Introduction to Optics for Astronomy

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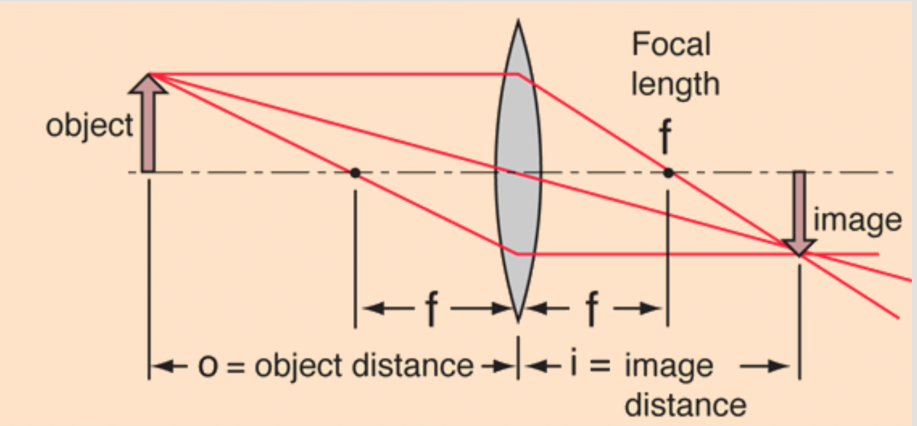
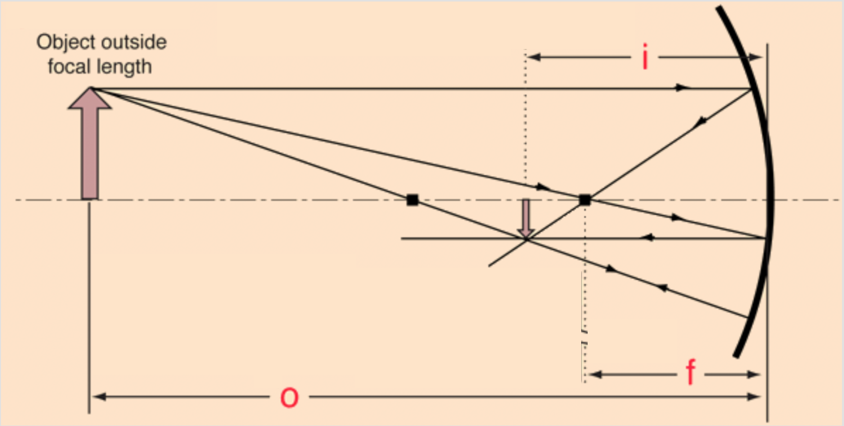




General Outline

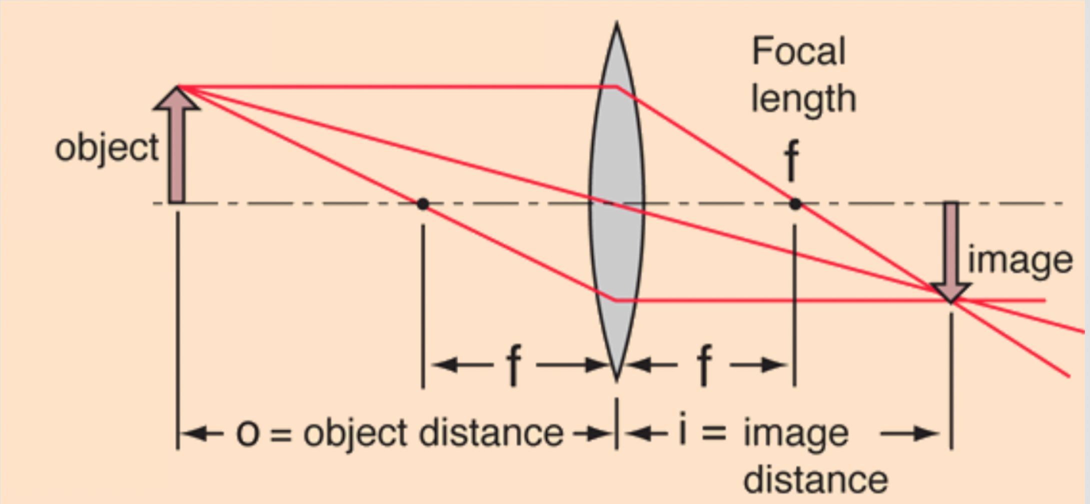
- Basic optics
- Aberrations
- Telescope design considerations
  - Field of view
  - Collecting area
  - Point spread function
  - Stray light
  - etc
- How do costs scale?

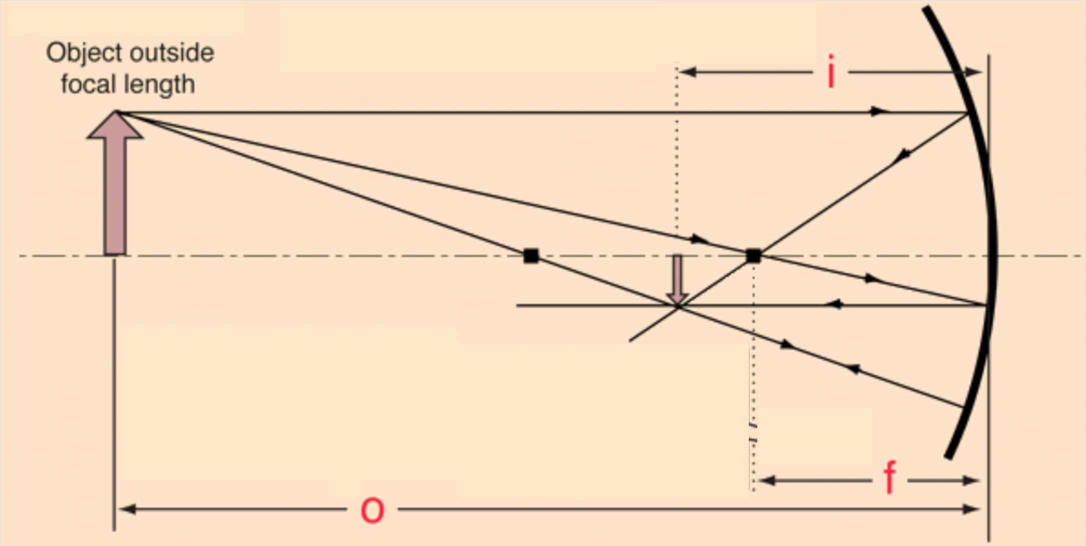
Why Do We Need Telescopes?

- Objects (or features) of interest are often dim
  - The number of photons received per unit time is proportional to the area of the primary aperture = π (D/2)^2
  - Specific example:
    - Diameter of a human pupil in dark conditions = 8 mm
    - A 1 m diameter telescope would collect 15,000 times more photons!
    - That 1 m telescope would still only receive 10 optical photons/second from a galaxy like the Milky Way at $z = 1$
- Objects (or features) of interest often have small angular sizes
  - Ignoring all other imperfections due to optics and atmosphere, diffraction limits angular resolution to λ/D
  - Specific example:
    - A 1 m diameter telescope observing (from space) in the near IR at 1 μm
    - λ/D = 1e-6 radians = 0.2 arcsec
    - Milky Way diameter = 25 kpc (0.7 arcsec at $z = 1$)

How Do We Focus Light?

