Astro 426/526

Fall 2019

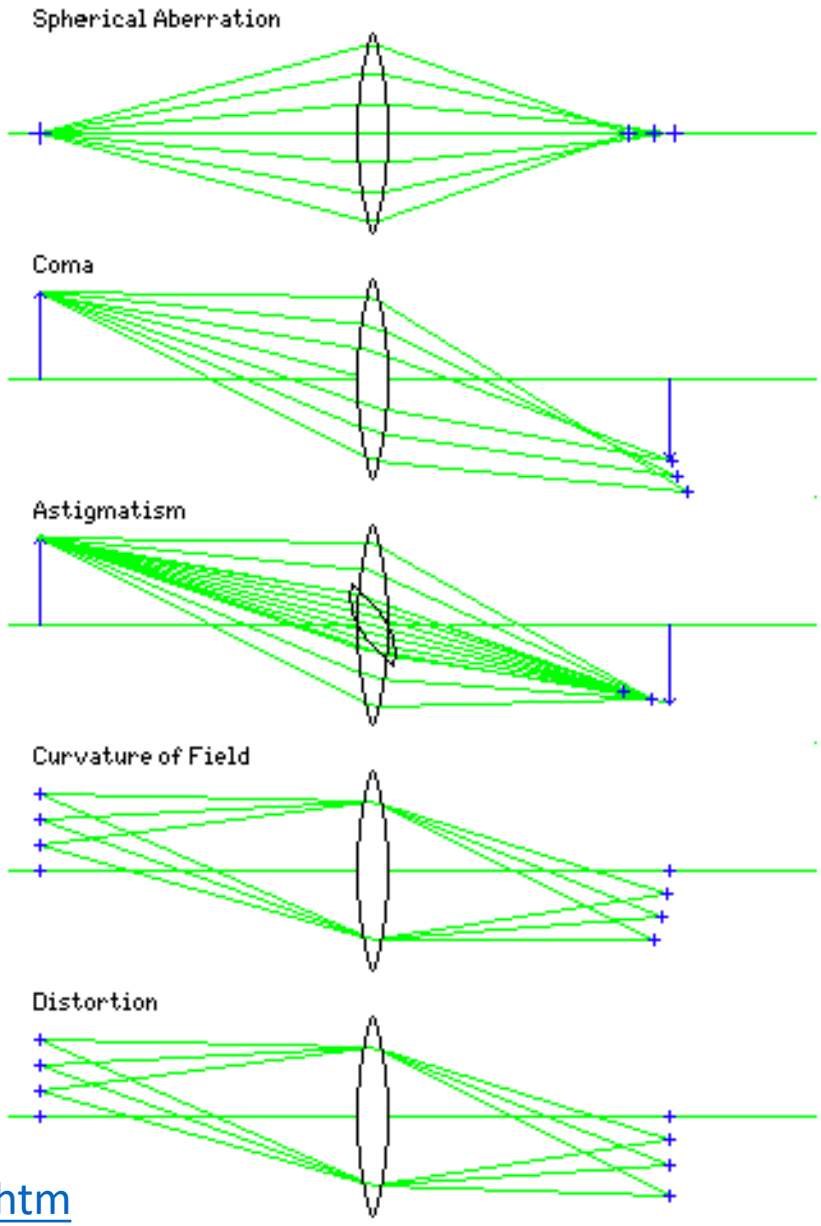
Prof. Darcy Barron

Lecture 6: Optical aberrations

Overview

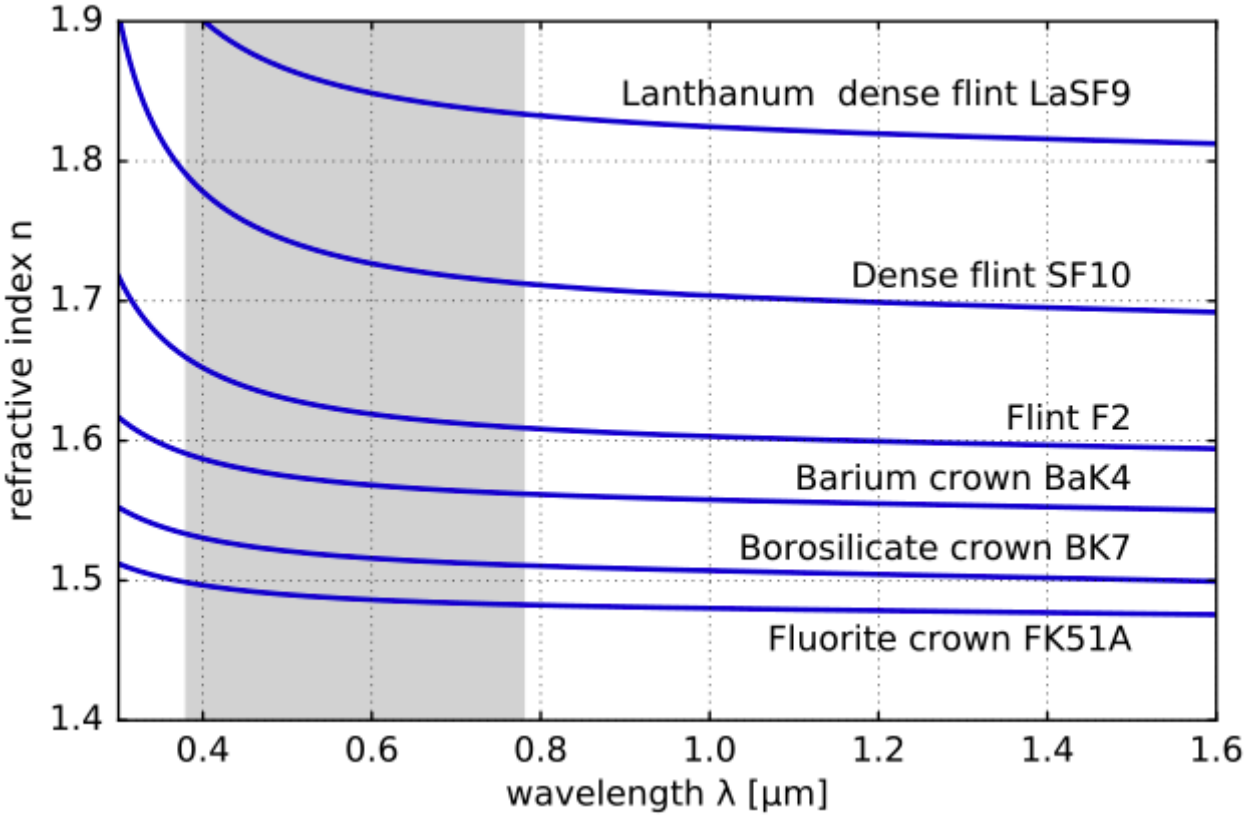
- Last week: Whirlwind tour of telescope design parameters, defining import variables, and a few telescope designs
  - Focal length f
  - Aperture size D
  - Focal ratio aka f/number F = f/D
    - Inversely proportional to energy per unit time onto pixel
    - Large number: “slow” (long exposure, slowly converging rays, but high magnification)
    - Small number: “fast” (short exposure, quickly convering rays)
    - An “effective” focal ratio can be determined at any point in the system and used to determine plate scale at that point
- This week: optical aberrations, and applying telescope design principles
- Reminder: everything we’re discussing is still relevant across wavelengths (although many properties are not wavelength-independent)

