Optical Filters: Flatness

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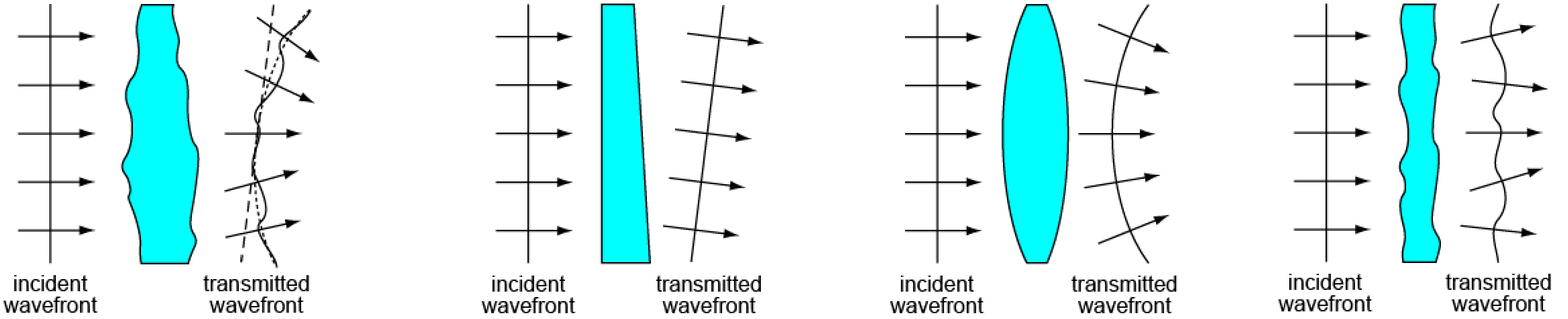
Wavefront error and flatness

- Transmitted Wavefront Error (TWE) is usually defined to be what is left after tilt (caused by wedge of a transmitting component) and spherical error (caused by lens-like nature of a component) are removed
- TWE is caused by deviations of a transmitting glass component from a perfect plane parallel plate, including both thickness deviations and inhomogeneity of the index of refraction

Total TWE = **Tilt TWE contribution** + **Spherical TWE contribution** + **Irregularity TWE contribution**



More on Transmitted Wavefront Error (TWE)

- TWE is measured using an interferometer (like a ZYGO system) and specified in units of “waves” – or wavelengths of light at either 633 nm (US standard) or 546 nm (ISO standard)
  - Thus the actual physical deviation of the distorted wavefront from a perfect wavefront is TWE in waves X 633 nm (or 546 nm)
- TWE is specified as an absolute (peak-to-peak) error, or as an RMS (root-mean-square) error, or both
  - When it is dominated by irregularity, it is common to take the RMS error to be ¼ of the absolute error
- Generally it is not too difficult to control the TWE to meet the most commonly desired tolerances (typically $\lambda/4$ to 1λ, RMS)
- *NOTE: for most filters, ONLY TWE matters – beware that many people try to specify flatness or reflected wavefront error when all they really need to control is the TWE!*

Reflected Wavefront Error and Flatness

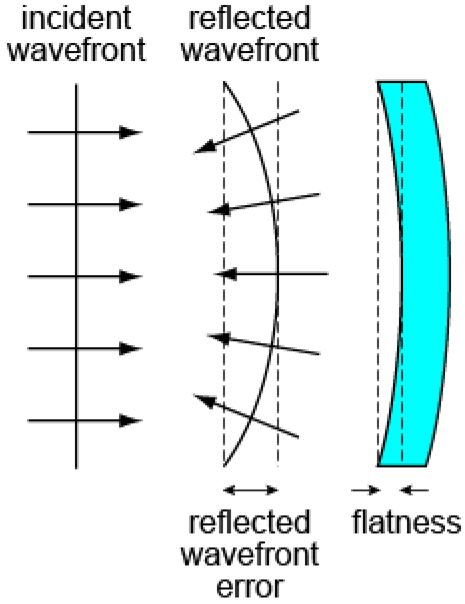
- Reflective Wavefront Error (**RWE**) is simply the deviation of a wavefront reflected off of a component relative to a perfect wavefront reflected off of a perfectly plane surface

- **Flatness** is the actual physical deviation of a component surface from a perfectly plane surface