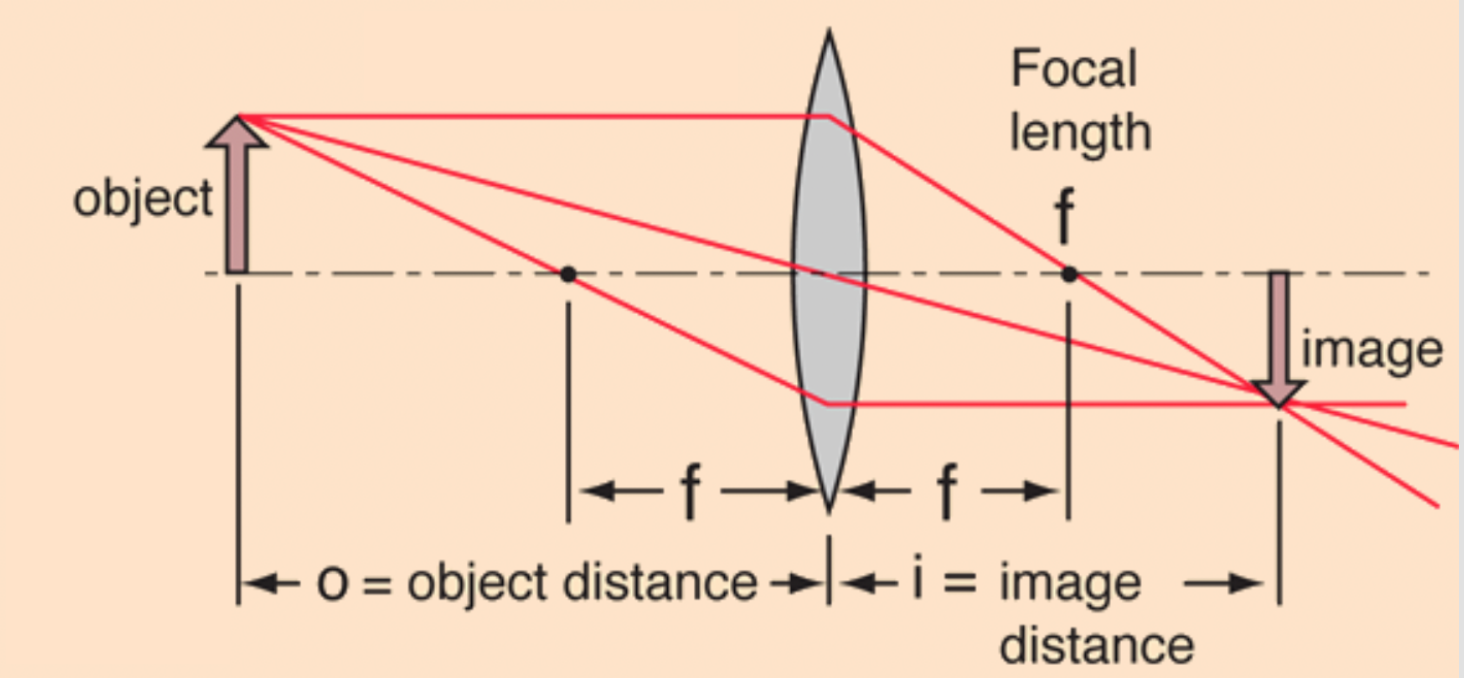
- Our primary telescope aperture collects light, but we then need to focus it
  - Either onto a detector array or onto an eyepiece
- Refractive optics (lenses)
- Reflective optics (mirrors)
- Images courtesy of hyperphysics

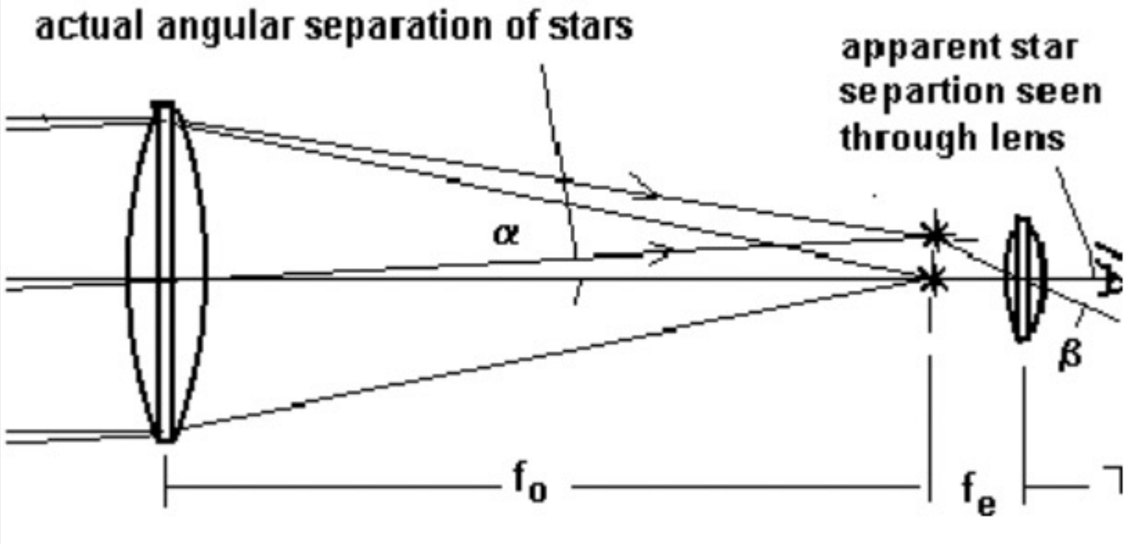




Lens Equation

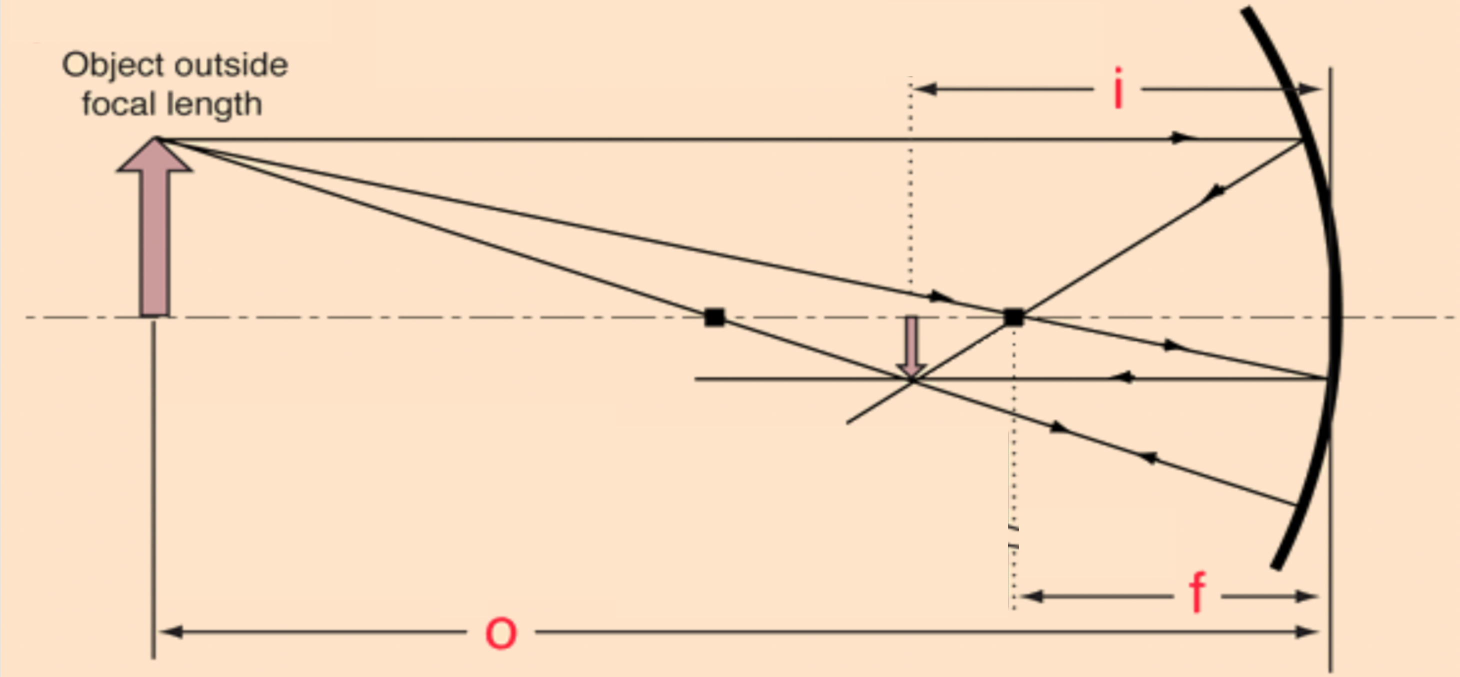
- Consider a lens with index n and radius of curvature R
  - The focal length of the lens is:
  - $f = \frac{\mathrm{R}}{2(\mathrm{n}-1)}$
- For “nearby” objects
  - $\frac{1}{f} = \frac{1}{o} + \frac{1}{i}$
  - Magnification $M = \frac{i}{o}$
- For astronomy $o = \infty$
  - $i = f$
  - $M \rightarrow 0$
- Why is magnification approaching 0?
  - Galaxies are very large and our detector array (or eyepiece) is very small
  - However, for an eyepiece we can determine the *angular* magnification