Primary Aberrations



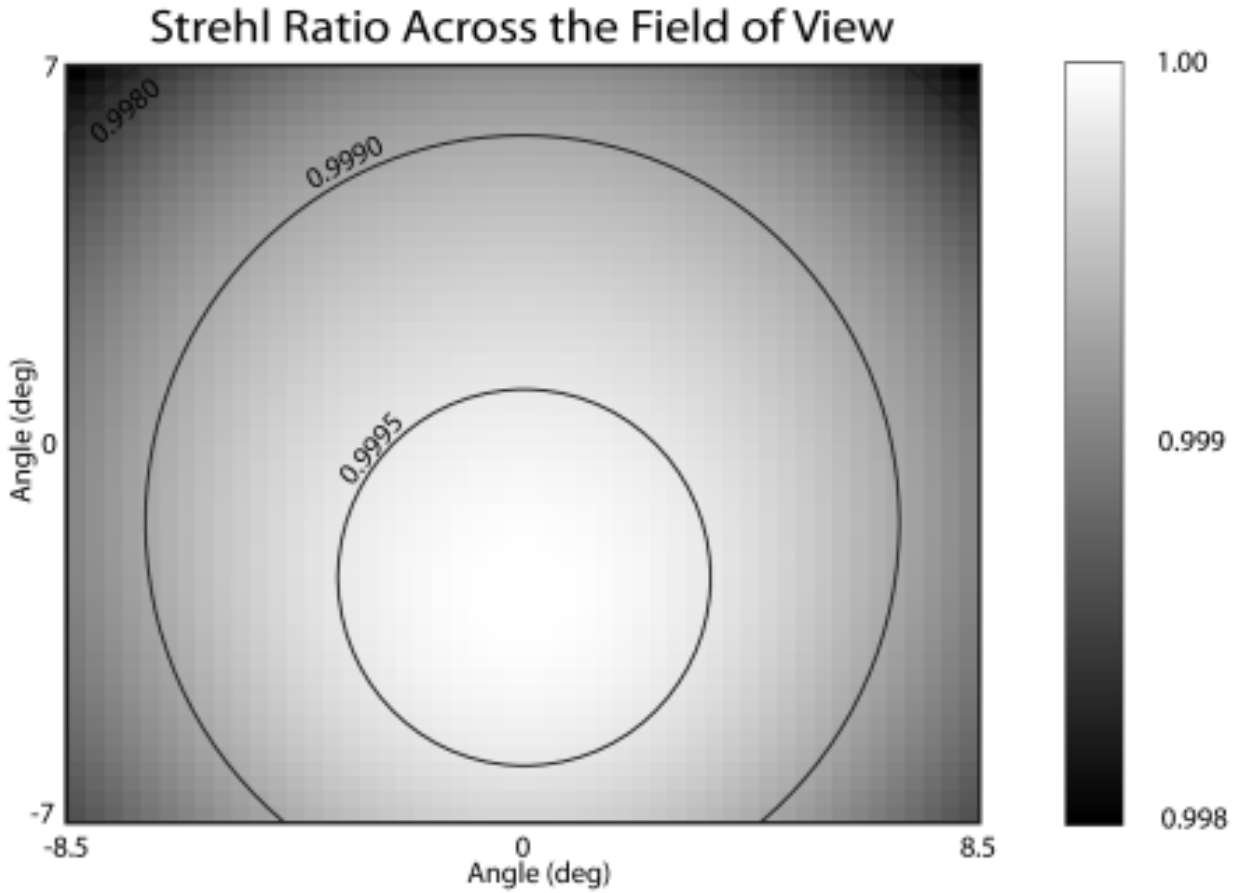
http://www.quadibloc.com/science/opt0505.htm

Chromatic aberrations



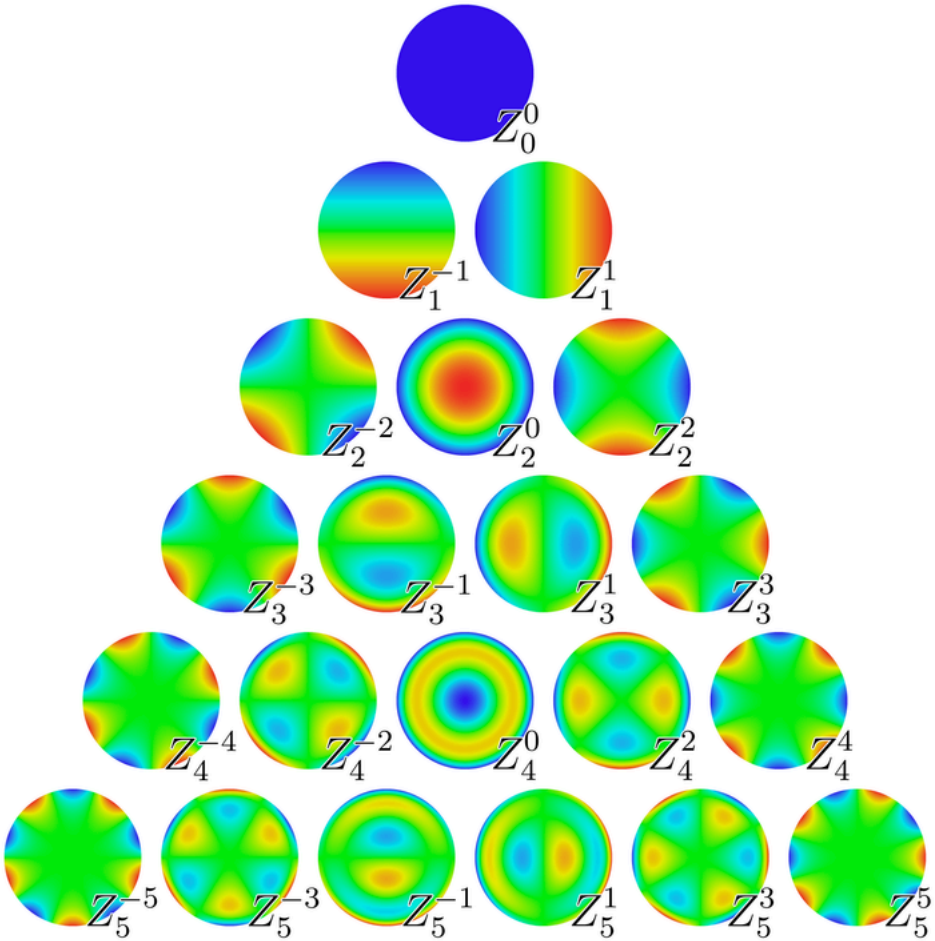
https://en.wikipedia.org/wiki/Refractive_index