- At normal incidence, the flatness and RWE are simply related by a factor of 2

RWE = 2 x Flatness

Flatness = ½ x RWE



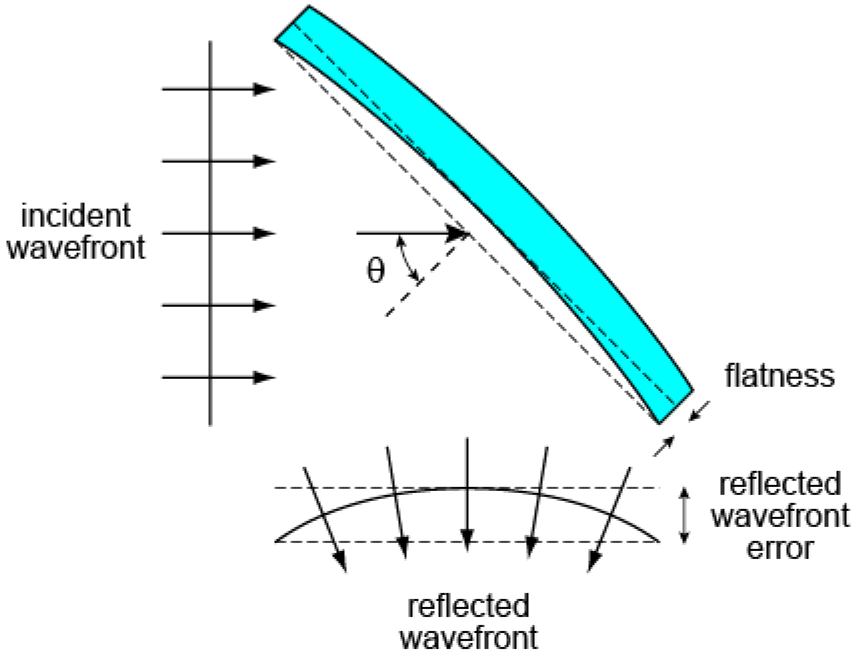
- *NOTE: flatness (and RWE) ONLY matters when a filter will be used in a reflection geometry!* *(example: 45 deg dichroic beamsplitter)*

RWE and Flatness – Non-normal Incidence

- At non-normal incidence, the relationship between flatness and RWE depends on the angle of incidence θ

$$\mathbf{RWE = 2 \times \cos\theta \times Flatness}$$

$$\mathbf{Flatness = \frac{1}{2 \times \cos\theta} \times RWE}$$

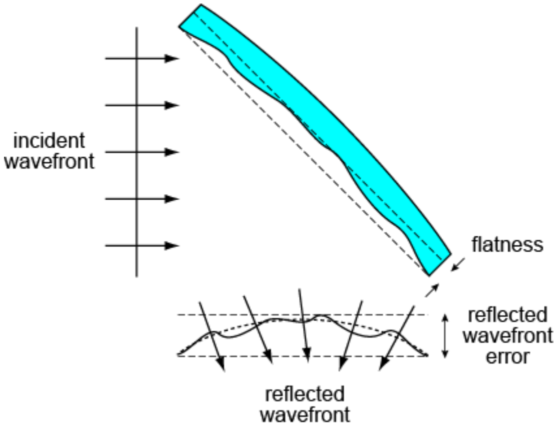


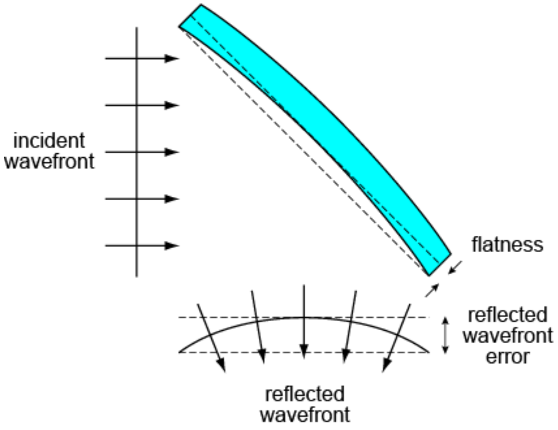
- *NOTE: flatness (and RWE) ONLY matters when a filter will be used in a reflection geometry!* (example: 45 deg dichroic beamsplitter)

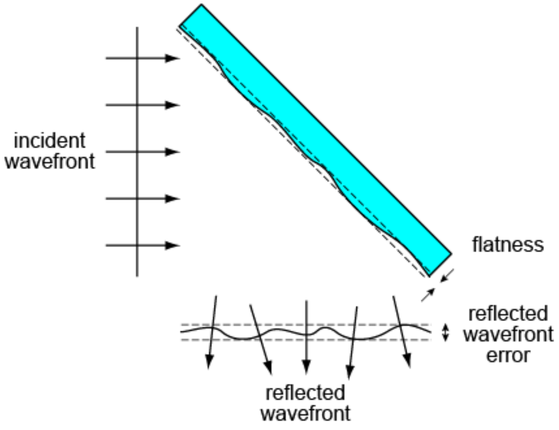
Contributions to Reflected Wavefront Error

- Reflected Wavefront Error (RWE) may also be separated into different contributions:
  - **Spherical** error – best fit of the reflected wavefront to a sphere
  - **Irregularity** – the remaining deviation from a flat wavefront

Total RWE = **Spherical** **RWE contribution** + **Irregularity** **RWE contribution**







RWE and Flatness – ISO specifications

- Flatness is specified in ISO 10110-5: “Surface form tolerances”
- Most common form is: **3/A(B)**
  - “3” is the code number that indicates the spec is surface form tolerance
  - “A” is the maximum permissible peak-to-peak spherical contribution
  - “B” is the maximum permissible peak-to-peak irregularity contribution
- Note:
  - “A” and “B” are measured in “fringes” at a wavelength of 546.07 nm, where one fringe corresponds to one half wavelength assuming the measurement is at normal incidence
  - At non-normal incidence, one fringe corresponds to 546 nm / (2*cosθ)
  - For waves of flatness (not RWE) at 633 nm, multiply the number of fringes by 0.863 / (2*cosθ)