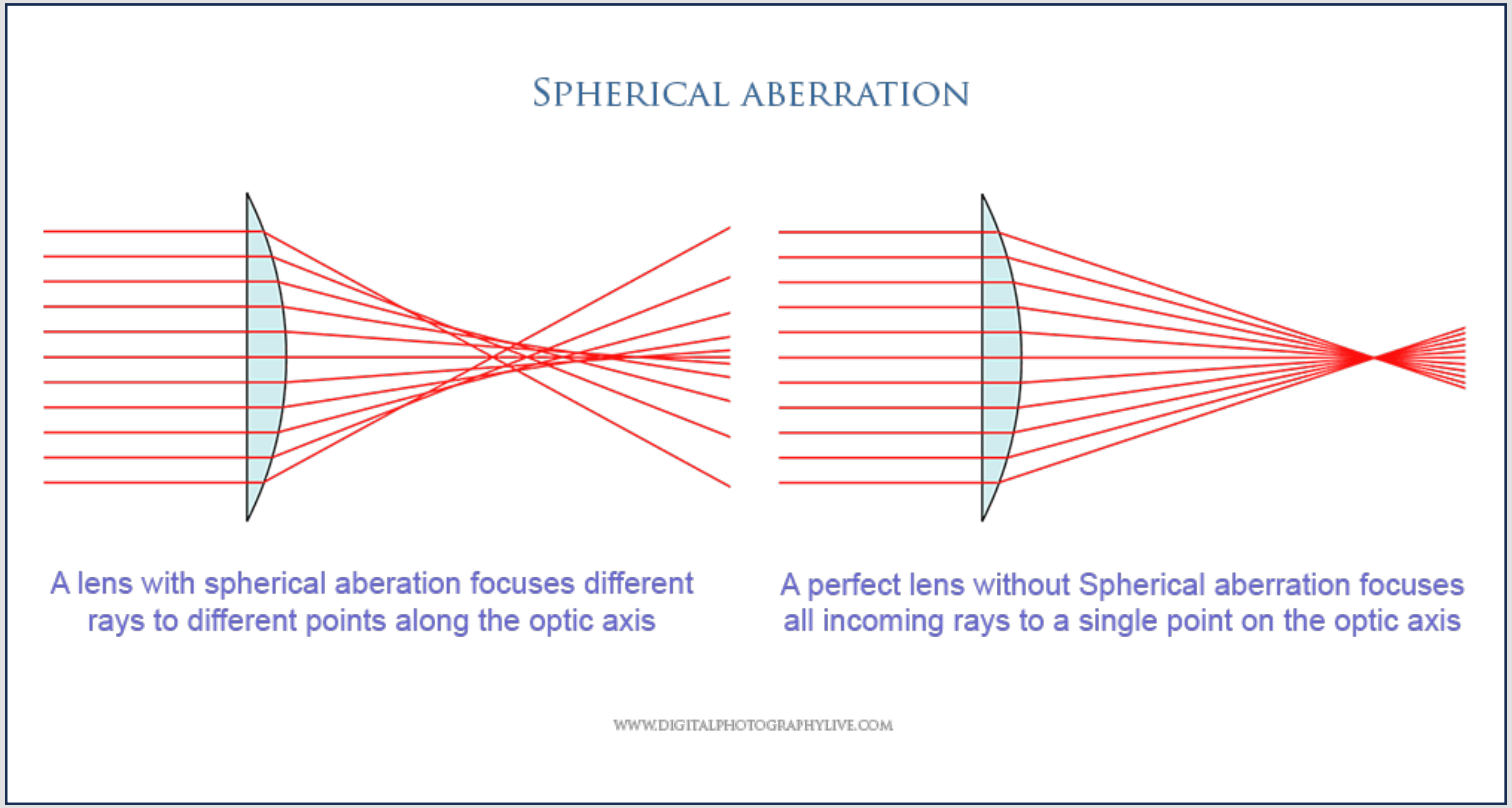
Lens Equation (For a Mirror)

- Focal length is analogous to the thin lens
  - But without the correction factor of (n-1)
  - $f = \frac{R}{2}$
- The other relations are also analogous



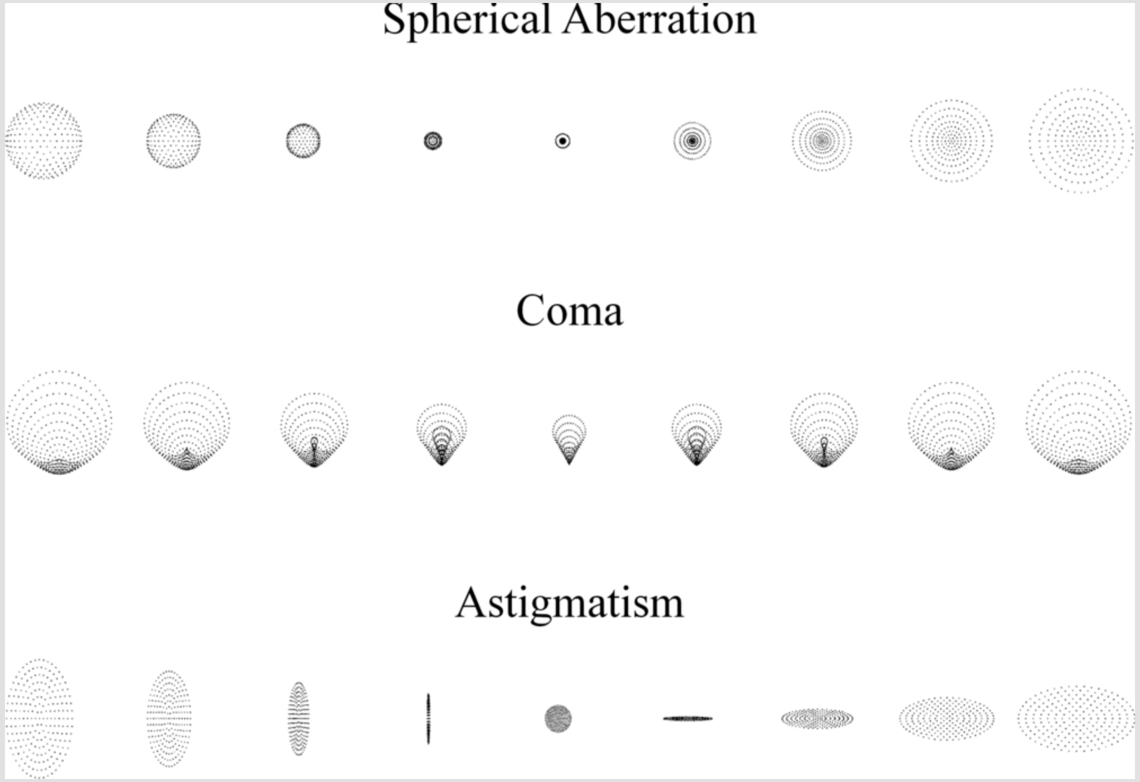
Aberrations

- Optical surfaces often have imperfections
  - Due to, e.g., intrinsic design, manufacturing tolerances
- Even “perfect” on-axis optics will produce aberrations off axis
  - e.g., at the edge of the field of view



What Are the Typical Aberrations?

