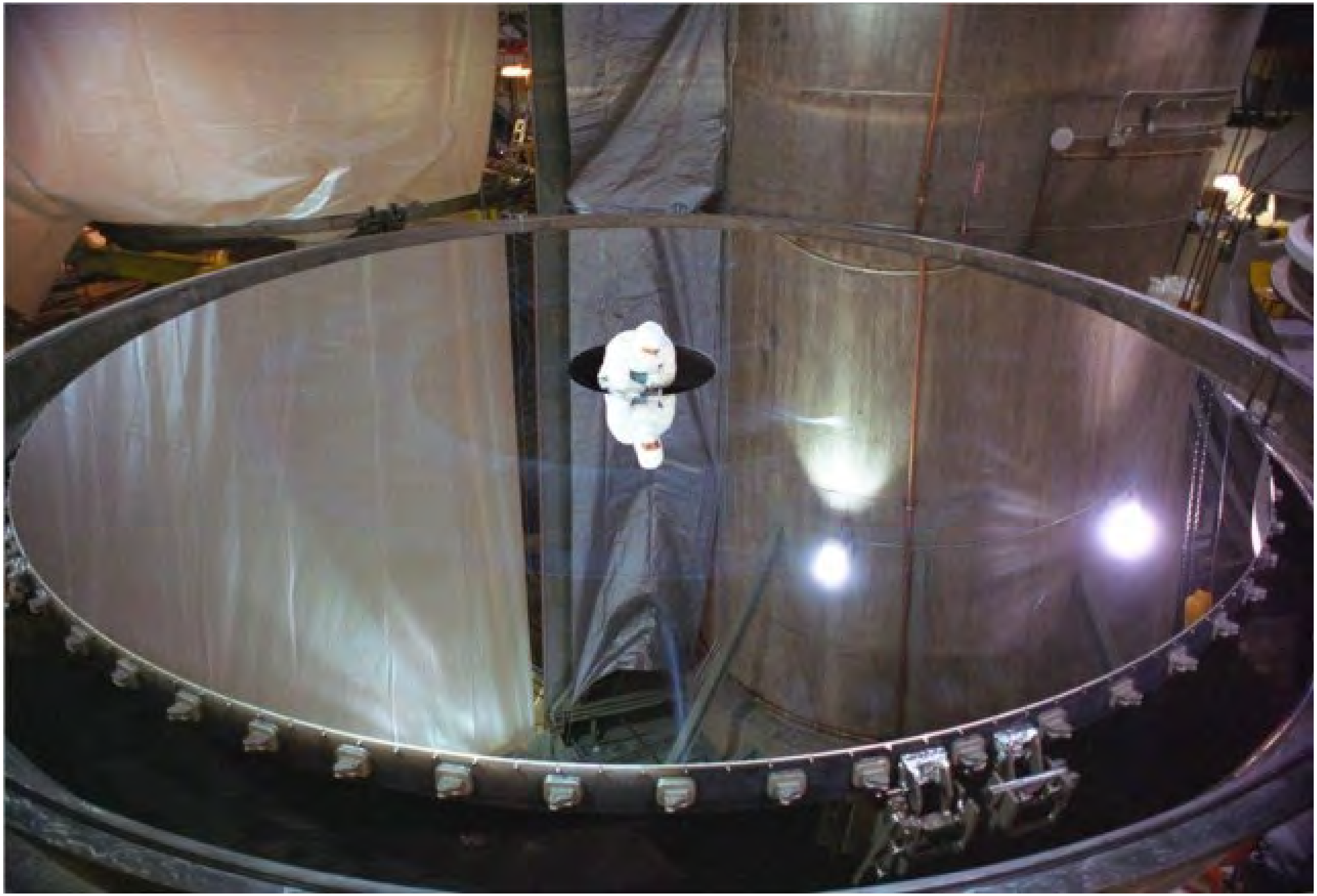
Flatness De-Mystified



8.1 m primary mirror of the Gemini North telescope, Mauna Kea, Hawaii

Contents

Definitions

- **Flatness**
  - Also called **Surface Form Tolerance**
  - A measure of a surface's deviation from perfectly flat
  - Related to **RWD** or **RWE**

- **RWD - Reflected Wavefront Deviation (or Distortion)**
  - Also called **RWE** ("error" for "deviation")
  - A measure of a wavefront's deviation from perfectly planar after reflecting off the surface of an optic
  - Related to **Flatness** or **Surface Form Tolerance**

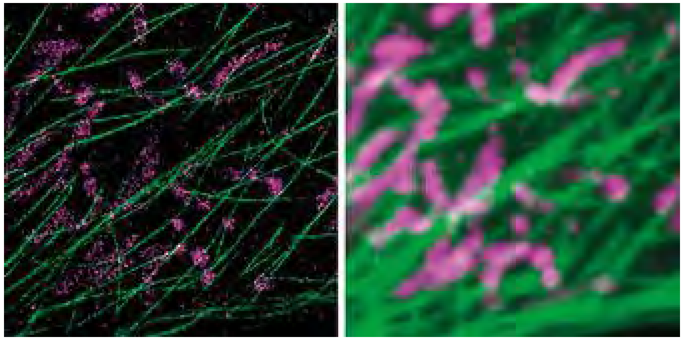
- **TWD - Transmitted Wavefront Deviation (or Distortion)**
  - Also called **TWE** ("error" for "deviation")
  - A measure of a wavefront's deviation from perfectly planar after passing through the optic
  - Related to **Centering**, **Wedge** or **Parallelism** and **Beam Deviation (although TWD metric is with "tilt" removed)**

- **Wedge**
  - Also called **Parallelism**
  - The angle made between two surfaces of an optic, or degree to which the two surfaces are parallel
  - For lenses, the angle between the optical and mechanical axes
  - Related to **Centering**, **TWD** or **TWE** and **Beam Deviation**

- **Beam Deviation**
  - How much the beam deviates due to wedge angle or non-parallel surfaces
  - BeamDev = Wedge * (substrate refractive index - 1); ex. 10arc-sec * (1.46 – 1) = 4.6arc-sec
  - Related to **Centering**, **TWD** or **TWE** and **Wedge** or **Parallelism**

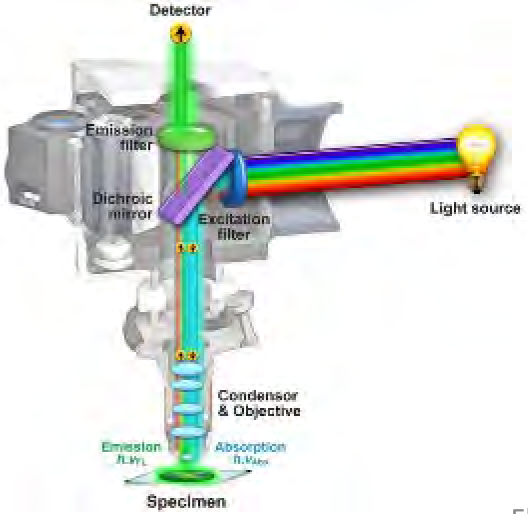
Why Flatness Matters

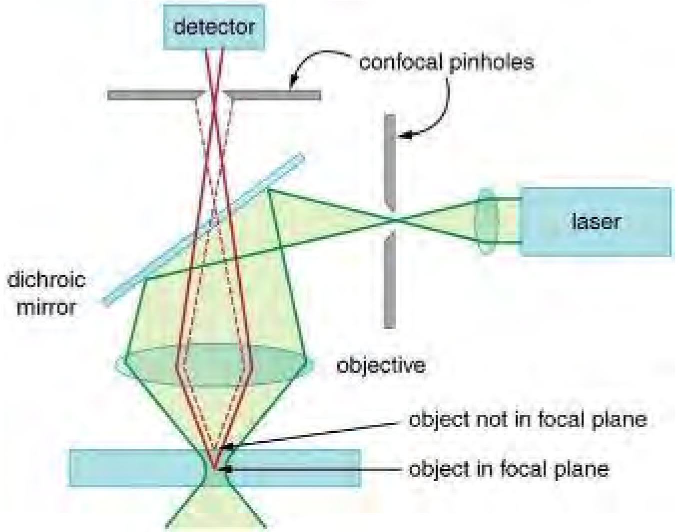
- Non-flatness, or non-ideal surface form leads to distorted images in an optical system.



- In the imaging path this can lead to blurry images.

- In the excitation path it can lead to distortions of the illumination beam – for example, in laser-based systems the laser spot size could be larger or smaller than needed.





What’s Going on?

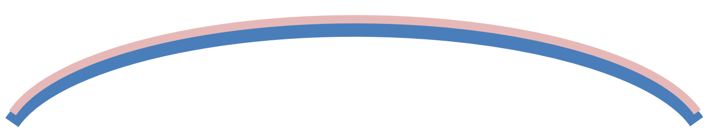
- Substrates end up non-flat due to their manufacture, i.e., grinding and polishing, which can add surface curvature or in general, surface inaccuracy.