Flatness depends on glass & coating

- Coating-stress-induced (CSI) bending contribution to flatness

$$\boxed{\delta\,[\mu m] = C\,\frac{D^2 f}{s^2}}$$

  - *C* is a dimensionless constant – depends on glass type & coating material…
  - *D* is the diameter (clear aperture) over which flatness is measured [mm]
  - *f* is the coating film thickness (for single-sided coating) or difference in film thickness (for dual-sided coating) [µm]
  - *s* is the substrate thickness [mm]

Flatness depends on glass & coating

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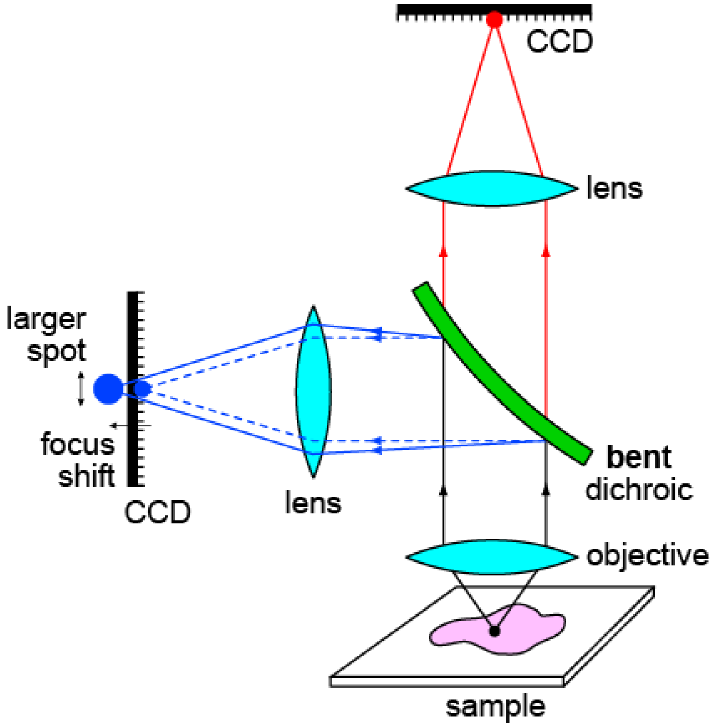
- Take-aways:
  - Flatness increases (degrades) in proportion to the **square** of the diameter *D*
  - Flatness decreases (improves) in inverse proportion to the **square** of the substrate thickness *s*
  - Flatness increases (degrades) **linearly** with the coating thickness *f*
- Conclusion: Diameter (clear aperture) and substrate thickness matter most when trying to achieve a tight flatness specification …coating thickness is of secondary importance

How to handle flatness – in summary

- Before specifying a very tight flatness tolerance, first make sure you really need flatness, and not simply TWE
- If you really do need good flatness, the best way to achieve it is with a thicker substrate (or a smaller diameter), so decide whether you have flexibility with the substrate thickness (or diameter)
- If there is no (or not enough) flexibility on substrate thickness (or diameter), it will cost something to achieve a very flat filter:
    - We can make the coating thinner, which might cost spectral performance
    - We can balance the coating on both sides of the substrate, but usually this approach requires substantially more coating time than is needed to meet the spectral requirements, and thus increases the cost of manufacturing
- At this point, turn to Semrock's experienced Applications Engineers to help you determine the most optimal solution for the customer

Flatness – why does it matter?

- When light is reflected off of a non-flat mirror or dichroic beamsplitter and then focused by a lens, two main effects result:
  1) The location of the **focus shifts** along the optical axis
  2) The focused **spot size increases**, thus causing blurring of an image
- For details, see Semrock white paper titled: "Flatness of Dichroic Beamsplitters Affects Focus and Image Quality"



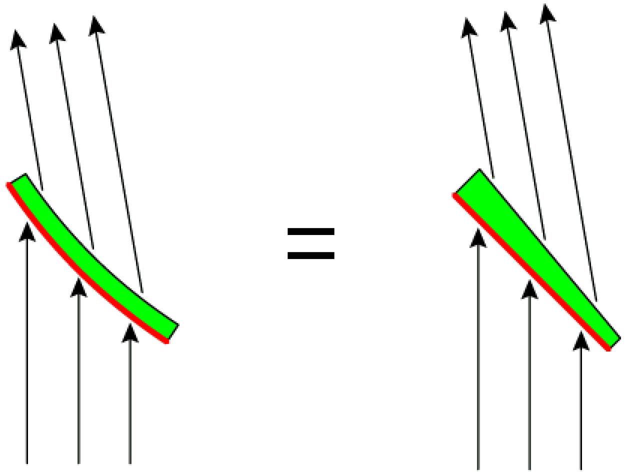
Flatness – when does it matter?