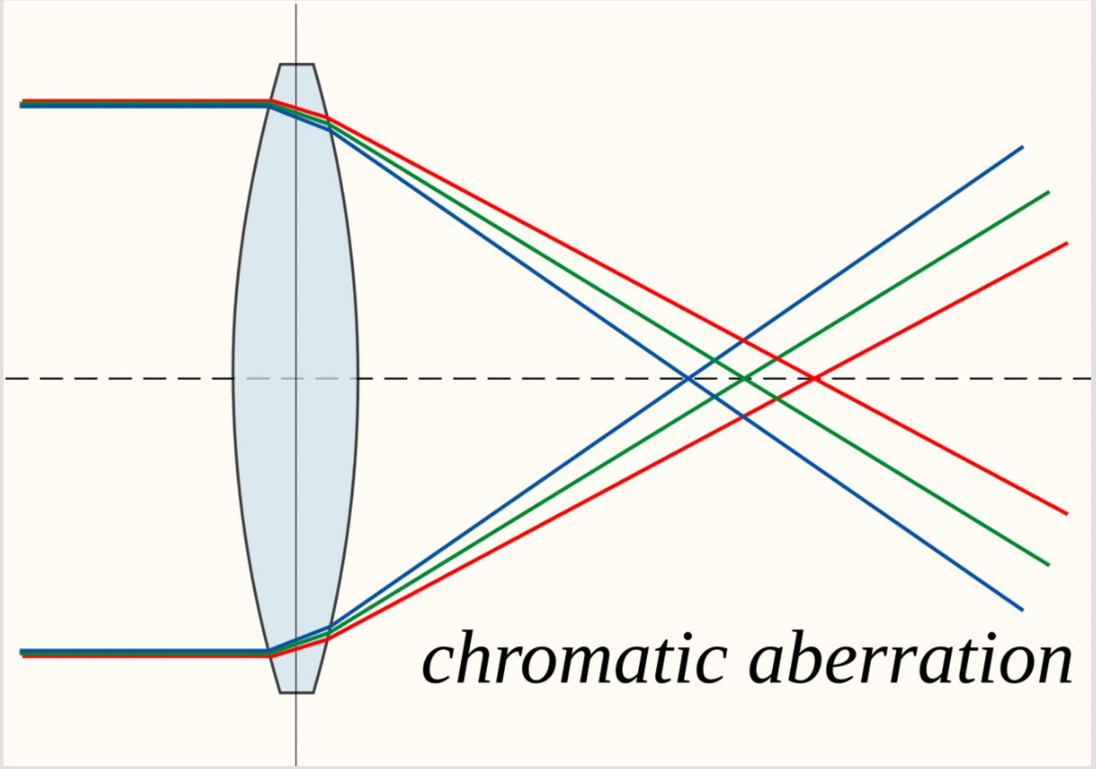
- Spherical
  - A spherical lens will focus parallel incoming rays at different image distances along the optical axis from the lens, even for on-axis rays
- Coma
  - The effective focal length can vary over the face of the lens for off-axis rays, resulting in an asymmetric “comet-like” aberration
  - Note that coma is asymmetric, and so the position of the source “moves”
- Astigmatism
  - The focal length differs in the two planes (e.g., off-axis rays with non-normal incidence on a symmetric lens)



From Introduction to Aberrations in Optical Imaging Systems by José Sasián

What Else Can Cause Image Degradation?

- Chromatic aberration
  - The index of most (all?) lens materials depends on wavelength
- Curved focal surface
  - Even if free from traditional aberrations, off-axis rays may focus in a different plane from on-axis rays
  - Most detector arrays are flat (planar), and so this results in a de-focusing of these off-axis rays
- Diffaction
  - λ/D (the fundamental limit)



From wikipedia

Lenses or Mirrors?

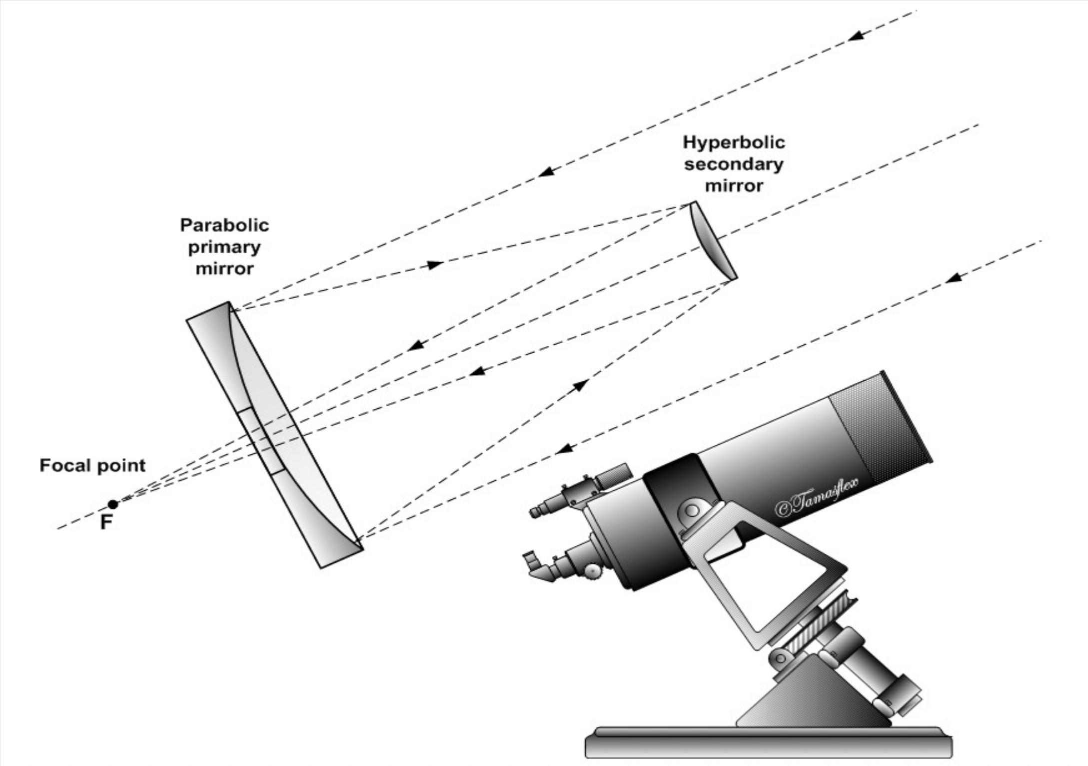
- Given the effective equivalence between lenses and mirrors, why choose one over the other?
- With lenses…
  - The optical system can be designed around a single axis without any obscurations (i.e., the optical elements solely focus, or defocus, without re-directing the optical path)
    - With mirrors the optical path can either be folded *or* there will be optical blockages from one or more mirrors being in the path of another mirror
  - With lenses the system is thus blockage free *and* symmetric about the optical axis
  - And the overall size of the optical system perpendicular to the optical axis is minimized
- With mirrors…
  - There are no chromatic aberrations
  - The entire optical path is in air (and/or vacuum), thus maximizing overall transmission
- Most systems contain a combination of both lenses and mirrors

How Do We Design Actual Telescopes?