- The thinner the substrate relative to it’s diameter (that is, the larger the aspect ratio), the harder it is to make flat.

Ideal starting substrate

Real starting substrate

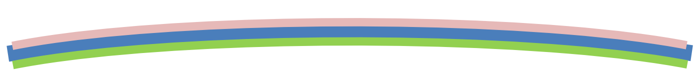
- Sputtered coatings apply compressive stress due to film density, “pulling” on the surface, bending (or straining) the substrate further.



Coated substrate

The thicker the substrate,
the less deformation
(but stress is the same)

- A sputtered anti-stress coatings applied to the opposite side applies compressive stress to compensate, effectively “flattening” the part.

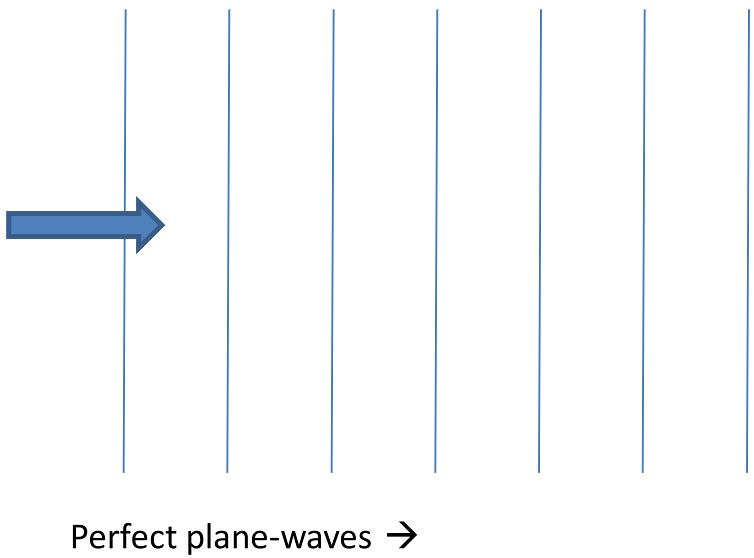


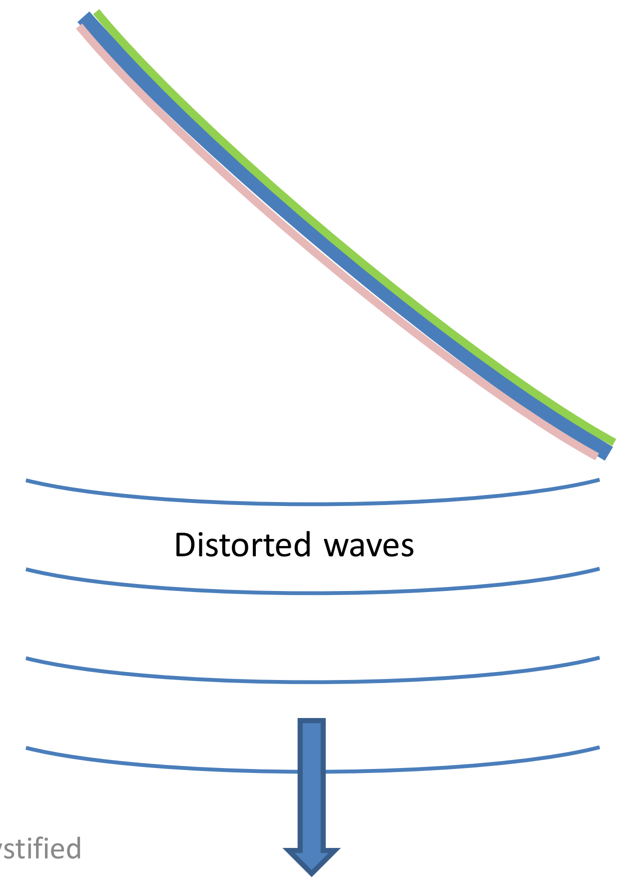
Flattened (anti-stressed) substrate

What’s Going on?

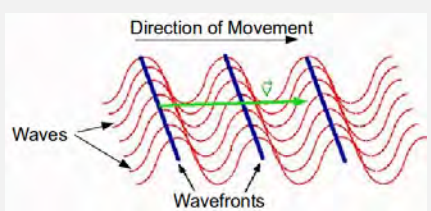
- Light incident on this part, assuming it’s perfect to begin with, will take on the shape of the surface it’s bouncing off of.

- The wavefront, if a perfect plane wave, will get bent out of shape upon reflection in the form of the surface it’s reflecting off of:

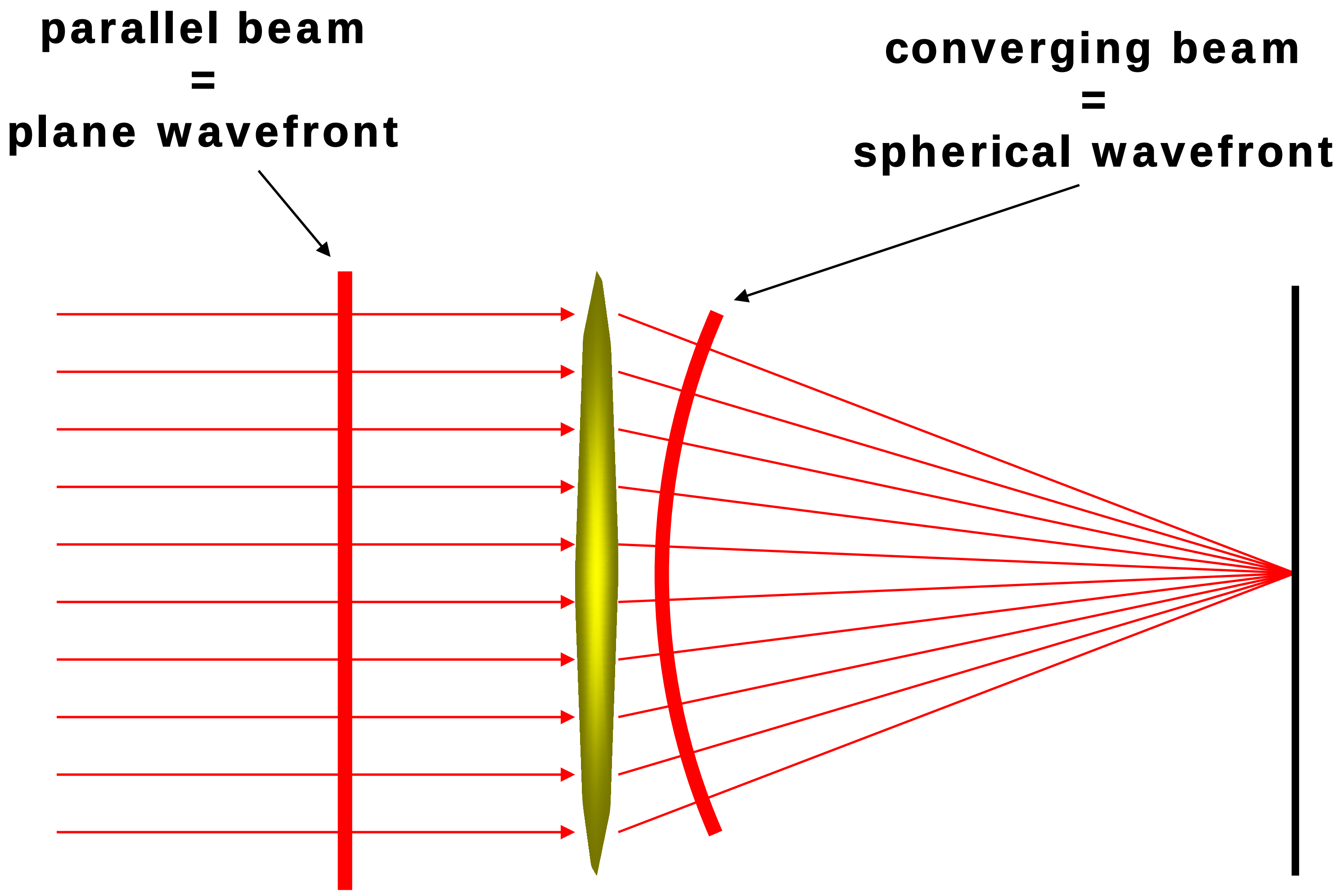




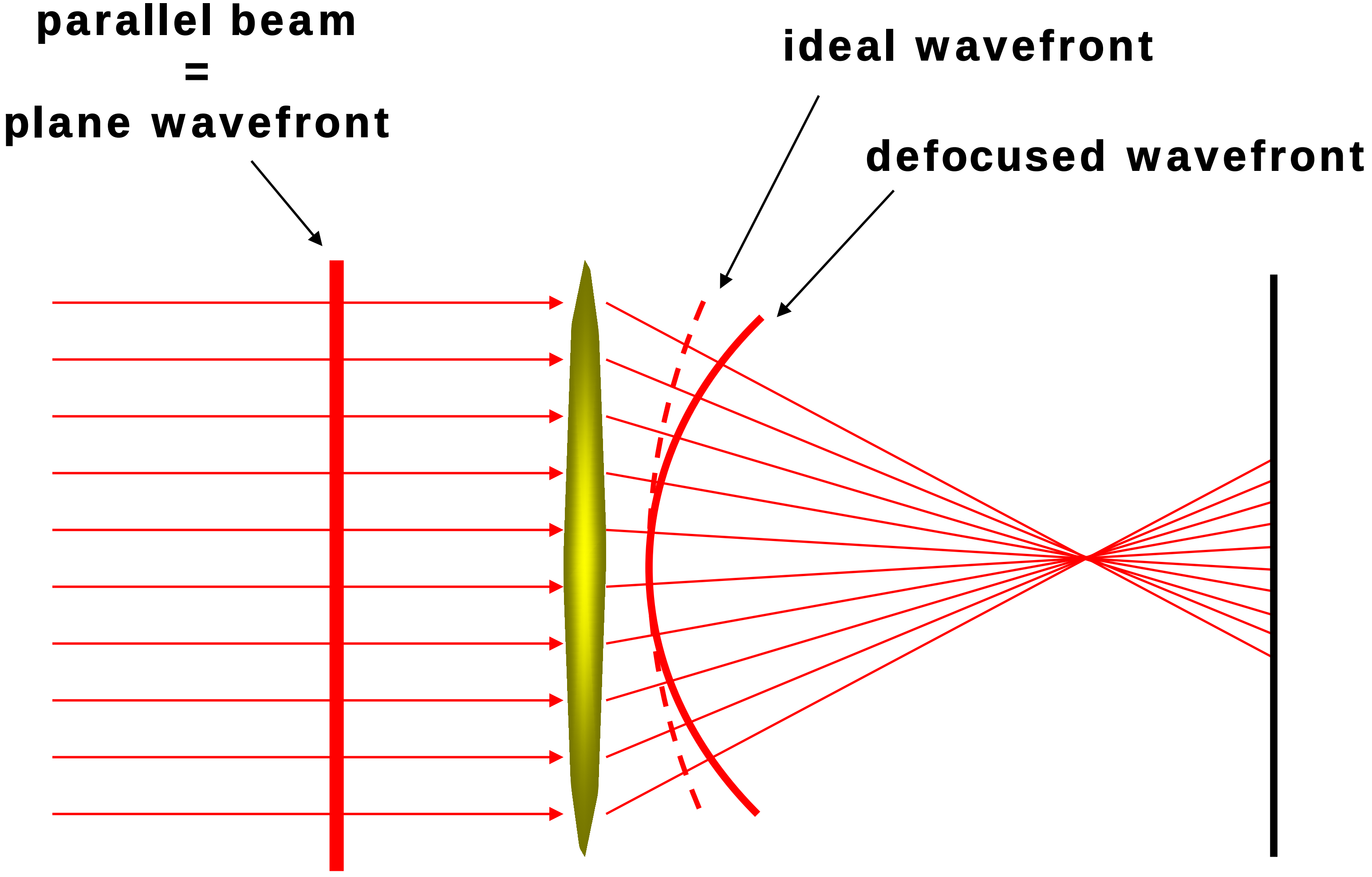
A wavefront is just a snap-shot representation of the continuous wave of light:



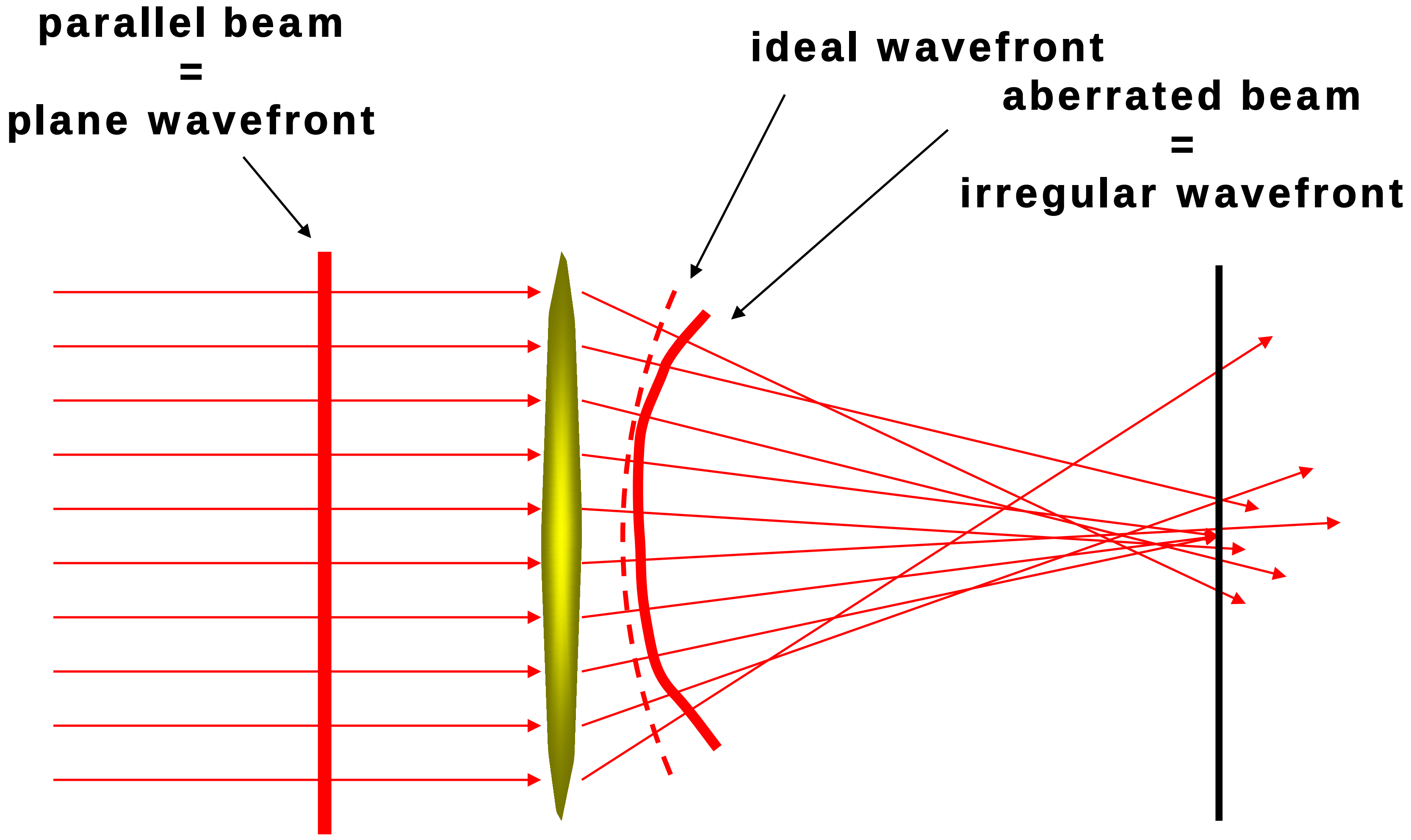
What is a Wavefront?