- Consider 3 cases:

1) **No light is reflected off of the filter (used only in transmission)**
    - Flatness does NOT matter!
    - Any Semrock dichroic beamsplitter will work well (“**Standard Flatness**”)
2) **Non-flatness causes a “defocus error” for smaller-diameter (laser) beams**
    - Primarily due to bending (the spherical contribution) only
    - Use BrightLine® Laser dichroic beamsplitters (“**Laser Flatness**”)
3) **Non-flatness causes spot-size blurring for larger-diameter (image) beams**
    - Due to bending and/or irregularity contributions
    - Use BrightLine Image-splitting dichroic beamsplitters (“**Imaging Flatness**”)

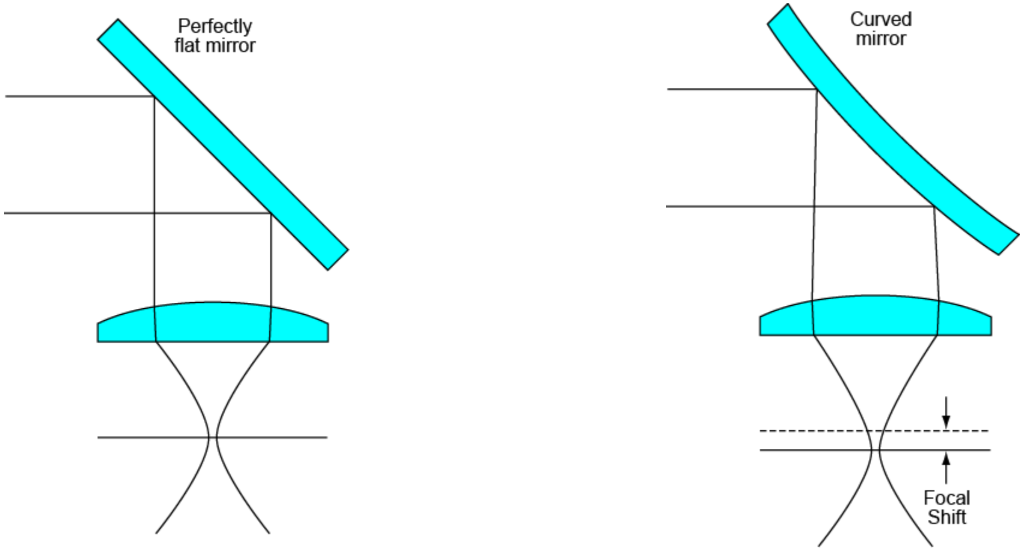
When does flatness matter? Case 1

- **Case 1:** no light is reflected off of the filter
  - In this case, the only thing that matters is Transmitted Wavefront Error (TWE) associated with light transmitted through the filter, so only TWE needs to be specified!
  - However, note that coating-stress-induced (CSI) bending causes an otherwise perfectly plane parallel plate to behave like a **wedge**, and thus results in **tilt** aberration, which causes **beam deviation**
    - So even though bending does not contribute to the TWE, it must be considered when there is a beam deviation specification or requirement



When does flatness matter? Case 2

- **Case 2:** non-flatness causes a “defocus error” for reflected smaller-diameter (laser) beams
  - CSI bending of a filter or mirror placed before a lens causes the plane of focus to shift relative to the plane with a perfectly flat mirror



- Unfortunately CSI bending can often be quite large in reflective filters (like dichroic beamsplitters), since such filters often perform best in transmission when the substrate is as thin as possible (0.5 to 1 mm), and thus customers often require thin substrates

When does flatness matter? Case 2

- **Case 2:** non-flatness causes a “defocus error” for reflected smaller-diameter (laser) beams
  - Another way to think about and/or estimate the magnitude of the defocus error is to recognize that a reflective optic with a radius of curvature *R* acts like a lens in the optical system with a focal length of *R*/2

$$\boxed{f = \frac{R}{2}}$$

  - In terms of flatness, the radius of curvature is

$$\boxed{R = \frac{D^2}{2 \times \text{flatness}}}$$

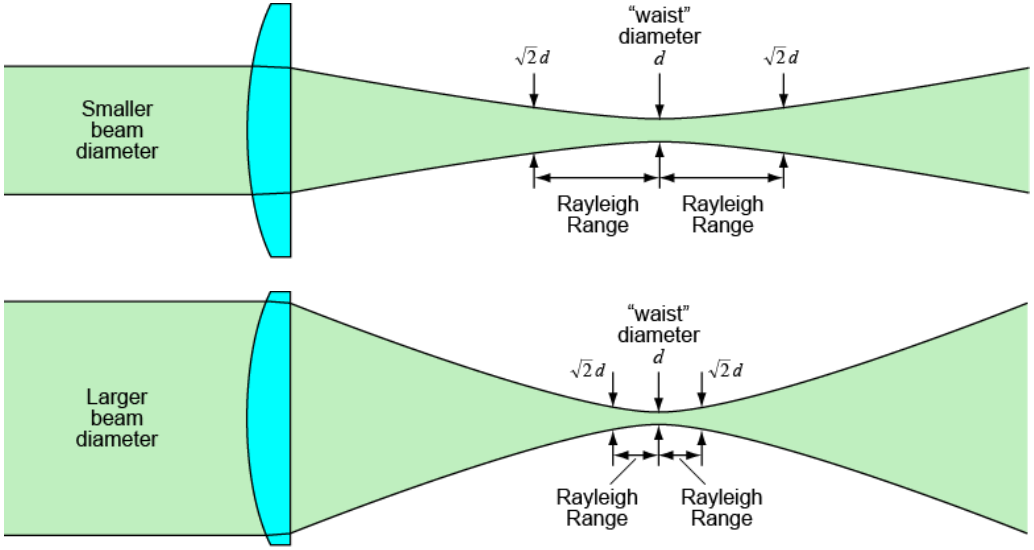
where *D* is the diameter of the region over which the flatness is specified (assuming that the flatness is dominated by spherical curvature)