- We generally want the largest possible field of view
  - Aberrations generally grow (quickly) when moving away from the optical axis
- We generally want the largest possible collecting area
  - As the size of the optics gets larger, the corrections required to control aberrations over a fixed field of view are more difficult to achieve
- We generally want the "ideal" point spread function
  - i.e., constant over the field of view (or at least as symmetric as possible)
- We generally want a flat focal surface to match the detector array
- The science goals of a particular project dictate the relative importance of these various design drivers
- By combining multiple optical elements it is possible to correct for aberrations
  - The corrections can be optimized based on the specific design goal in mind (e.g., maximizing the field of view)

Example Telescope - ”Classical” Cassegrain

- Parabolic primary mirror combined with a hyperbolic secondary mirror
- Pros
  - Simple 2-element design
  - Secondary removes spherical aberrations
- Cons
  - Secondary mirror “blocks” the primary for on-axis Cassegrains
  - Significant coma off-axis
    - Limited field of view
    - Incorrect astrometry
  - Curved focal surface



From wikipedia

Example Telescope – Ritchey-Chrétien Cassegrain

- The parabolic primary mirror of the classical Cassegrain can be replaced with a hyperbolic surface
- Pros
  - Still a simple 2-element design
  - Coma can be removed to provide a larger field of view and accurate astrometry (although it is replaced with astigmatism)
- Cons
  - The secondary still blocks the primary mirror
  - And the focal surface is still curved

Hubble Space Telescope

Example Telescope – Cassegrain w/ Corrector

- Corrector plates (lenses) can be added to Cassegrain systems to suppress aberrations and produce a flatter focal surface
- Pros
  - Significantly improved image quality
- Cons
  - These designs can become quite complicated, and contain a large number of elements
  - Refractive optics can be lossy and wavelength-dependent
- See examples to the right from Ackermann, McGraw, and Zimmer 2008

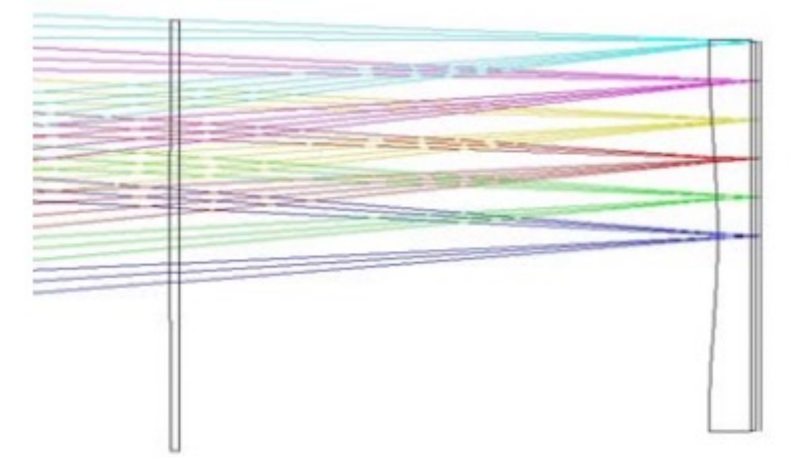


Fig. 2. SDSS corrector optics.

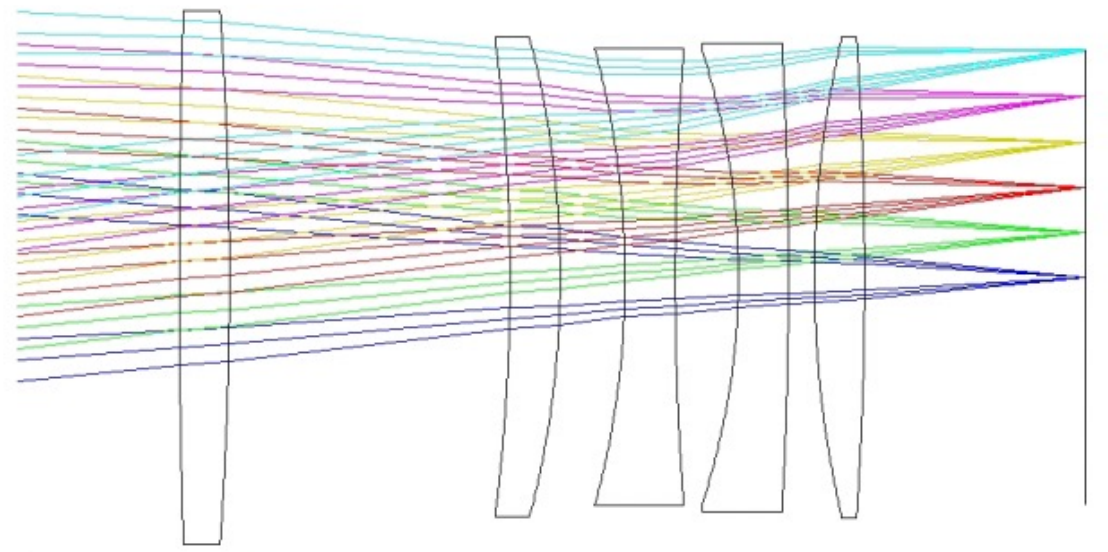
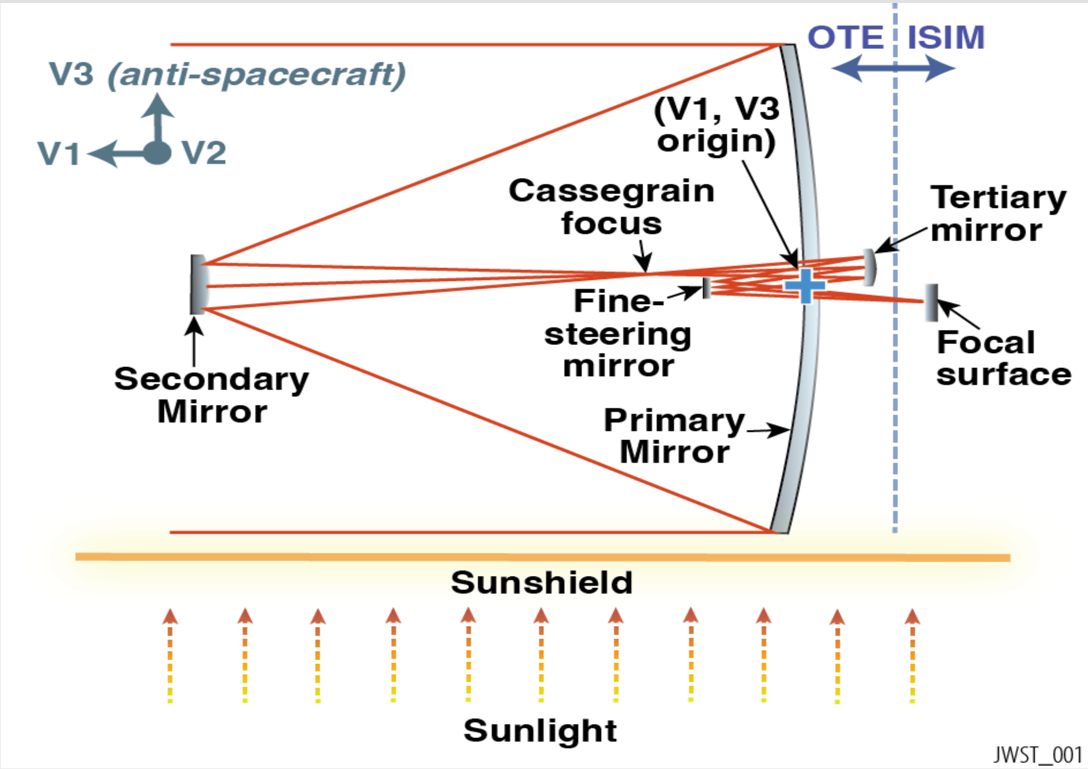


Fig. 9. Layout of five lens corrector for Sloan telescope.