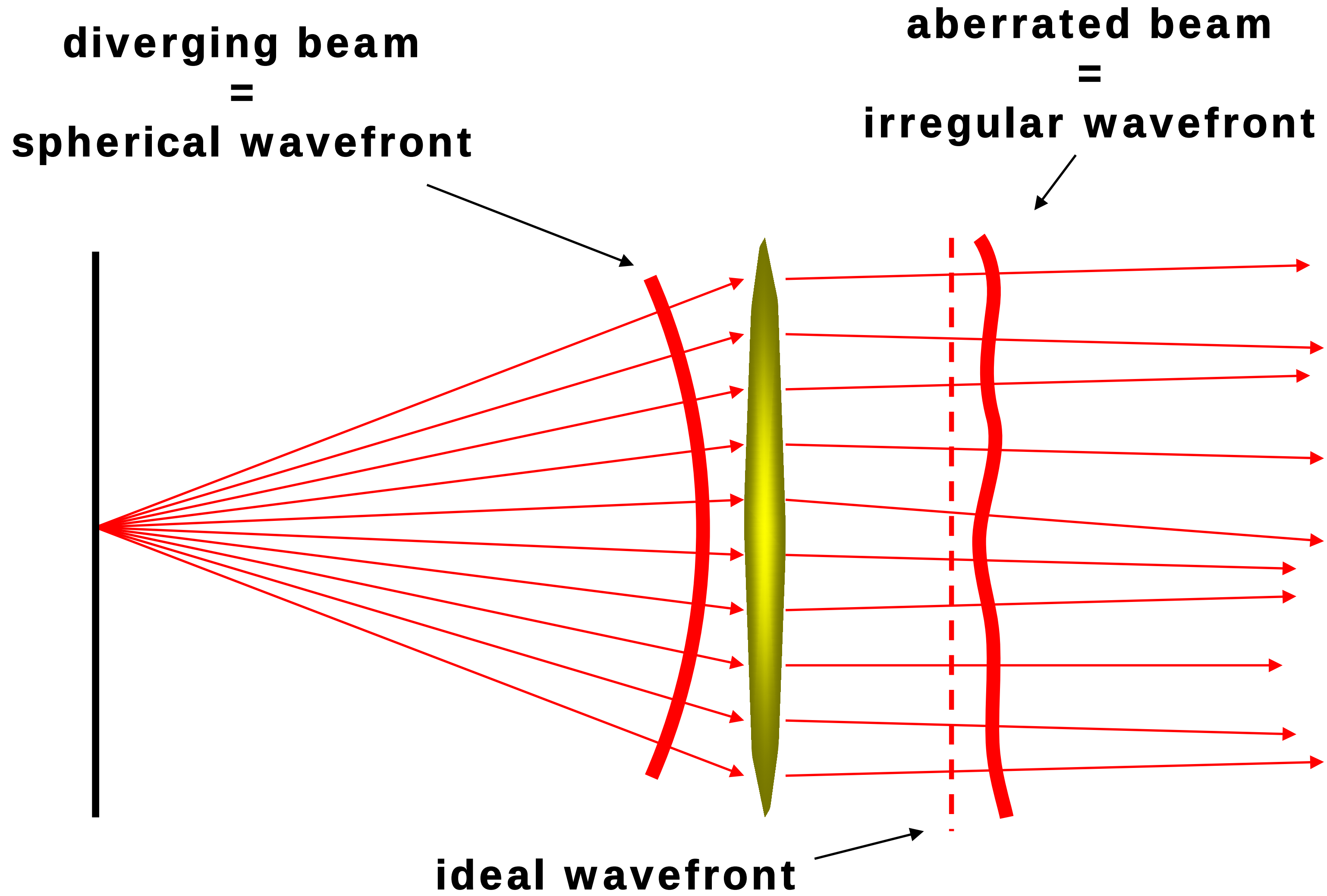
What is the Wavefront?



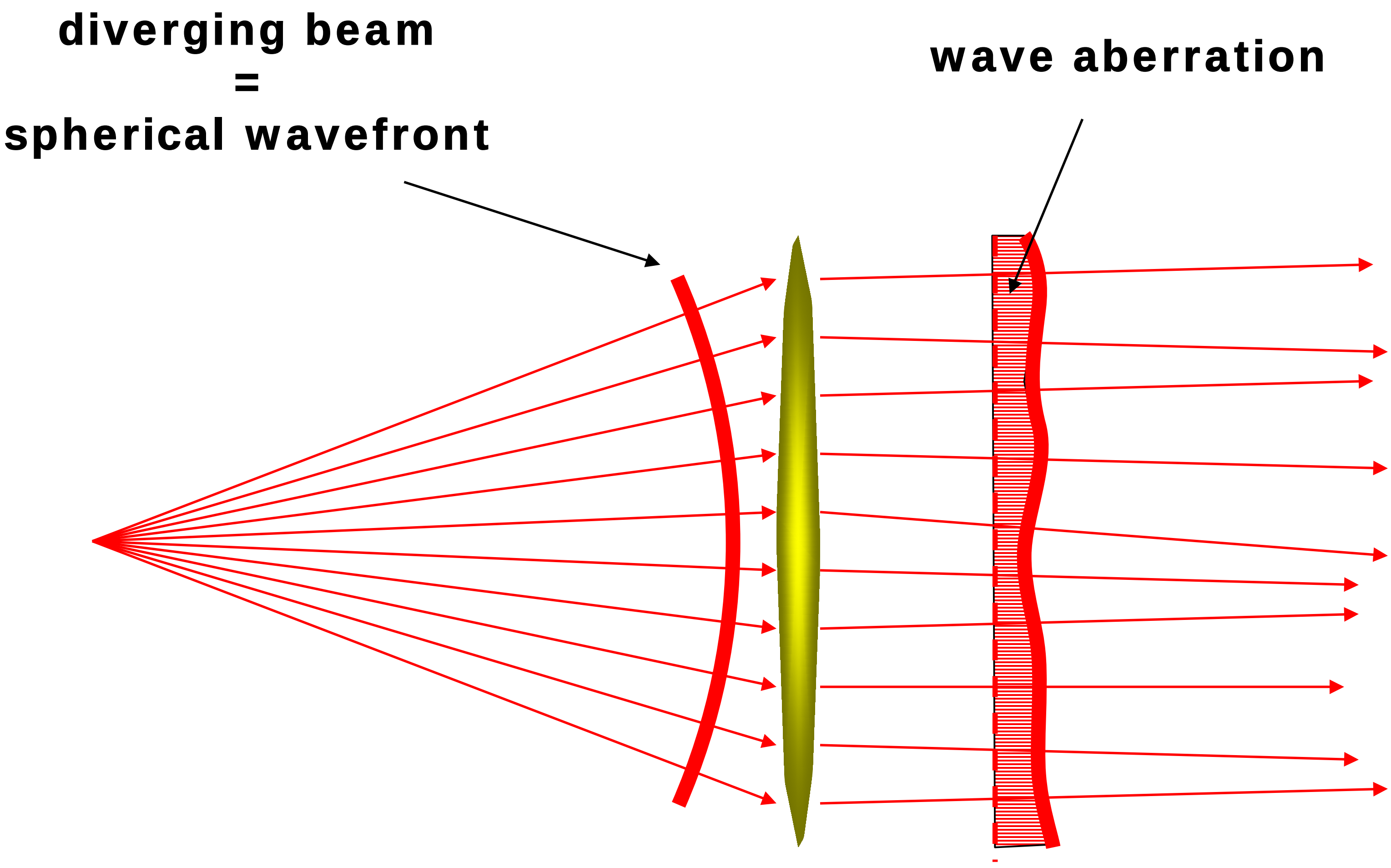
What is the Wavefront?



What is the Wavefront?

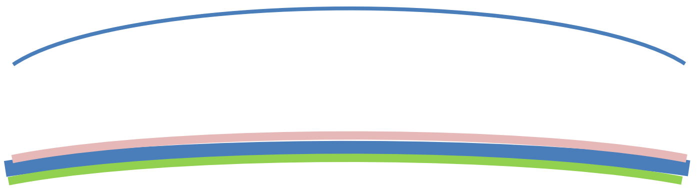


What is the *Wave Aberration*?



What's Going on?

- We can characterize the wavefront, or we can characterize the surface; since they share a shape, you can measure one and figure out the other.



- The relationship between the surface form and the wavefront is simple:

The wavefront feature is 2x the surface feature.

RWD = 2 x Flatness
Flatness = 1 / 2 x RWD

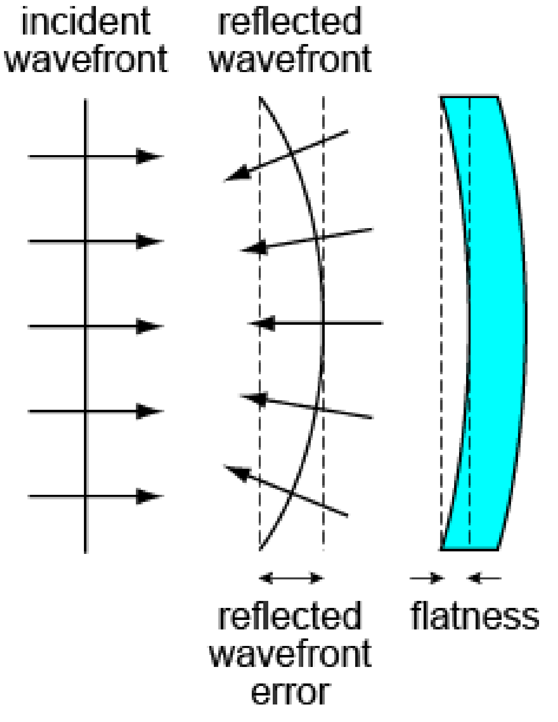
NOTE: flatness (and RWD) ONLY matters when a filter will be used in a reflection

Reflective Wavefront Distortion (**RWD**) 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 RWD are simply related by a factor of 2