When does flatness matter? Case 2

- **Case 2:** non-flatness causes a "defocus error" for reflected smaller-diameter (laser) beams
  - Usually *defocus error is NOT a problem in non-imaging systems*, where for example the light reflected off of the filter or mirror is simply directed onto a detector (like a Si photodiode or a PMT)
  - *In most imaging systems, defocus error is easily managed* since the position of the lens or the imaging plane itself (e.g., a CCD camera) can usually be adjusted
  - One case where a simple adjustment won't work is when the same lens is used to focus light reflected off of a non-flat filter onto a sample AND to focus light returning from the sample in the opposite direction
    - A common example is a laser-based microscope in which a dichroic reflects a laser beam that passes through the same microscope objective that collects fluorescence or Raman light from the sample

When does flatness matter? Case 2

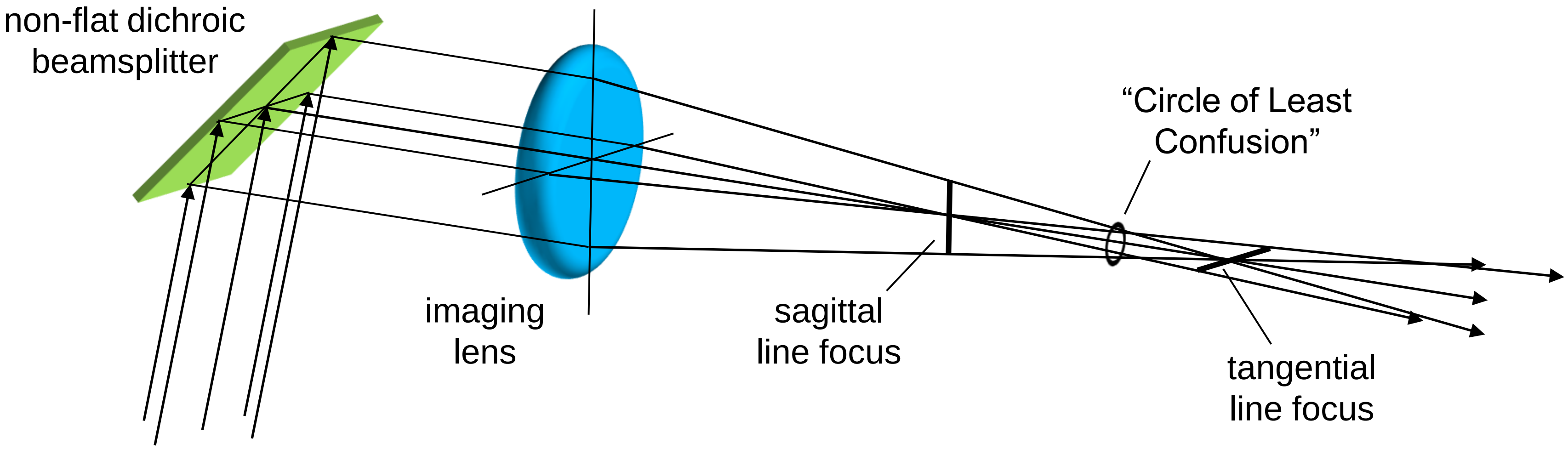
- Defocus error in a laser-based microscope
  - In this case we require the filter to be flat enough so that the focal shift is less than one “Rayleigh Range” for a given beam diameter



- For most imaging systems, the system appears to be “in focus” as long as the focal plane is within one Rayleigh Range of the exact focal plane
- Fortunately, the Rayleigh Range depends only on the (incoming) beam diameter and the wavelength of light, and is not a function of the focal length of the lens – that’s why we don’t need to specify the focal length