Strehl Ratio



https://arxiv.org/abs/1211.0041

Zernike polynomials



https://en.wikipedia.org/wiki/Zernike_polynomials

Goodbye Aberration: Physicist Solves 2,000-Year-Old Optical Problem

JUL 05, 2019 EDUARDO MACHUCA

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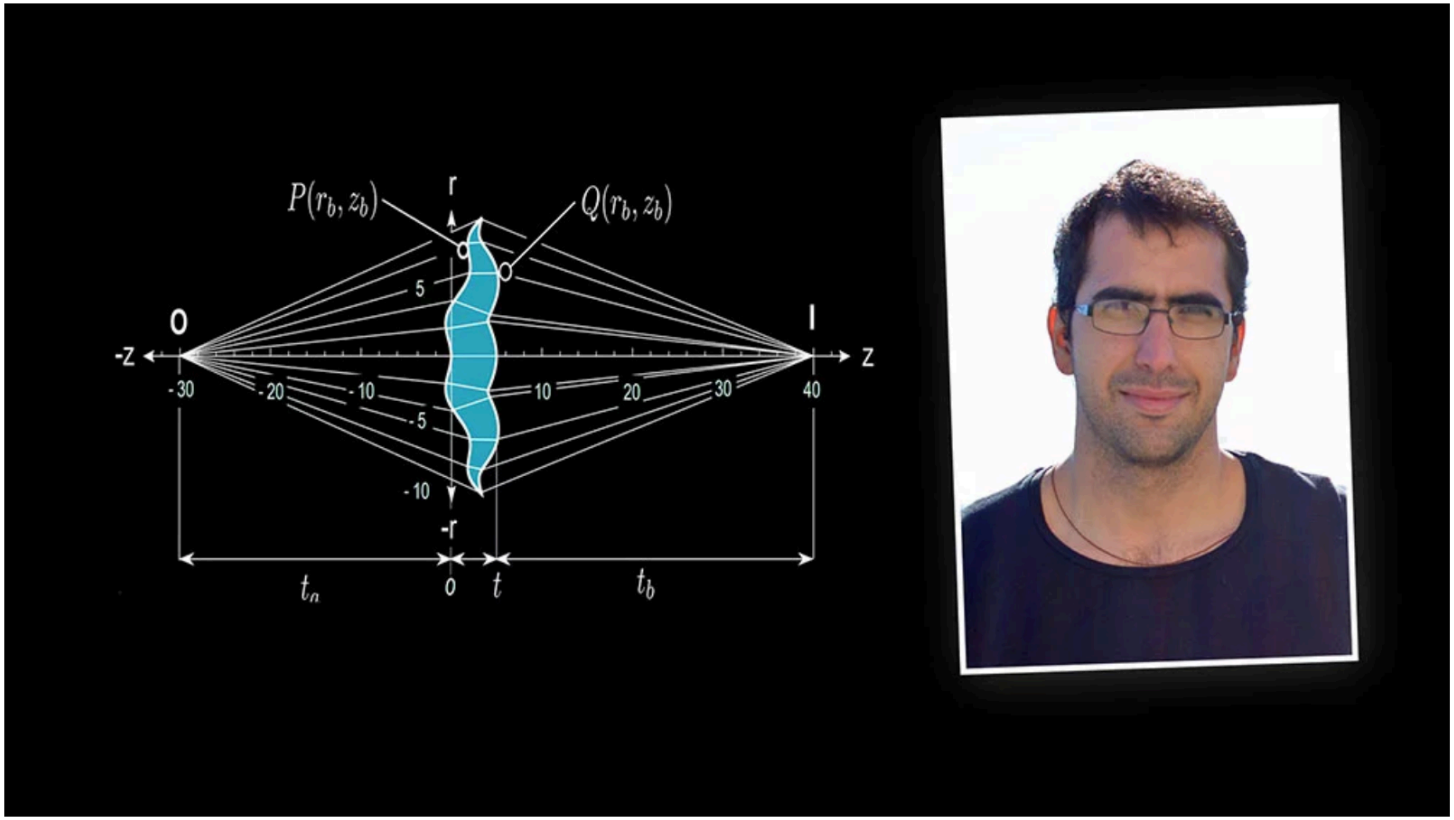
https://petapixel.com/2019/07/05/goodbye-aberration-physicist-solves-2000-year-old-optical-problem/



https://www.osapublishing.org/DirectPDFAccess/E42C93D1-0D3C-B7DE-A1FC3D46EADC0D22_399640/ao-57-31-9341.pdf?da=1&id=399640&seq=0&mobile=no