RWD = 2 x Flatness
Flatness = 1 / 2 x RWD



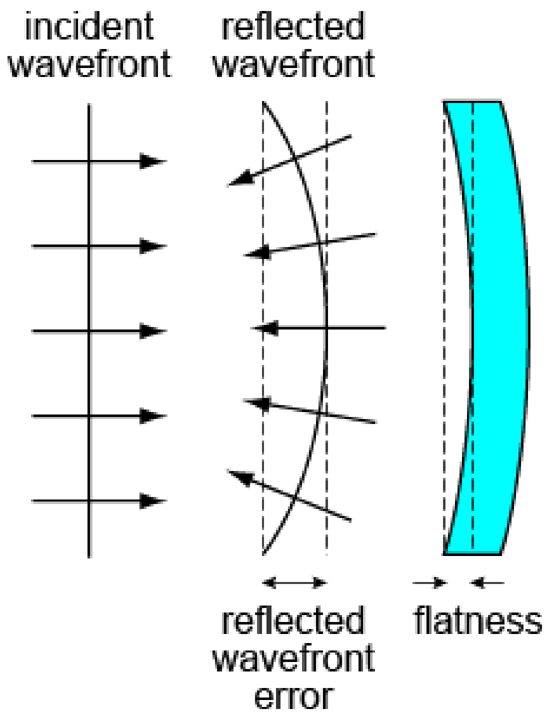
NOTE: flatness (and RWD) ONLY matters when a filter will be used in a reflection

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

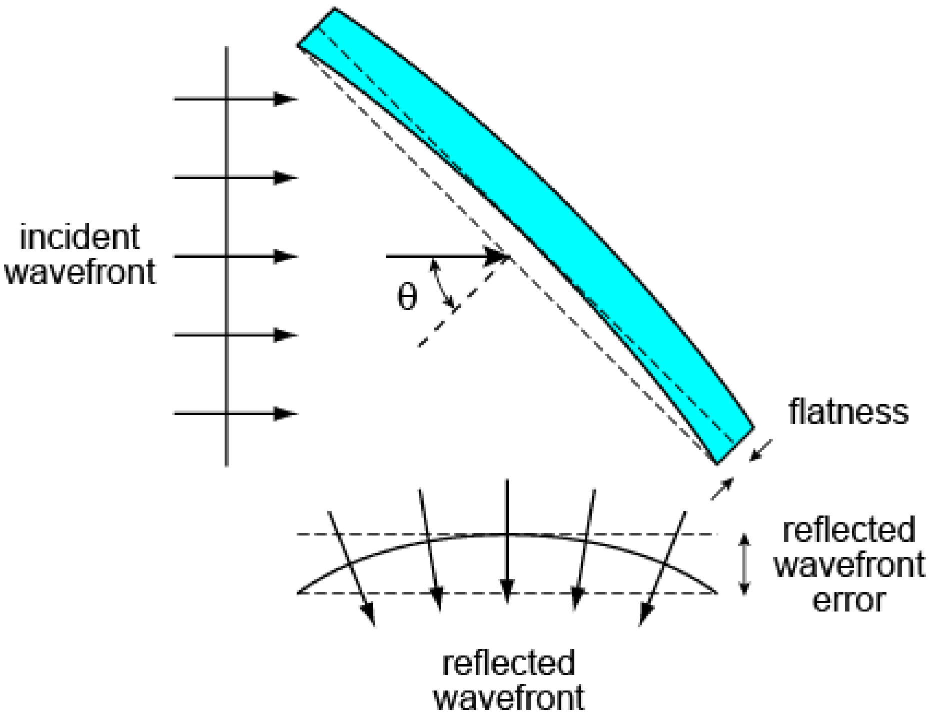
RWD = 2 x Flatness
Flatness = 1 / 2 x RWD

RWD = 2 x cosθ x Flatness
Flatness = 1 / 2 x cosθ x RWD

0° AOI



45° AOI



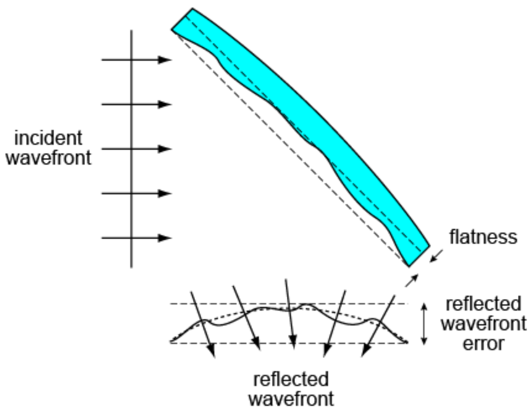
NOTE: flatness (and RWD) ONLY matters when a filter will be used in a reflection

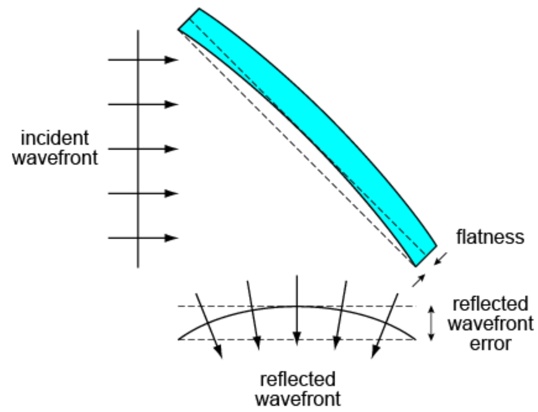
Reflective Wavefront Distortion (**RWD**) may also be separated into different contributions:

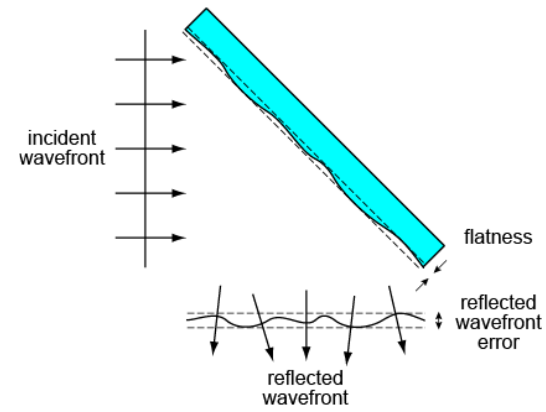
- **Power** (or spherical error) – best fit of the reflected wavefront to a perfect sphere
- **Irregularity** – the remaining deviation from a perfectly flat wavefront

Surface Flatness also can be separated into these components.

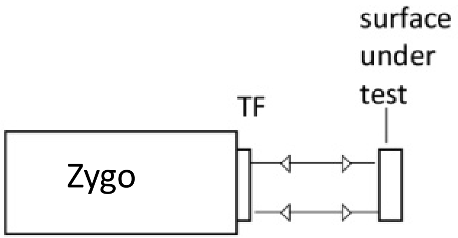
RWD or Flatness Total = **RWD or Flatness Power** + **RWD or Flatness Irregularity**





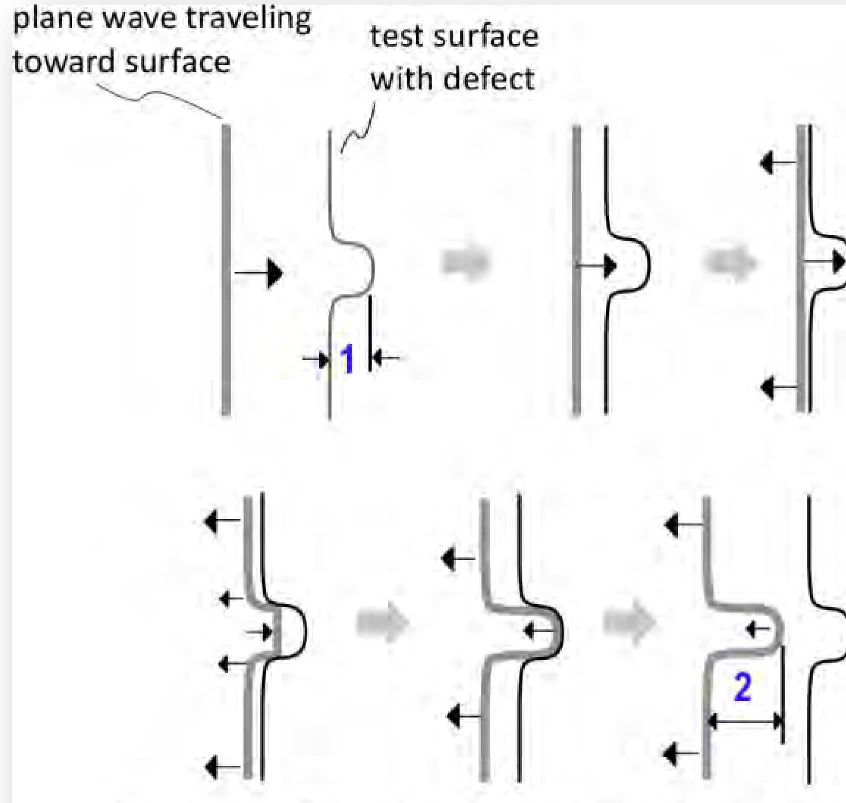


What's Going on?



Fizeau double-pass normal incidence one reflection from test surface

Interpretation	ISF
surface form error	0.5



Plane Wavefront Incident on Test Surface

- Wait, so the Zygo actually measures the (0deg AOI) reflected wavefront distortion, but then we just divide by 2?! …. Yup! Zygo calls this the ISF, or interference scaling factor … set to 0.5 it measures surface form … set to 1 it measured (0deg AOI) RWD!