When does flatness matter? Case 3

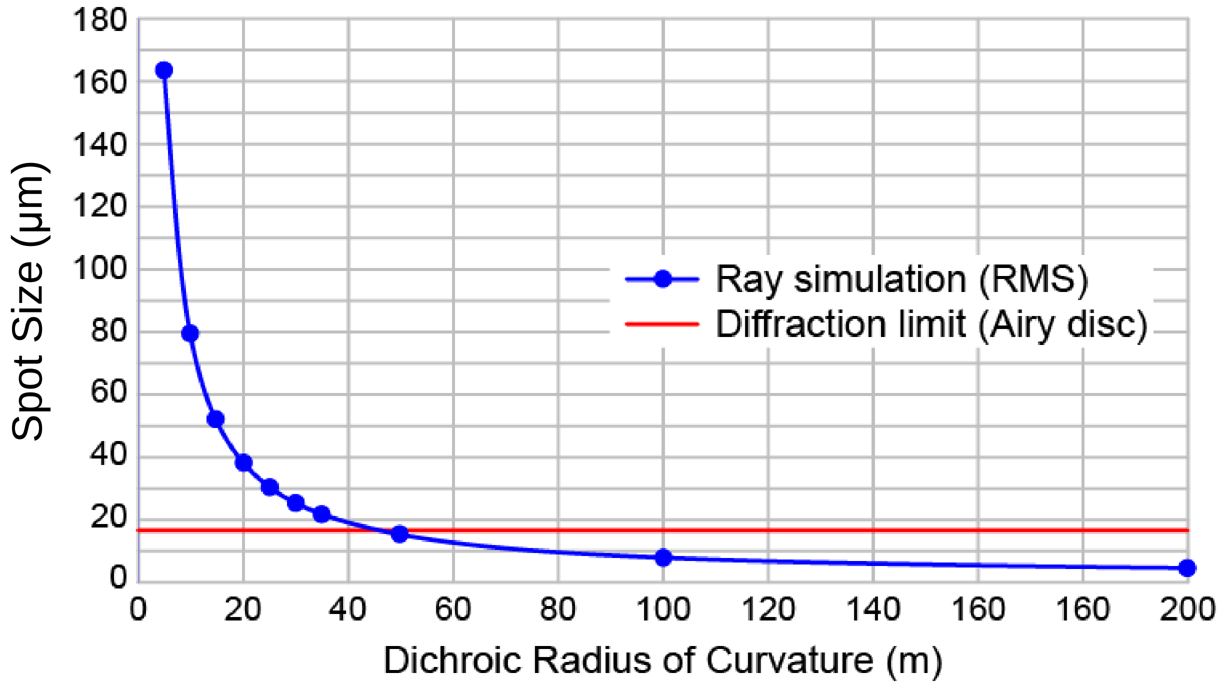
- **Case 3:** Non-flatness causes spot-size blurring for reflected larger-diameter (image) beams
  - One common problem is that light reflected off of curved dichroic at a 45º AOI experiences appreciable **astigmatism** aberrations



  - The smallest spot size (at the "Circle of Least Confusion") can be significantly larger than the diffraction-limited spot size

When does flatness matter – spot size

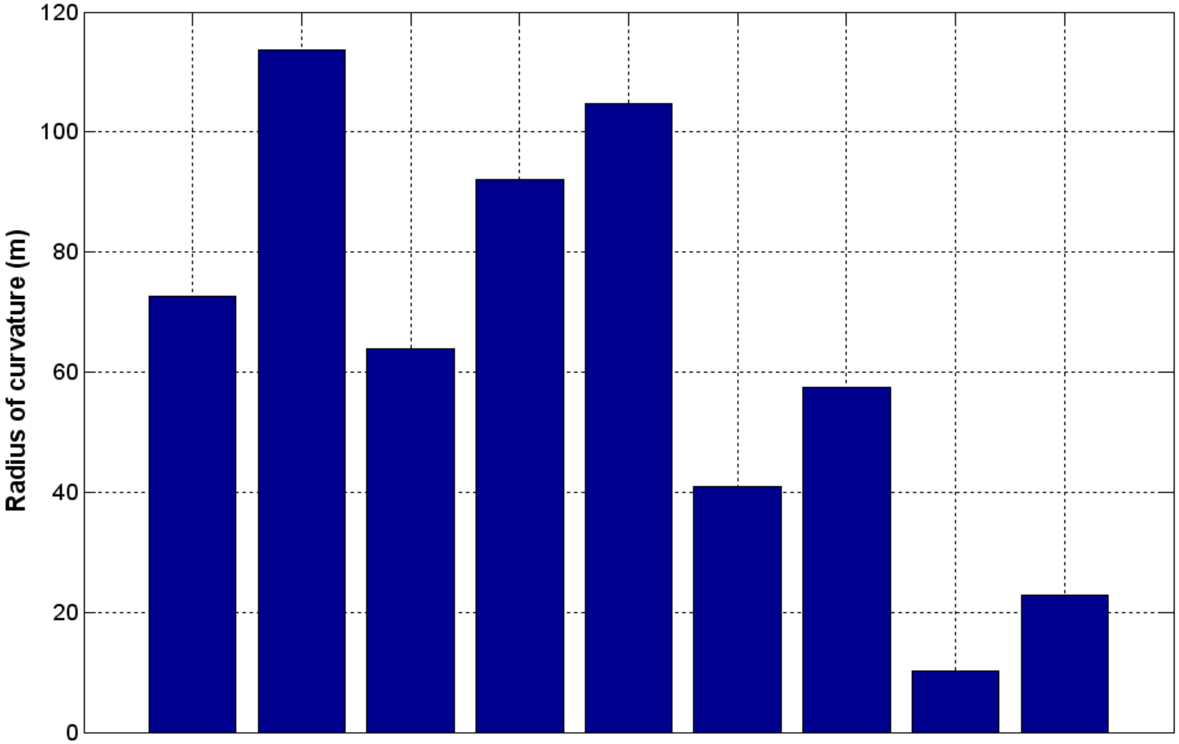
- A non-flat dichroic causes aberrations to an imaging beam reflected off of the filter, resulting in a larger spot size than the ideal, “diffraction-limited” spot size that might result when using a perfectly flat dichroic
- In the example below the radius of curvature of a bent dichroic should be greater than about 50 meters to ensure that the aberrations caused by curvature are less than blurring caused by diffraction