FÓRMULA GENERAL PARA DISEÑAR UNA LENTE SINGLETE BIASFÉRICA

$$
\left(-\left(t\left(\frac{\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}+\frac{z_a'(r_a)\left(r_a+(z_a(r_a)-t_a)z_a'(r_a)\right)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}\right)+z_a(r_a)\right)n^2+\left(t_a-\mathrm{tb}-\mathrm{sgn}(t_a)\sqrt{r_a^2+(t_a-z_a(r_a))^2}\right)\left(\frac{\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}+\frac{z_a'(r_a)\left(r_a+(z_a(r_a)-t_a)z_a'(r_a)\right)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}\right)n+(t+\mathrm{tb})\left(\frac{\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}+\frac{z_a'(r_a)\left(r_a+(z_a(r_a)-t_a)z_a'(r_a)\right)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}\right)^2
$$

$$
+s1\sqrt{\begin{array}{l}
\left(\frac{\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}+\frac{z_a'(r_a)\left(r_a+(z_a(r_a)-t_a)z_a'(r_a)\right)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}\right)^2\left(\left(\left(r_a^2+2t\left(\frac{r_a+(z_a(r_a)-t_a)z_a'(r_a)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}-\frac{z_a'(r_a)\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}\right)r_a+(\mathrm{tb}-z_a(r_a))^2\right.\right.\right.\\
\left.+t^2\left(\left(\frac{\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}+\frac{z_a'(r_a)(r_a+(z_a(r_a)-t_a)z_a'(r_a))}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}-1\right)^2+\left(\frac{r_a+(z_a(r_a)-t_a)z_a'(r_a)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}-\frac{z_a'(r_a)\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}\right)^2\right)-2t(\mathrm{tb}-z_a(r_a))\left(\frac{\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}+\frac{z_a'(r_a)(r_a+(z_a(r_a)-t_a)z_a'(r_a))}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}-1\right)\right)n^2\\
-2\left(t_a-\mathrm{tb}-\mathrm{sgn}(t_a)\sqrt{r_a^2+(t_a-z_a(r_a))^2}\right)\left(t\left(\frac{r_a+(z_a(r_a)-t_a)z_a'(r_a)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}-\frac{z_a'(r_a)\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}\right)^2+r_a\left(\frac{r_a+(z_a(r_a)-t_a)z_a'(r_a)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}-\frac{z_a'(r_a)\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}\right)\\
+\left(-\mathrm{tb}+t\left(\frac{\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}+\frac{z_a'(r_a)(r_a+(z_a(r_a)-t_a)z_a'(r_a))}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}-1\right)+z_a(r_a)\right)\left(\frac{\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}+\frac{z_a'(r_a)(r_a+(z_a(r_a)-t_a)z_a'(r_a))}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}\right)\right)n\\
-\left(r_a\left(\frac{\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}+\frac{z_a'(r_a)(r_a+(z_a(r_a)-t_a)z_a'(r_a))}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}\right)+\left(\frac{r_a+(z_a(r_a)-t_a)z_a'(r_a)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}-\frac{z_a'(r_a)\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}\right)(t+\mathrm{tb}-z_a(r_a))\right)^2\\
+\left(t_a-\mathrm{tb}-\mathrm{sgn}(t_a)\sqrt{r_a^2+(t_a-z_a(r_a))^2}\right)^2\left(\left(\left(\frac{\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}+\frac{z_a'(r_a)(r_a+(z_a(r_a)-t_a)z_a'(r_a))}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}\right)^2+\left(\frac{r_a+(z_a(r_a)-t_a)z_a'(r_a)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}-\frac{z_a'(r_a)\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}\right)^2\right)\right)
\end{array}}
$$