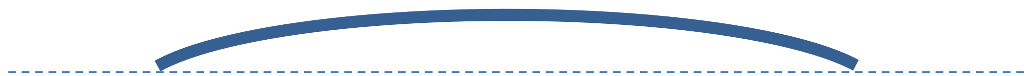
Flatness – what are we talking about?

- Forget for a moment that we're talking about glass and optics, or wavefronts and waves.
- Perfectly "flat" can be represented as a line (1D, or no height):

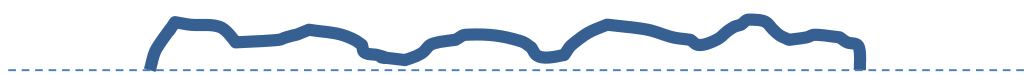
- Non-flat, a 2D shape, i.e. a "line" with height (relative to some "bottom"):

E:\FILMCAD\Calculators_and_worksheets\X-Y_plot.xlsx

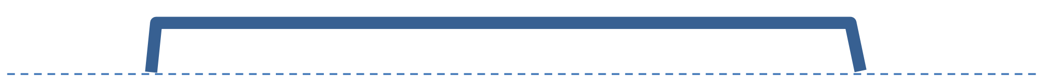
ex. an arc:



ex. a squiggle:

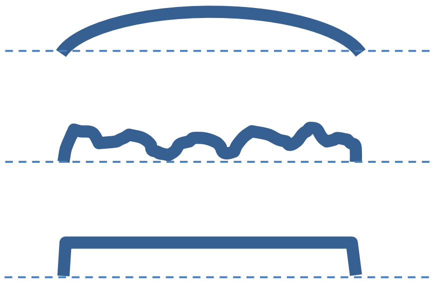


ex. a box:



Flatness – what are we talking about?

- For any of these shapes you can measure the height (relative to some bottom reference) in a few different ways:
  - Average height
  - Total height (peak-to-valley)
  - RMS height

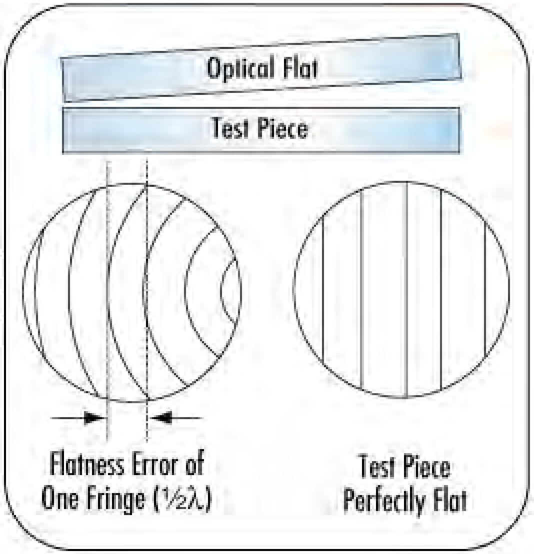


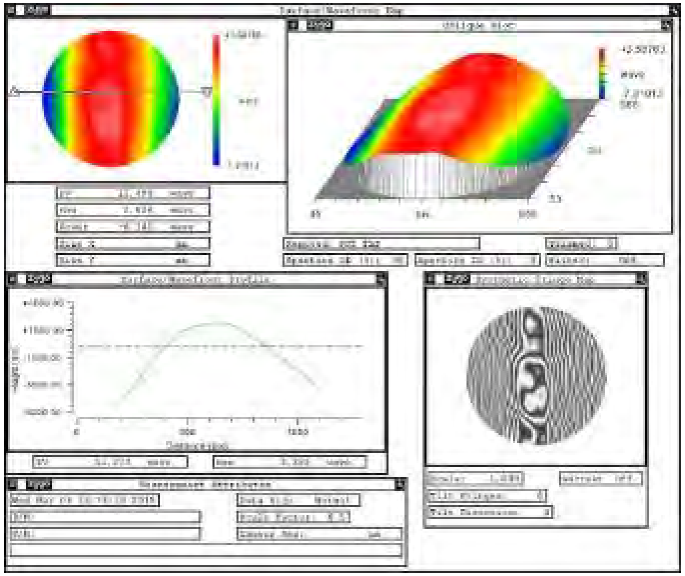
- **You might also want to know how much of that height is due to purely spherical curvature (power, or SAG), and how much is due to everything else (irregularity).**
  - With "MIL" specs, we might say "half-wave flat", or "2 wave power, 1 wave irregularity".
  - With ISO 10110-5, we have the "3/" plus some coded language (see table below)

PV term	type of distortion	RMS term
PV	total	RMSt
A	power	
B	irregularity (power removed)	RMSi
C	irregularity (rotationally invariant, power removed)	RMSa

Flatness – what are we talking about?

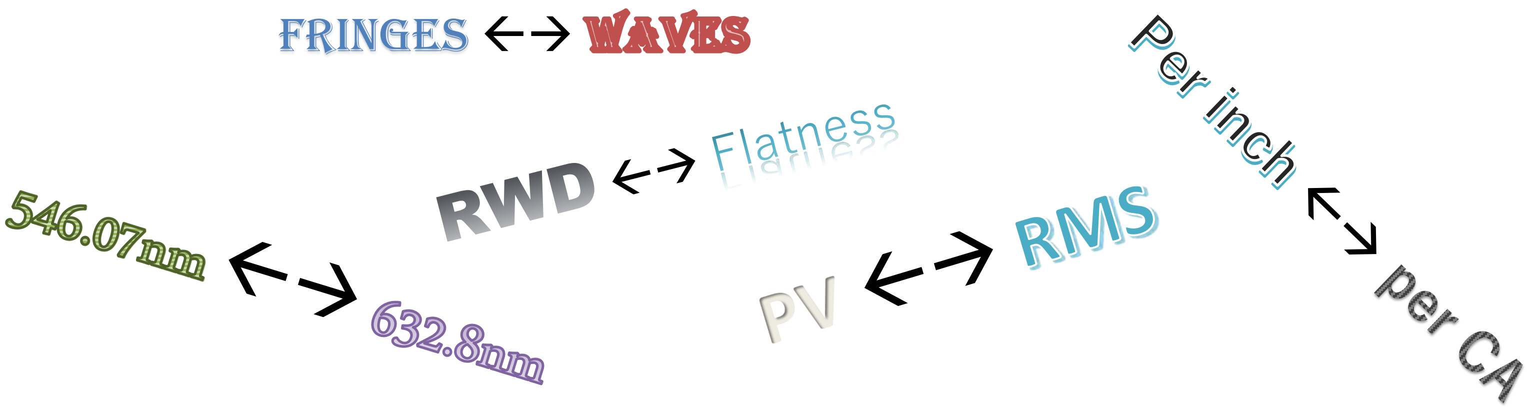
- Peak to valley total, or just simply "PV", is the maximum measurement and the worst-case scenario, taking into account the difference between the surface's lowest and highest points. It is by far the most widespread flatness specification used today.
- A more accurate measurement of surface flatness is rms, as it takes into account the entire optic and calculates deviation from the ideal form.
- Traditionally, optical flats with monochromatic light (ex. 546.07nm) have measured surface flatness in fringes; today, however, laser interferometers at 632.8 nm measure most optical components and can output fringes or waves **(or sensible units, like microns)**.





Conversions

- What makes this whole subject difficult (and annoying) is all the different conversions.



- To convert from a per inch to a per CA, multiply by the ratio of the diameters (or longest lengths, for example diagonal if rectangular piece) squared:
  - Convert from 1 wave/CA PV @ 632.8nm to waves/inch PV @ 632.8nm given CA is:
    - 25.4 diameter: 1 wave x $(25.4/25.4)^2$ = 1 wave
    - 10mm diameter: 1 wave x $(25.4/10)^2$ = 6.45 waves
    - 35 x 27 rectangle: 1 wave x $(25.4/44.2)^2$ = 0.33 waves
    - 35 x 27 ellipse: 1 wave x $(25.4/35)^2$ = 0.53 waves

Conversions

- What makes this whole subject difficult (and annoying) is all the different conversions.

FRINGES ←→ WAVES

RWD ←→ Flatness

546.07nm ←→ 632.8nm

PV ←→ RMS

Per inch ←→ per CA

- To convert from 546.07nm to 632.8nm, simply multiply by 0.86
- **To reverse, multiply by 1.16**

Conversions

- What makes this whole subject difficult (and annoying) is all the different conversions.

