{Collimator}}} \]

- Spatial frequencies of collimator aberrations are scaled by the magnification.
Example Refractive Collimator

- 365.5 mm Doublet
  (Edmund Optics #31-402)
A Typical Lens To Be Tested

- 25 mm EFL F/2 lens.
- Entrance Pupil Diameter of Lens is 12.5 mm
- Let’s consider measurements at 200 lp/mm.
Ratio of Focal Lengths

- Ratio of Lens to Collimator Focal Lengths is: \( \frac{25.0}{356.5} = 0.070 \)

- Spatial frequency in the plane of the 25mm lens scales to the collimator focal plane:
  - \( 200 \text{ lp/mm} \times 0.070 = 14.0 \text{ lp/mm} \)

- Longitudinal aberrations scale with the square of magnification:
  - \( 0.070 \times 0.070 = 0.0049 \)
Effect of Collimator Aberrations

- F/2 Lens has \( \approx \pm 4 \) microns depth of focus
- Lens Design shows collimator has 300 microns of longitudinal chromatic aberration over the visible spectrum (400-700 nm)

\[
300 \times 0.0049 = 1.48
\]

- This becomes 1.48 microns in the focal plane of the 25 mm lens... not a problem.
Effects of Collimator Aberrations

- Effective F/# of Collimator is 356.5/12.5 ~ F/30
- 200 lp/mm * 0.07 = 14 lp/mm
- At 14 lp/mm, the collimator is nearly diffraction limited... great!
Effect of Collimator Aberrations

- What if we tried to test a 250 mm F/8 with this same refractive collimator?

- Lens has Entrance Pupil Diameter of 31.25 mm

- Let’s consider measurements at 100lp/mm.
Ratio of Focal Lengths

- Ratio of Lens to Collimator Focal Lengths is: \( \frac{250}{356.5} = 0.70 \)

- Spatial frequency in the plane of the 25mm lens scales to the collimator focal plane:
  - \( 100 \text{ lp/mm} \times 0.70 = 70 \text{ lp/mm} \)

- Longitudinal aberrations scale with the square of magnification:
  - \( 0.7 \times 0.7 = 0.49 \)
Effect of Collimator Aberrations

- F/8 Lens has $\approx \pm 64$ microns depth of focus

- Lens Design shows 300 microns of longitudinal chromatic aberration over the visible spectrum (400-700 nm)

- $300 \times 0.49 = 148$ microns

- This becomes 148 microns in the focal length of the 250 mm lens... This is a problem!
Effects of Collimator Aberrations

- Effective F/# of Collimator is 356.45/12.5 ~ F/30
- 100 lp/mm * 0.7 = 70 lp/mm
- At 70 lp/mm, the collimator is NOT diffraction limited!
Summary

- For refractive collimators, be sure to have sufficient magnification (focal ratio) to minimize collimator aberrations.

- For reflective collimators, be sure that extended targets do not exceed the useable field of view.
Questions?
Infinite vs. finite conjugate testing
A customer had a problem lens

- A customer asked us to troubleshoot a poorly performing lens.
- They expected good performance according to lens specifications.
The customer did not understand why their lens wouldn’t work at infinite conjugates.
Imaging at multiple conjugates

- On a theoretical basis, these restrictions exist because of the need to satisfy both the Abbe and Herschel conditions.
- It is very difficult to design a highly corrected system to work at differing magnifications over a non-zero field of view.
Example: Doublet at two conjugate pairs

Object at infinity

Object at 1 m (Best focus at 50% cutoff)

$\lambda = 590 \text{ nm}$
Optical imaging systems are designed to work for specific image and object conjugate pairs and fields of view.

It is important to calculate or measure the optical performance at the conjugates at which the system will be used.

Extrapolating performance to differing conjugates is not advisable.

**Conclusion**

Infinite conjugate

Finite conjugates
Questions?
Optical Transmission of a system
Measuring Optical Transmission

Is this system measuring optical transmission?
Measuring Optical Transmission

What optical phenomenon do you want to measure?

**Relative Illumination**
Apparent relative transmission of the optical system across the image plane.

**Spectral transmission**
Spectral variation of transmission due to glass/coatings/filters.

**T/##**
Optical collection based upon étendue.

**Absolute transmission**
The ratio of beam intensity with and without the lens in place.

**Ghost reflections/ lens flare/veiling glare**
Increased transmission of light from off axis sources or internal reflections.
You are not able to gain information on collection efficiency due to étendue, spectral transmission, stray light effects, effects due to the pupil distortion, vignetting, etc.

Difficult to measure spectral effects.
You can look at the effects of scattered light in the system.

Spectral information can be obtained with a polychromatic source and a spectrometer.

The addition of a beam dump in the field of view of the detector will allow you to measure veiling glare.
Illuminate the optical system with a collimated beam.

The collimated beam diameter is set by a controlled aperture.

An integrating sphere with an aperture larger than the controlled aperture collect all transmitted light.

An optical system is then placed behind the aperture.

The integrating sphere is placed in the image plane.