Assumes a beam from a 40X 0.75 NA microscope objective reflected off of a dichroic and then imaged by a tube lens with a focal length of 200 mm

When does flatness matter – spot size

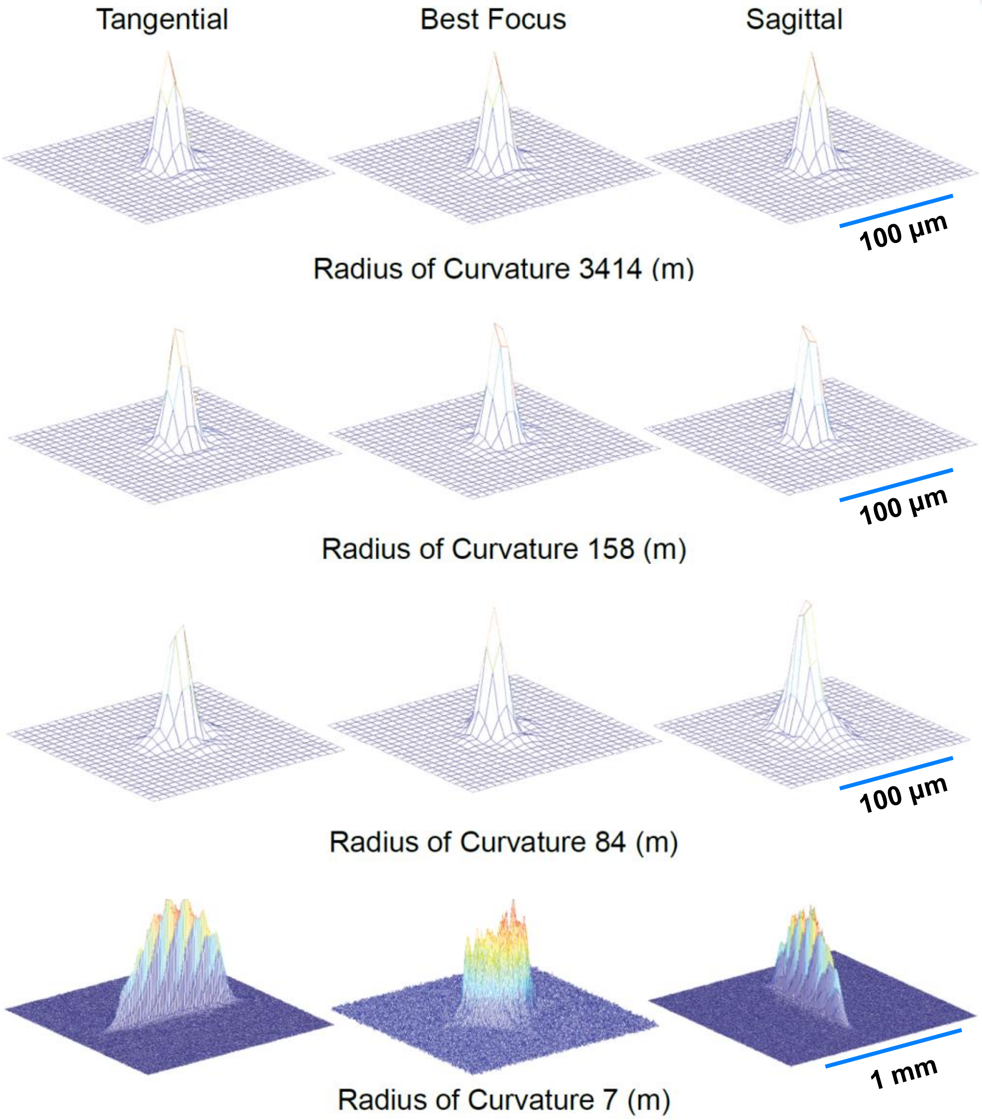
- Different microscope objectives and tube lenses require different degrees of flatness (here quantified by radius of curvature) to ensure aberrations caused by a non-flat dichroic are less than blurring due to diffraction