FRINGES ←→ WAVES

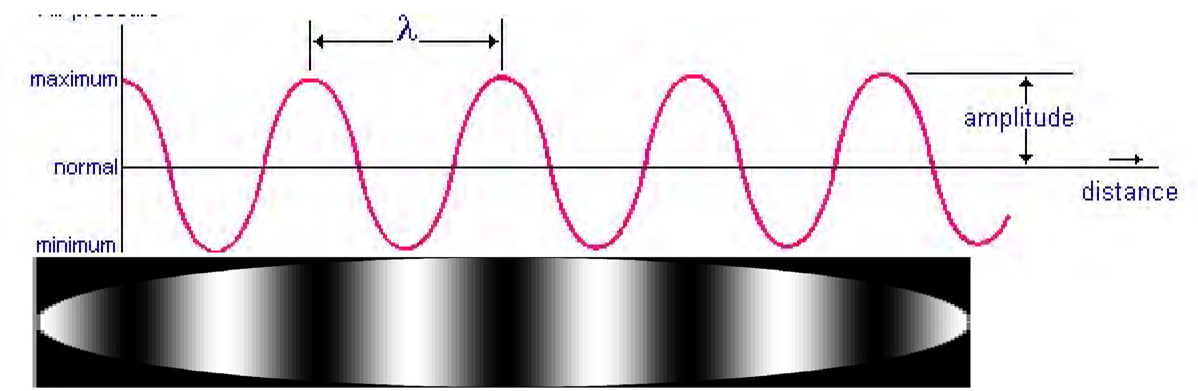
RWD ←→ Flatness

546.07nm ←→ 632.8nm

PV ←→ RMS

Per inch ←→ per CA

- A fringe is a half a wave
- Or 1 wave is 2 fringes



Conversions

- What makes this whole subject difficult (and annoying) is all the different conversions.

FRINGES ←→ WAVES

RWD ←→ Flatness

546.07nm ←→ 632.8nm

PV ←→ RMS

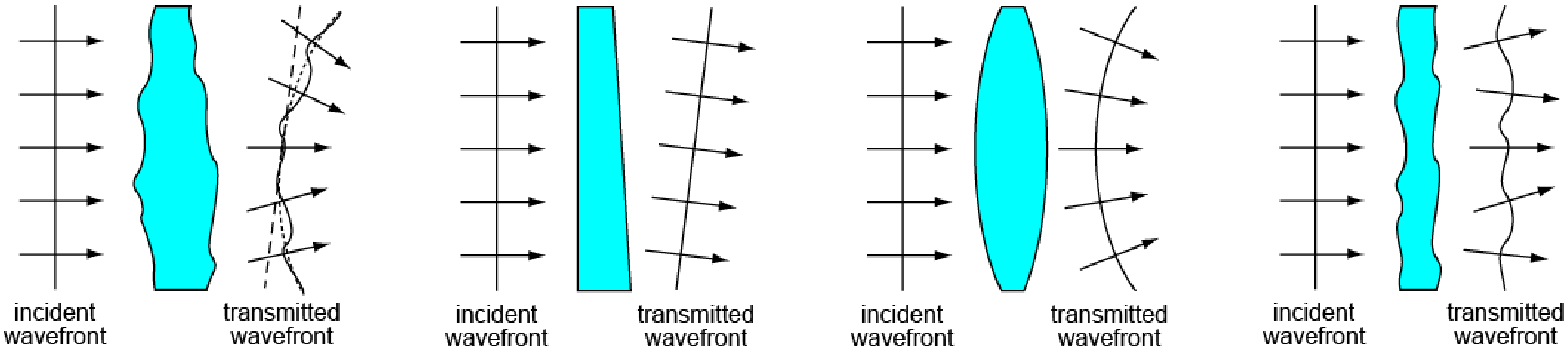
Per inch ←→ per CA

E:\FILMCAD\Calculators_and_worksheets\Flatness_Calc_ja2.xlsx

TWD

- Transmitted Wavefront Distortion (TWD) is typically the error left over after wedge (tilt) is removed.
- TWD is caused by deviations in thickness across the part and/or inhomogeneity of the index of refraction.

Total TWD = Wedge (tilt) + Spherical + Irregularity

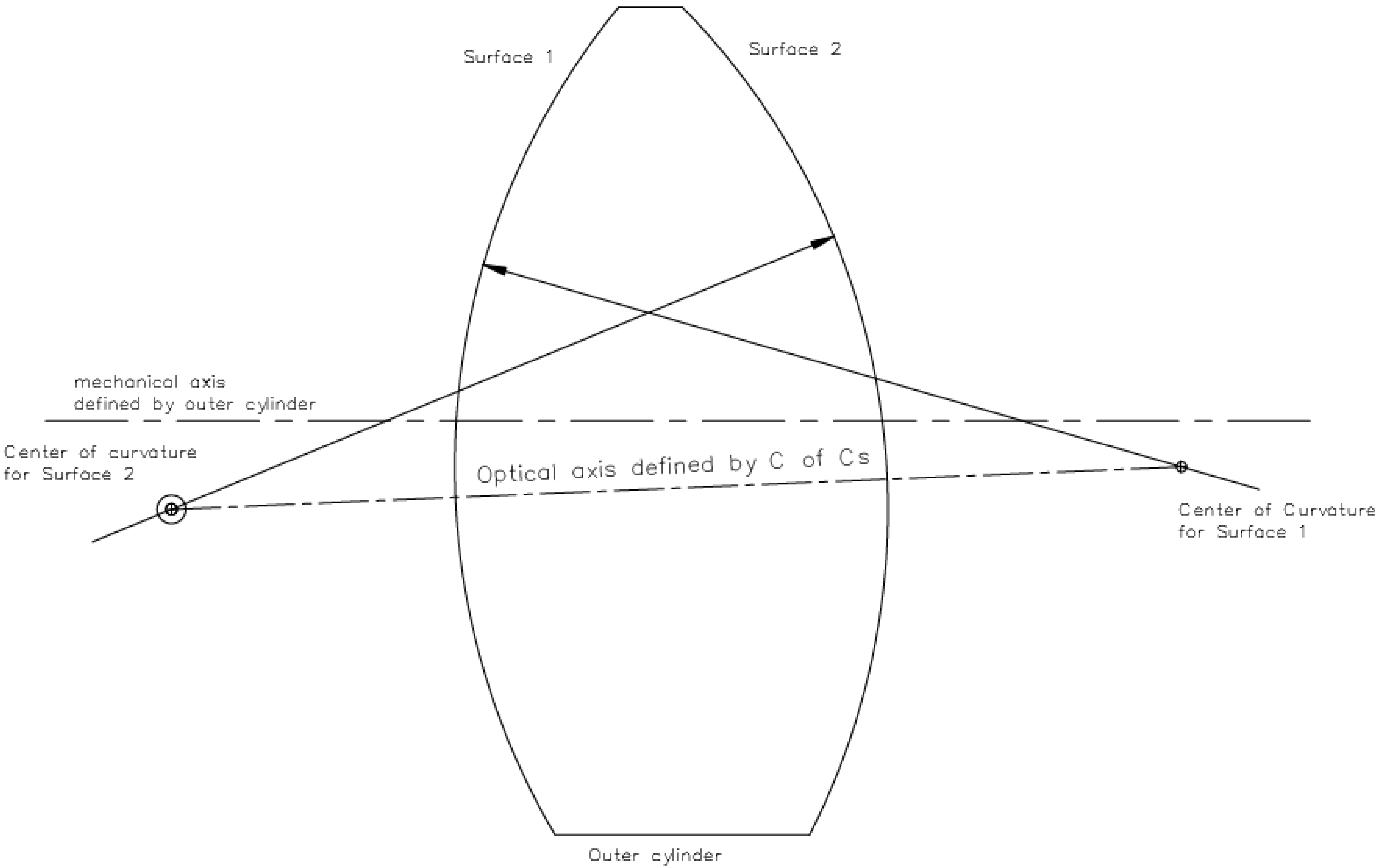


NOTE: Wedge (or tilt) is removed intentionally from Zygo measurements when measuring for TWD.

Understanding wedge in a lens

- “wedge” in a lens refers to an asymmetry between the “mechanical axis”, defined by the outer edge and the “optical axis” defined by the optical surfaces.
  - The optical axis of a lens defined by line connecting centers of curvature of the optical surfaces
  - The mechanical axis defined by outer edge, used for mounting.