The ratio of these two measurements is the absolute transmission.
Remember!

- What are you trying to measure?
- This will guide how you measure transmission.
Questions?
Measuring the Strehl Ratio
Customer request

- We were asked by a company to measure the performance of a UV imaging system.
  - We were asked to calculate the Strehl ratio.

- Our Strehl ratio calculations were always 5% to 13% lower than the customer’s.

- We were using MTF to calculate the Strehl ratio, the customer was using measured wavefront.

- After much investigation we discovered there were significant system effects not captured in the interferometric Strehl ratio calculation:
  - Surface roughness
  - Scattering from coatings
  - Scattering from the central obscuration
  - Ghost reflections
  - Scattering within the glass materials
Strehl Ratio

- Strehl ratio is an optical performance metric proposed by Karl Strehl.
- Interferometry and MTF measurement can be used to calculate the Strehl ratio.

\[ S = \frac{I}{I_{diff}} \]  
\[ S = e^{-i4\pi\sigma^2} \]
Advantage of Modulation Transfer Function

Strehl ratio calculations based on MTF will capture effects of stray light and ghosting.
Interferometry can be used to measure the optical system wavefront aberration.

The measured wavefront deviation can be used to calculate the Strehl ratio:

\[ S = e^{-i4\pi \sigma^2} \]

What isn’t seen with an interferogram?
- Stray light/Ghosts/Scatter
- Chromatic effects
Example: Dirty vs. Clean lens

“Dirty Lens”

PV = 0.212, RMS = 0.033, PTS = 4041

“Clean Lens”

PV = 0.214, RMS = 0.037, PTS = 4084

Modulation (%) vs. Frequency (lp/mm)
Conclusions

- Strehl ratio can be a useful metric to assess system performance of high quality optical systems with a single number.
- The Strehl ratio can be calculated using measurements of the wavefront error or MTF of an optical system.
- Measuring the wavefront error alone may hide some sources of optical performance degradation such as:
  - Stray light
  - Ghost imaging
  - Scattering
  - Polychromatic effects
- Measuring MTF is a more comprehensive way to calculate the Strehl ratio.
Questions?
Concatenating MTF’s
An optical system can be thought of as a linear system where the MTF is the frequency response of the optical system.

There are situations where the system MTF can be approximated by the multiplication of two separate MTFs.
Example: Relay system
Example: Measuring MTF

How can you remove the source and analyzer contributions from the measured MTF to yield the test lens MTF?
Example: Measuring MTF

- Answer: You cannot correct for contributions from the collimator or image analyzer.
- The image analyzer and collimator optics need to have diffraction limited performance over the F/# of the unit under test.
- Aberrations in the unit under test will define the geometric optics contribution to the pupil function.
- The unit under test needs to be limiting aperture.
Example: Optical MTF and Sensor MTF

• You can calculate the best case sensor MTF using the pixel pitch.
• The system MTF is the product of the lens MTF and the sensor MTF.
Questions?
Thermal Source Calibration
Thermal Target Generation

Thermal Target Generators are used for qualifying IR camera systems.

- Generally consist of a temperature-controlled plate mounted behind an ambient temperature aperture target.
- Source plate temperature is controlled, but both the source plate and the aperture target temperatures are measured using physical temperature probes.
Thermal Target Collimation

- Quite often, these target generators are used with reflective or refractive collimators to present an infinitely distant object to the UUT.
Does Source Temperature Matter?

- Some measurements, such as MTF, FOV, and Distortion, do not require the source temperature to be known.

- Others, such as SiTF, MRTD, NETD do.
How Hot (or Cold) is the Target?

- Hotter (or Colder) than it looks!
- We can measure the Physical Temperature very precisely
- Photon flux leaving the source \((e<1)\) is less than the flux leaving a perfect blackbody of the same temperature
- Photons flux is attenuated by collimating optics
- Need to calibrate the “blackbody temperature” of the source as seen by the UUT (Unit Under Test) as a function of physical temperature
The Infrared Radiometer

- Radiometric Calibration is performed using a scanning Infrared Radiometer
- A single pixel Infrared Imager
Transfer Standard

- The radiometer is a transfer standard from an ideal blackbody source...

...to the target system
Radiometric calibration

- In systems that generate thermal contrast, calibration is carried out in the same manner using a scanning radiometer and an edge target.

- Edge target is scanned by the radiometer at several different physical temperature differences.

- In each trace, the radiometric temperature difference is measured.
Calibration Example

- The result from each trace becomes a single point on a calibration curve for the system.
- A curve is fitted to the graph. Flux is proportionately attenuated by a collimation system, and flux is not a linear function of temperature.
- So ...
...radiometric temperature differences are **not** proportional to physical temperature differences

But over modest temperature ranges they very nearly are. A second-order fit is a very good approximation.
And finally...

The test software can take the closed-form calibration equation and use it to set an apparent blackbody temperature.

Now the target will appear to be precisely as warm as you need it be.

In thermal imager testing, it’s all about appearances.
Questions?
Questions and Answers

❖ Thank you! Please submit any questions!

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