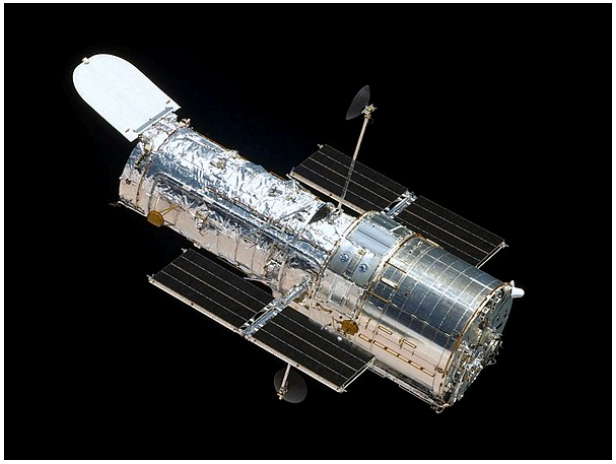
$$
\left(-r_a\left(\frac{\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}+\frac{z_a'(r_a)\left(r_a+(z_a(r_a)-t_a)z_a'(r_a)\right)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}\right)\left(\frac{r_a+(z_a(r_a)-t_a)z_a'(r_a)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}-\frac{z_a'(r_a)\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}\right)+\left(\frac{r_a+(z_a(r_a)-t_a)z_a'(r_a)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}-\frac{z_a'(r_a)\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}\right)^2z_a(r_a)\right)
$$

$$
z_b r_a=\frac{}{-n^2+\left(\frac{\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}+\frac{z_a'(r_a)\left(r_a+(z_a(r_a)-t_a)z_a'(r_a)\right)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}\right)^2+\left(\frac{r_a+(z_a(r_a)-t_a)z_a'(r_a)}{n\sqrt{r_a^2+(t_a-z_a(r_a))^2}\left(z_a'(r_a)^2+1\right)}-\frac{z_a'(r_a)\sqrt{1-\frac{(r_a+(z_a(r_a)-t_a)z_a'(r_a))^2}{n^2\left(r_a^2+(t_a-z_a(r_a))^2\right)\left(z_a'(r_a)^2+1\right)}}}{\sqrt{z_a'(r_a)^2+1}}\right)^2}
$$

https://petapixel.com/2019/07/05/goodbye-aberration-physicist-solves-2000-year-old-optical-problem/

Hubble Space Telescope

- Ritchey-Chretien telescope
  - 2.4 meter primary mirror
  - 57.6 meter focal length
  - Focal ratio f/24 (big and slow)
- Four main instruments observe in near infrared, visible, and ultraviolet wavelengths
- Launched in 1990 to low-earth orbit
  - Could last a few more decades
  - Only telescope designed to be maintained by astronauts



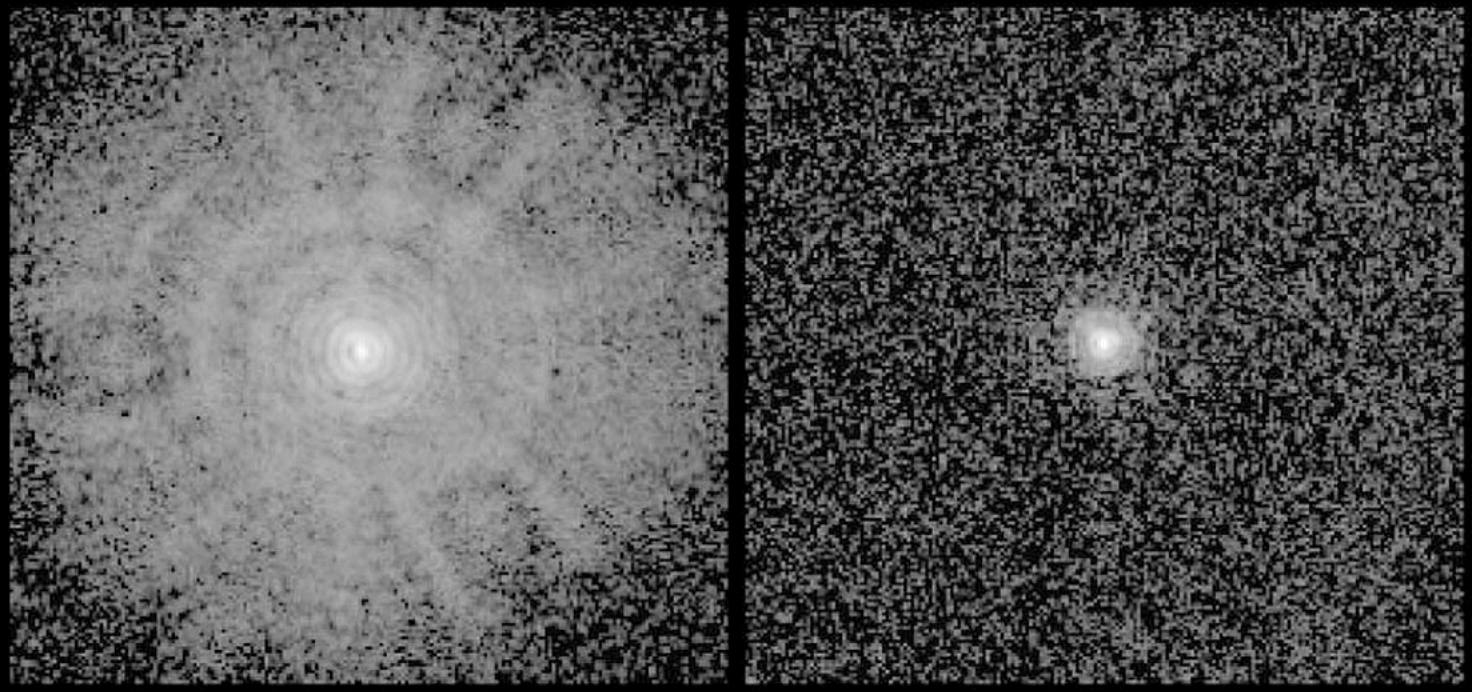
What happened with Hubble?