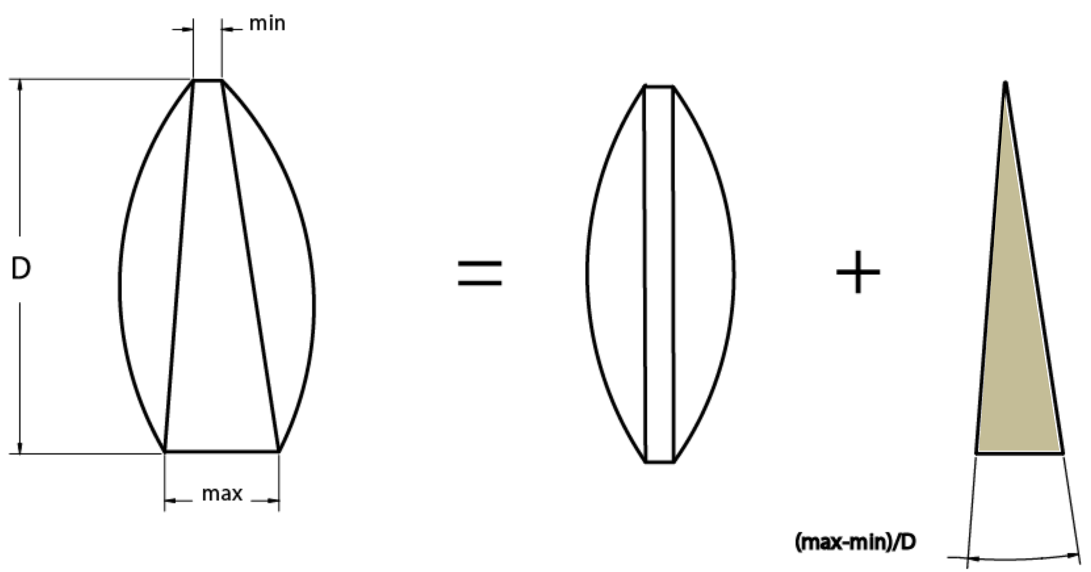
Understanding wedge in a lens



Understanding wedge in a lens

- "wedge" in a lens refers to an asymmetry between the "mechanical axis", defined by the outer edge and the "optical axis" defined by the optical surfaces.
  - The optical axis of a lens defined by line connecting centers of curvature of the optical surfaces
  - The mechanical axis defined by outer edge, used for mounting.

Wedge angle: α = Edge Thickness Difference (ETD)/Diameter
Beam Deviation: $\delta = \alpha(n-1)$ defined by light going through the lens

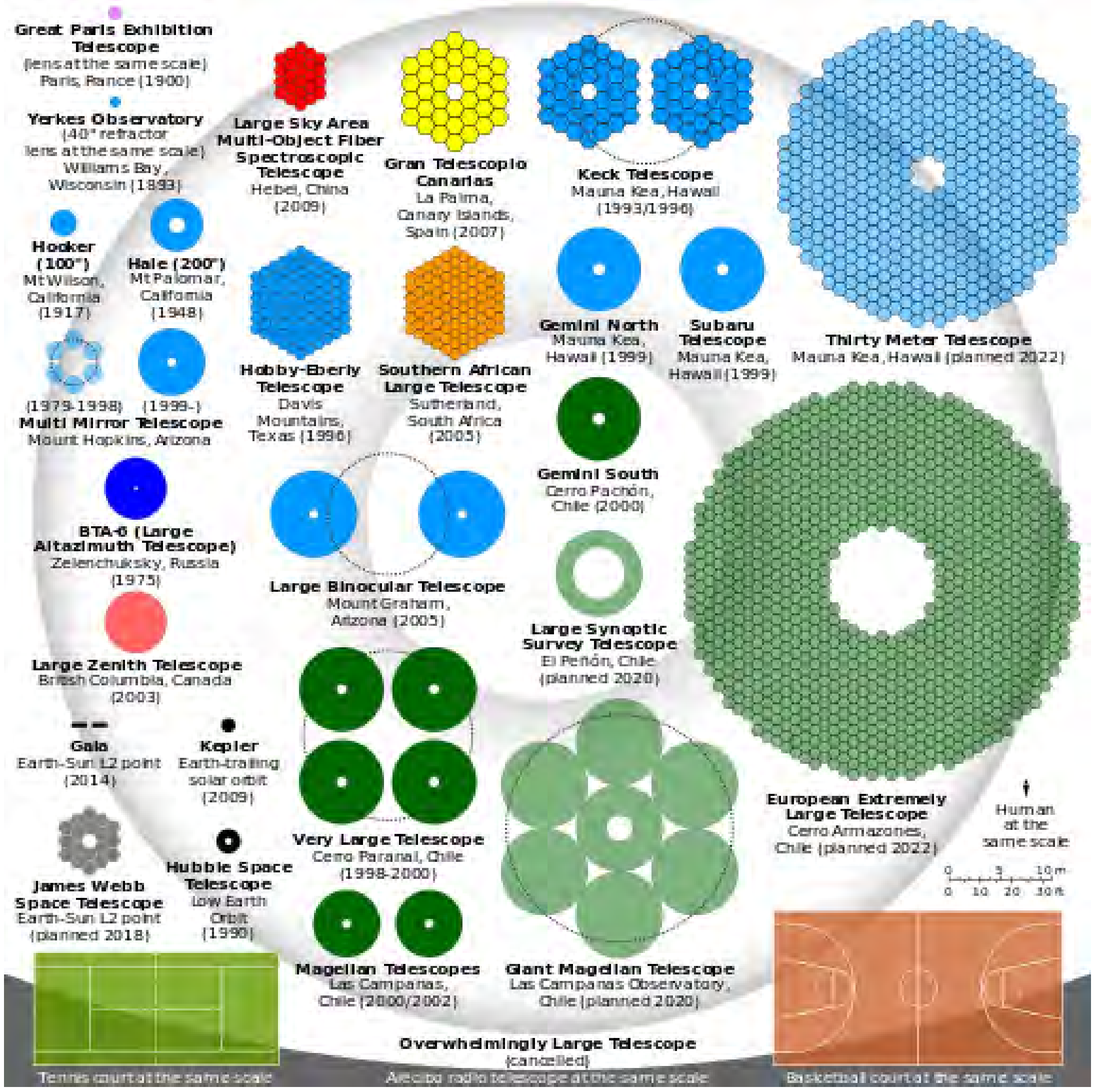


Same for flats!

ETD = max - min
α= ETD / D
$\delta = \alpha(n - 1)$

Example:
Wedge, α = 5 arc-sec
n = 1.46 (fused silica)
δ = 5 (1.46 -1) = 5 x 0.46
δ = 2.3 arc-sec

Thanks!


Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor
lens at the same scale)
Williams Bay, Wisconsin (1893)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China (2009)
Gran Telescopio Canarias
La Palma, Canary Islands, Spain (2007)
Keck Telescope
Mauna Kea, Hawaii (1993/1996)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
Hooker (100")
Mt Wilson, California (1917)
Hale (200")
Mt Palomar, California (1948)
Hobby-Eberly Telescope
Davis Mountains, Texas (1996)
Southern African Large Telescope
Sutherland, South Africa (2005)
Gemini North
Mauna Kea, Hawaii (1999)
Subaru Telescope
Mauna Kea, Hawaii (1999)
(1979-1998) (1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
Gemini South
Cerro Pachón, Chile (2000)
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia (1975)
Large Binocular Telescope
Mount Graham, Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile (planned 2020)
Large Zenith Telescope
British Columbia, Canada (2003)
Gaia
Earth-Sun L2 point (2014)
Kepler
Earth-trailing solar orbit (2009)
Very Large Telescope
Cerro Paranal, Chile (1998-2000)
European Extremely Large Telescope
Cerro Armazones, Chile (planned 2022)
Human at the same scale
James Webb Space Telescope
Earth-Sun L2 point (planned 2018)
Hubble Space Telescope
Low Earth Orbit (1990)
Magellan Telescopes
Las Campanas, Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory, Chile (planned 2020)
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale

Flatness, Etc.

- **Chroma's Measurement with the Zygo Interferometer**
  - Typically given as Peak-to-Valley in number of waves (@633nm) per inch, at 0deg AOI …only on a single surface, and with any tilt (or wedge) factored out.
  - *"Interferometers function by dividing a wavefront into two or more parts, principally a reference wavefront and a test wavefront, which travel different paths and then combine to form an interference fringe pattern. The geometrical properties of the interference fringe pattern are determined by the difference in optical path traveled by the recombining wavefronts."*
    http://www.zygo.com/?sup=/resource/faqs.cgi?id=60
  - Basically, at 0deg AOI, Flatness is RWD/2 … OR **…** **RWD is 2x Flatness**
  - The general formula is RWD = 2 x cosθ x Flatness, so at 45deg AOI, RWD = 2 x cos45 x Flatness = 2 x 0.707 x Flatness … (for flatness of 1 wave, then, RWD = 1.4 waves).
  - Or Flatness = RWD/(2 x cosθ)

- **Wait, Flatness is measured using reflected wavefront deviation analysis!**
  - So when we want to measure flatness we actually measure RWD and then convert to our in-house Flatness? Why?
  - **The answer is because "Flatness" is an industry-standard term that both our substrate suppliers and many of our customers use.**

- Covered by ISO 10110-5 Standard , called "Surface Form Tolerance" Which the Zygo Measures directly
  - Indicated by the drawing code "3/"
  - Units are in fringes @ 546.07nm, where one fringe is 2x waves
  - To go from this to **Flatness** we convert measured P-V fringes to waves and Waves @ 633nm = Fringes @ 546.07nm * (546.07/632.8) / 2
  - (NOTE: we say "633", but it's actually 632.8nm)
  - See slides 20-25: http://www.visualopticslab.com/opti515r/notes/section5slides.pdf