Magnification	**10X**	**10X**	**40X**	**40X**	**40X**	**60X**	**60X**	**100X**	**100X**
Numerical Aperture	**0.25**	**0.25**	**0.75**	**0.9**	**1.2**	**0.9**	**1.4**	**0.75**	**1.4**
Tube Lens Focal Length (mm)	**160**	**200**	**200**	**200**	**160**	**200**	**160**	**200**	**160**

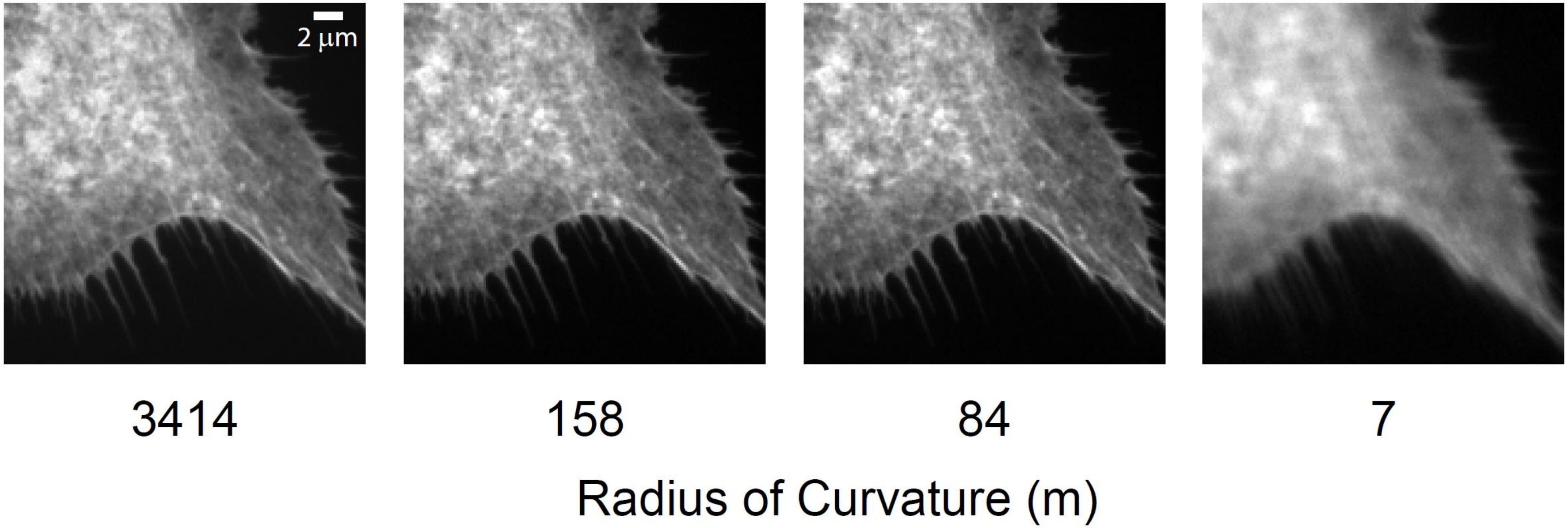
When does flatness matter – spot size

- Examples demonstrating that astigmatism is the dominant aberration caused by reflection off of a bent dichroic
- An 11 mm diameter collimated laser beam was reflected off of dichroics and mirrors with varying radii of curvature, and then focused onto a camera with a 300 mm focal length lens
- For this case the astigmatism is just noticeable for the 84 m radius case, and is extremely apparent for the 7 m case



Larger spot size results in image blurring

- A larger spot size caused by aberrations leads to blurring of an image
- This example shows that a “standard” epifluorescence dichroic designed to reflect only excitation light leads to significant blurring of when image light is reflected



Images of F-actin in bovine pulmonary artery endothelial cells (Fluo Cells prepared slide #1 from Invitrogen) after reflection off of dichroics or mirrors of varying radii of curvature (Olympus BX41 microscope; 40X 0.75NA objective; QImaging Retiga CCD camera)

Flatness of Semrock dichroic beamsplitters

Flatness Classification	Dichroic Family (Examples)	Nominal Radius of Curvature	Application Specification (*NOT Manufacturing Specification*)
Standard Flatness	BrightLine® Dichroics (FF495-Di02-)	~ 6 meters	**Transmission:** causes insignificant aberrations to a transmitted beam over the full clear aperture **Reflection:** designed to reflect broadband excitation light that is not focused or imaged
Laser Flatness	BrightLine Laser Dichroics (Di01-R488-) RazorEdge® Dichroics (LPD01-488RU-) LaserMUX™ Dichroics (LM01-503-)	~ 30 meters	**Transmission:** causes insignificant aberrations to a transmitted beam over the full clear aperture **Reflection:** contributes less than one Rayleigh Range of shift in focus (relative to a perfectly flat mirror) at the focal plane of a lens after reflecting a laser beam with a diameter up to 2.5 mm
Imaging Flatness	Image Splitting Dichroics (FF509-FDi01-)	~ 100 meters	**Transmission:** causes insignificant aberrations to a transmitted beam over the full clear aperture **Reflection:** contributes less than 1.5 x Airy Disk diameter to the RMS spot size of a focused, reflected beam with a diameter up to 10 mm

Thank you!