Example Telescope – Three-Mirror Anastigmat

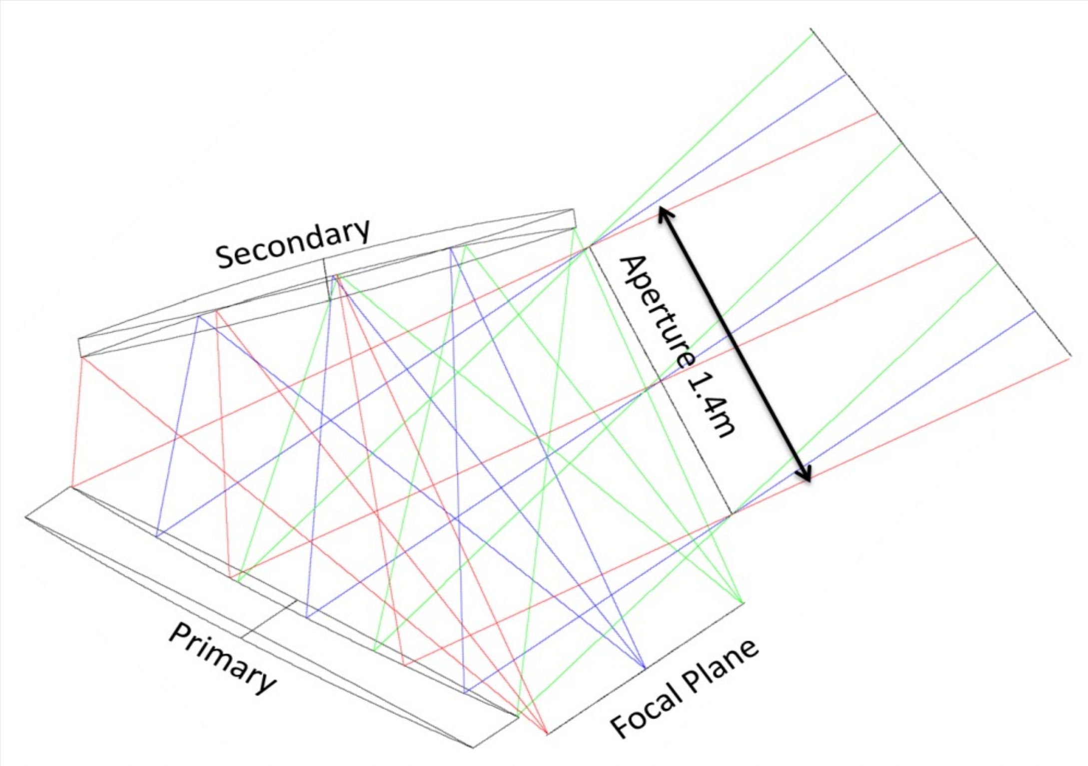
- Instead of a corrector plate(s), a third mirror can be added
  - In combination, all of the primary aberrations can be largely cancelled (spherical, coma, astigmatism)
- Pros
  - Provides a highly corrected large field of view without refractive optics
- Cons
  - More complicated and less compact optical path compared to corrector plates



JWST Optical Design

Example Telescope – Crossed Dragone

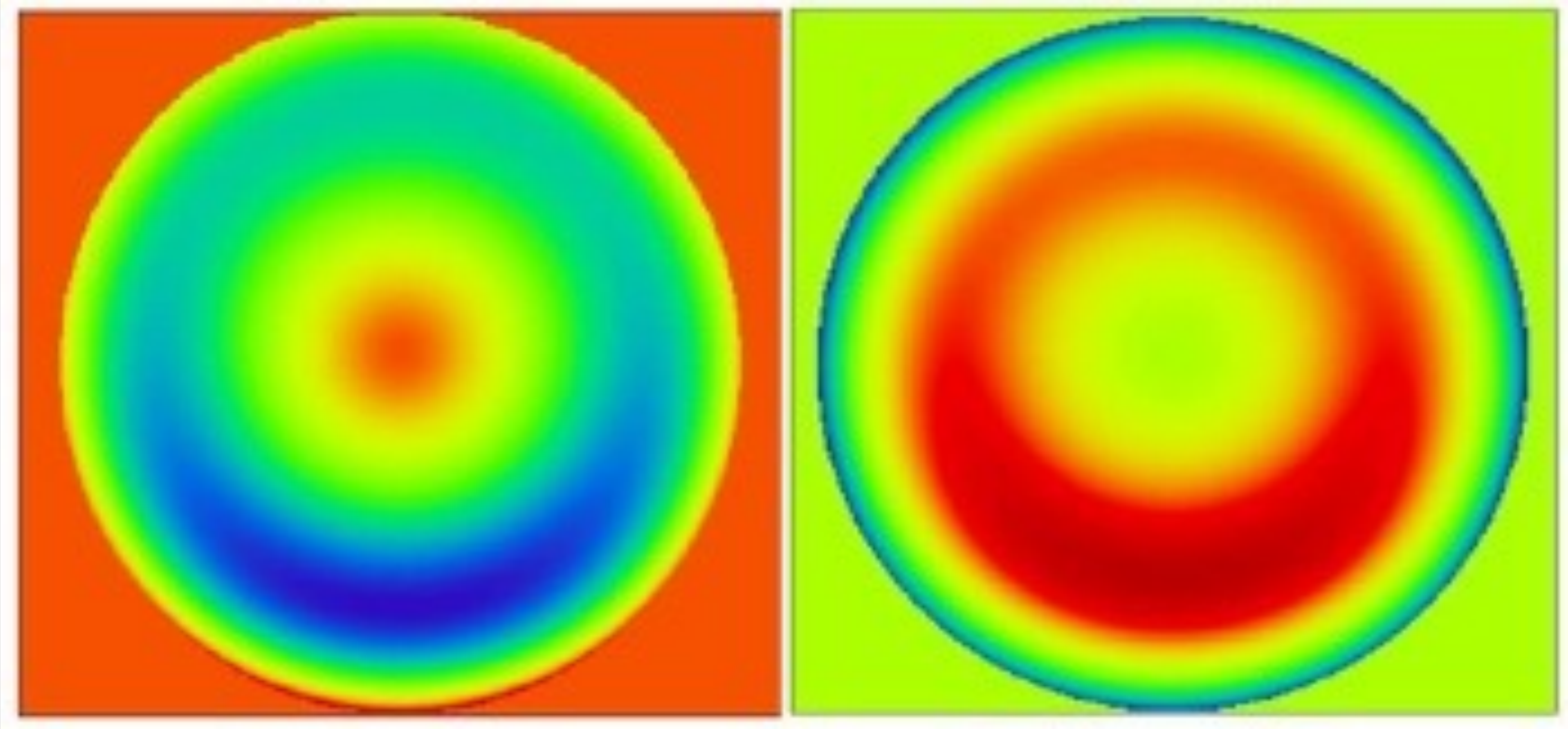
- The mirrors can also be placed off-axis to remove the secondary blockage (e.g., crossed Dragone)
  - This allows for very large secondary mirrors, which can produce excellent image quality over large fields of view
- Pros
  - Compact two-mirror design
- Cons
  - The large secondary mirror significantly increases costs for a given primary mirror size