- On initial commissioning, Hubble was found to have very bad **spherical aberration**
- This resulted in blurry images and a resolution that was 10x worse than expected

HUBBLE SPACE TELESCOPE

FAINT OBJECT CAMERA

COMPARATIVE VIEWS OF A STAR



BEFORE COSTAR

AFTER COSTAR

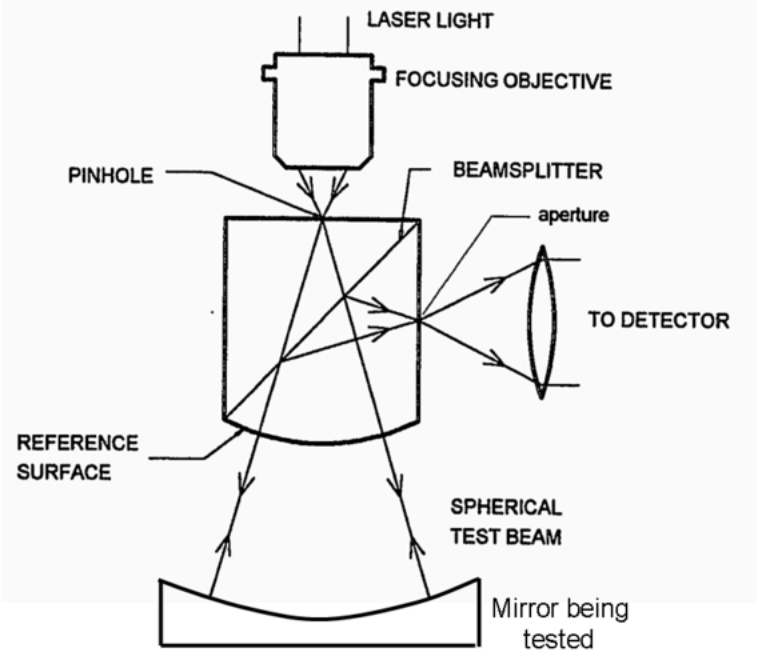
https://www.spacetelescope.org/images/opo9408a/

What happened with Hubble?

- The mirror had been ground extremely precisely, especially since it needed to be good enough to observe ultraviolet wavelengths
- Demonstrator mirror that this level of finishing was even possible is in storage at UNM (Prof. McGraw)
  - Smooth to 10 nm - If Hubble's primary mirror were scaled up to the diameter of the Earth, the biggest bump would be only six inches tall.
- The edge of the mirror was too flat, by 2200 nm

What happened with Hubble?