EPIC-IM Concept from Tran+2010

Example Telescope – Aspheric Surfaces

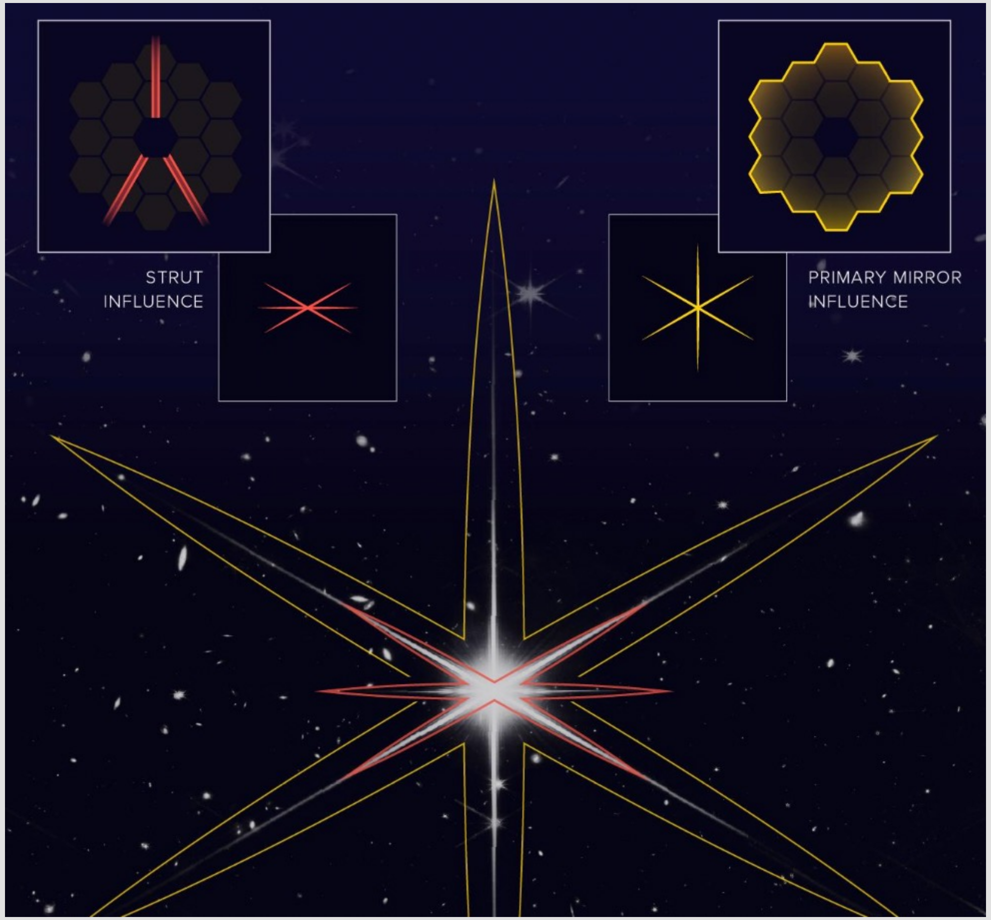
- Modern computers allow for optimization of mirror surfaces via small deviations from conic sections
- Pros
  - Improved image quality
- Cons
  - Manufacturing costs (e.g., all panels of segmented mirrors are slightly different in profile)



Deviations of the primary (left) and secondary (right) mirrors for CCAT-P (Parshley et al. 2018)

Diffraction Artifacts

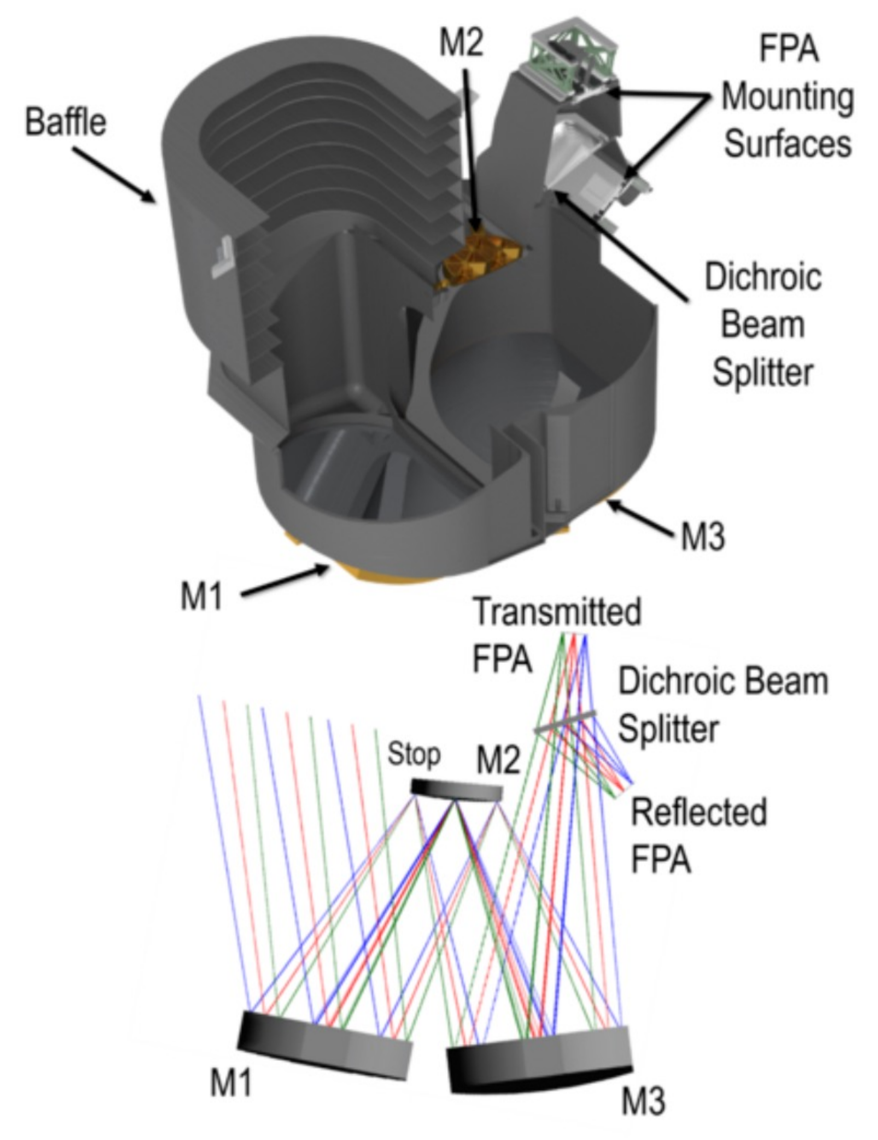
- The support structures required for on-axis secondary mirrors produce diffraction spikes
- So do the segmented panels required for very large mirrors
- This results in point spread functions with artifacts that differ from those due to typical aberrations
  - Such diffraction spikes are usually only visible for very bright objects such as stars