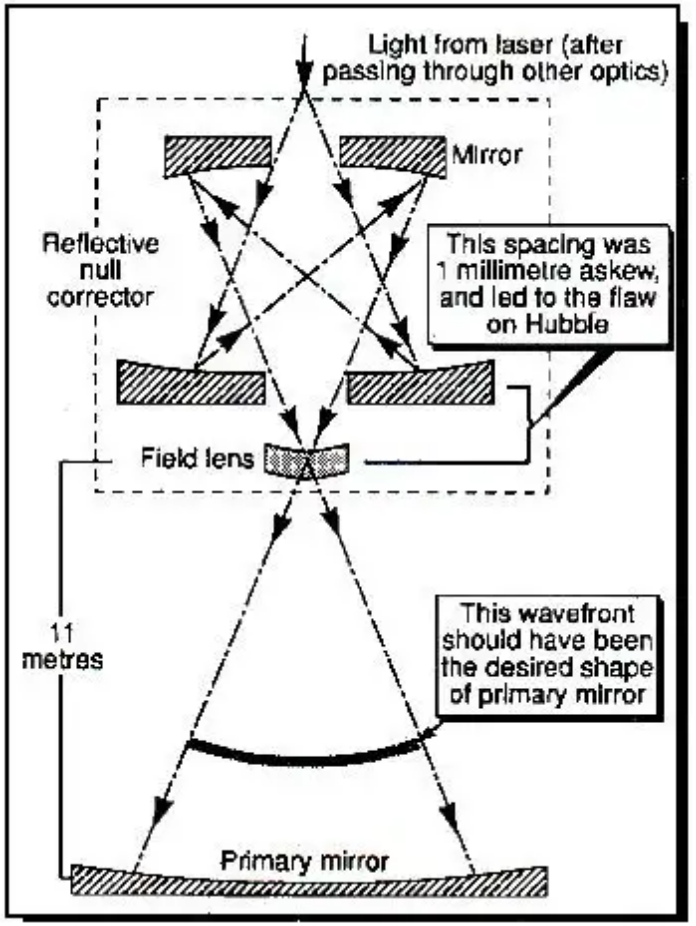
- Many different methods to test the shape of a mirror, and complex mirrors require more complex methods
- Nulling interferometry requires complex equipment but should be straightforward to understand
- Checks the deviation from a perfect spherical surface, to sub-wavelength precision



https://en.wikipedia.org/wiki/Null_corrector

What happened with Hubble?

- Aspherical surfaces can be tested using a null corrector
  - Setup for Hubble mirror shown at right
- Complicated setup of null corrector must be correct, to give the right surface figure to follow
- Hard to double-check if this is the only way to verify the figure
  - The company ignored problems with a coarser measurement since it wasn't supposed to be 'accurate'

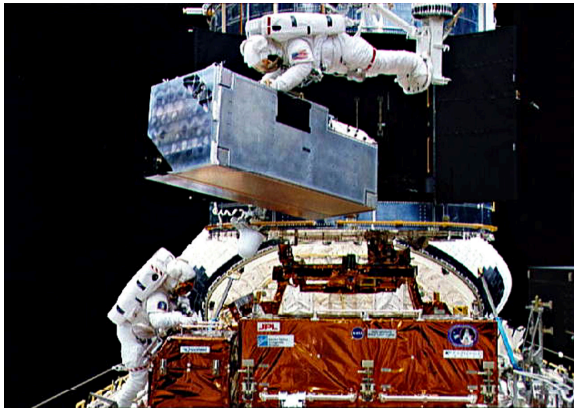


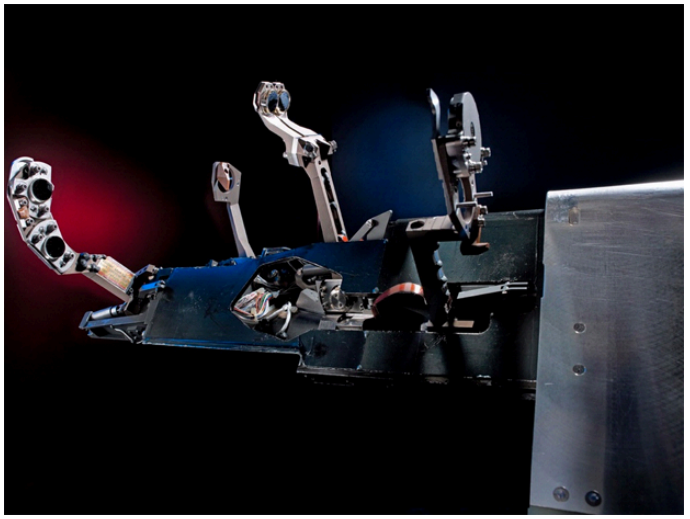
https://www.newscientist.com/article/mg12717301-000-the-testing-error-that-led-to-hubble-mirror-fiasco/

How was Hubble fixed?

- COSTAR: Corrective Optics Space Telescope Axial Replacement (COSTAR)
- 10 small mirrors on motorized arms corrected for the aberration on each of Hubble's instruments
- Instruments have been replaced and upgraded to correct for aberration, so COSTAR is no longer in use
    - Is on display at the Smithsonian

https://www.spacetelescope.org/about/general/instruments/costar/





Trump Tweets Sensitive Surveillance Image Of Iran

August 30, 2019 · 4:22 PM ET

GEOFF BRUMFIEL

https://www.npr.org/2019/08/30/755994591/president-trump-tweets-sensitive-surveillance-image-of-iran

A commercial satellite image from the company Maxar (bottom); the image tweeted by President Trump (top) appears to be of better quality.

(Bottom) Satellite image ©2019 Maxar Technologies; (top) @realDonaldTrump