JWST diffraction spikes

Baffling/Stray Light

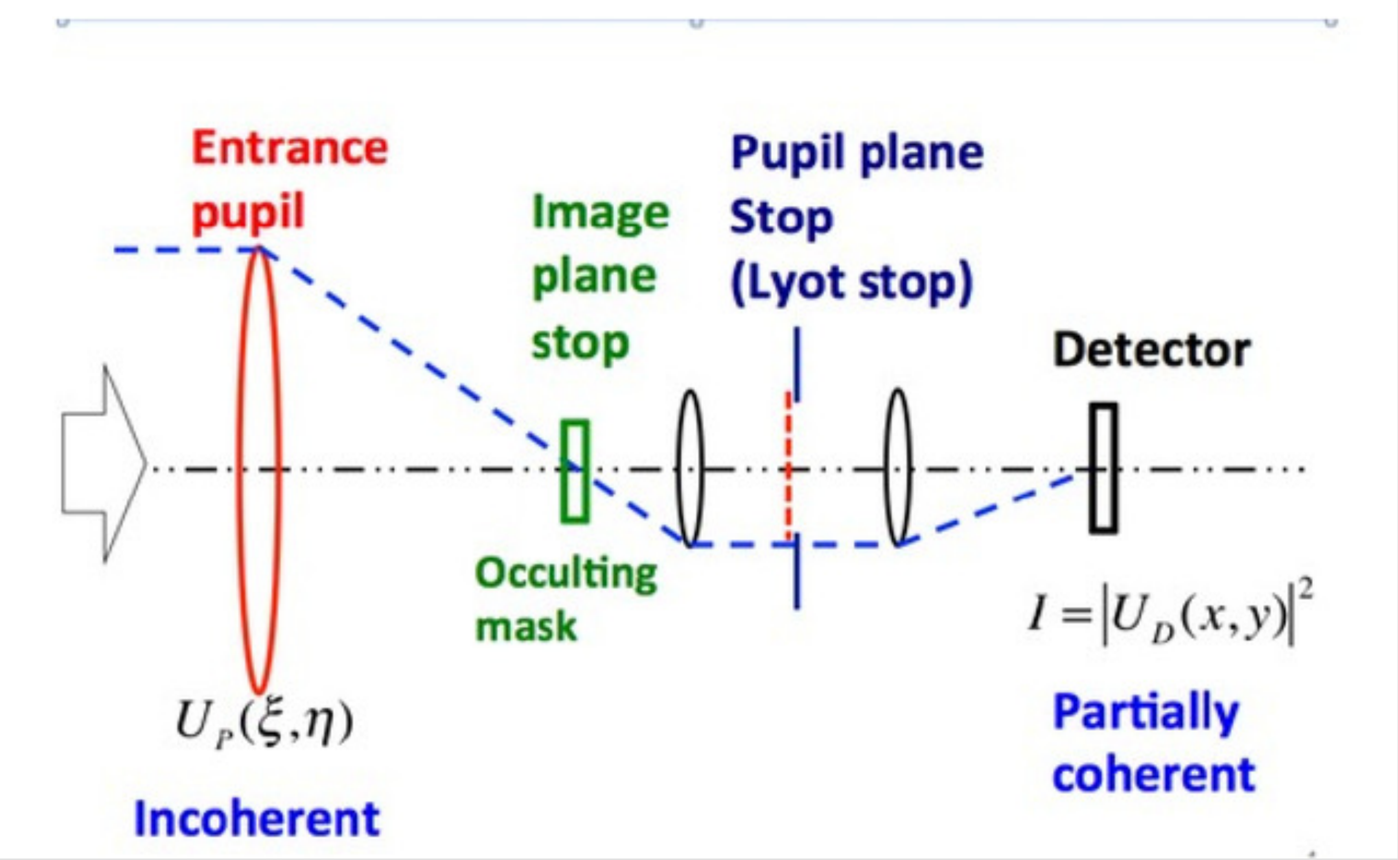
- Unwanted light from outside of the desired optical path can enter the system and be incident on the detector array
- This can cause a range of problems
  - Spurious signal (e.g., based on the angular separation between the optical axis and bright objects like the sun, moon, planets, etc.)
  - Even if the stray light is constant with angle, it still results in an elevated background signal and an increase in photon noise



SPHEREx optical baffles

Aperture (Image) Stop(s)

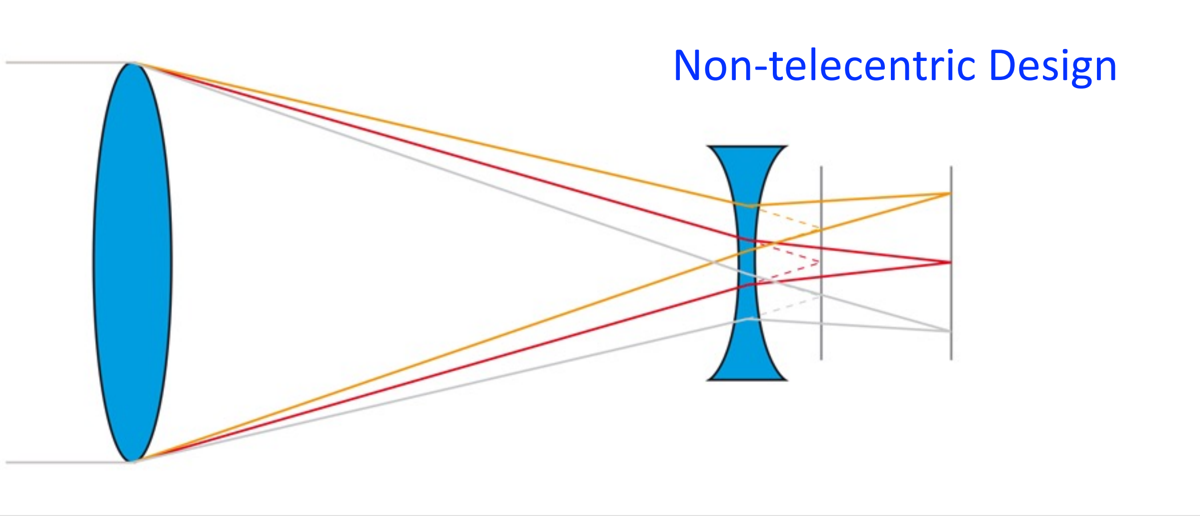
- In addition to baffles, stops are useful in mitigating stray light
- This requires "re-imaging" the telescope focal plane
  - An image plane stop, with a cutout matching the projected size of the focal plane, is placed at the original focus to block light outside of that footprint
  - An image of the primary mirror (entrance pupil) is then formed, with another stop matching the projected size of the primary

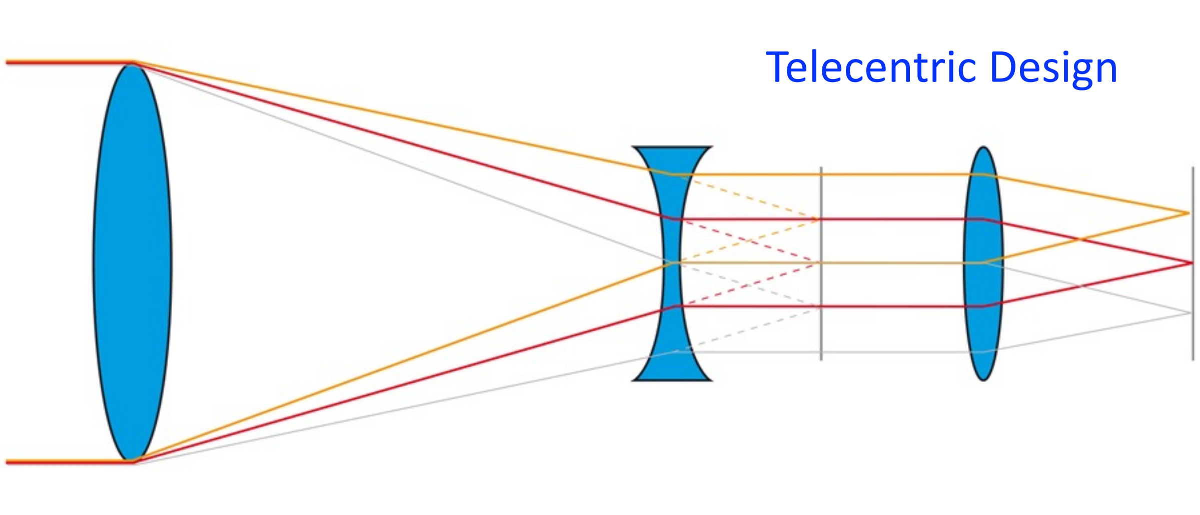


Schematic of a typical Lyot coronograph (from Breckinridge et al. 2018)

Telecentricity

- Most detectors are designed to optimally couple to incoming light with a chief ray normal to the detector plane
  - It is thus generally desirable to have a “telecentric” focal plane, with approximately normal incidence for all off-axis positions
  - This requires the final optic in the system to be at least as large as the focal plane, and often involves some trade off versus aberration control





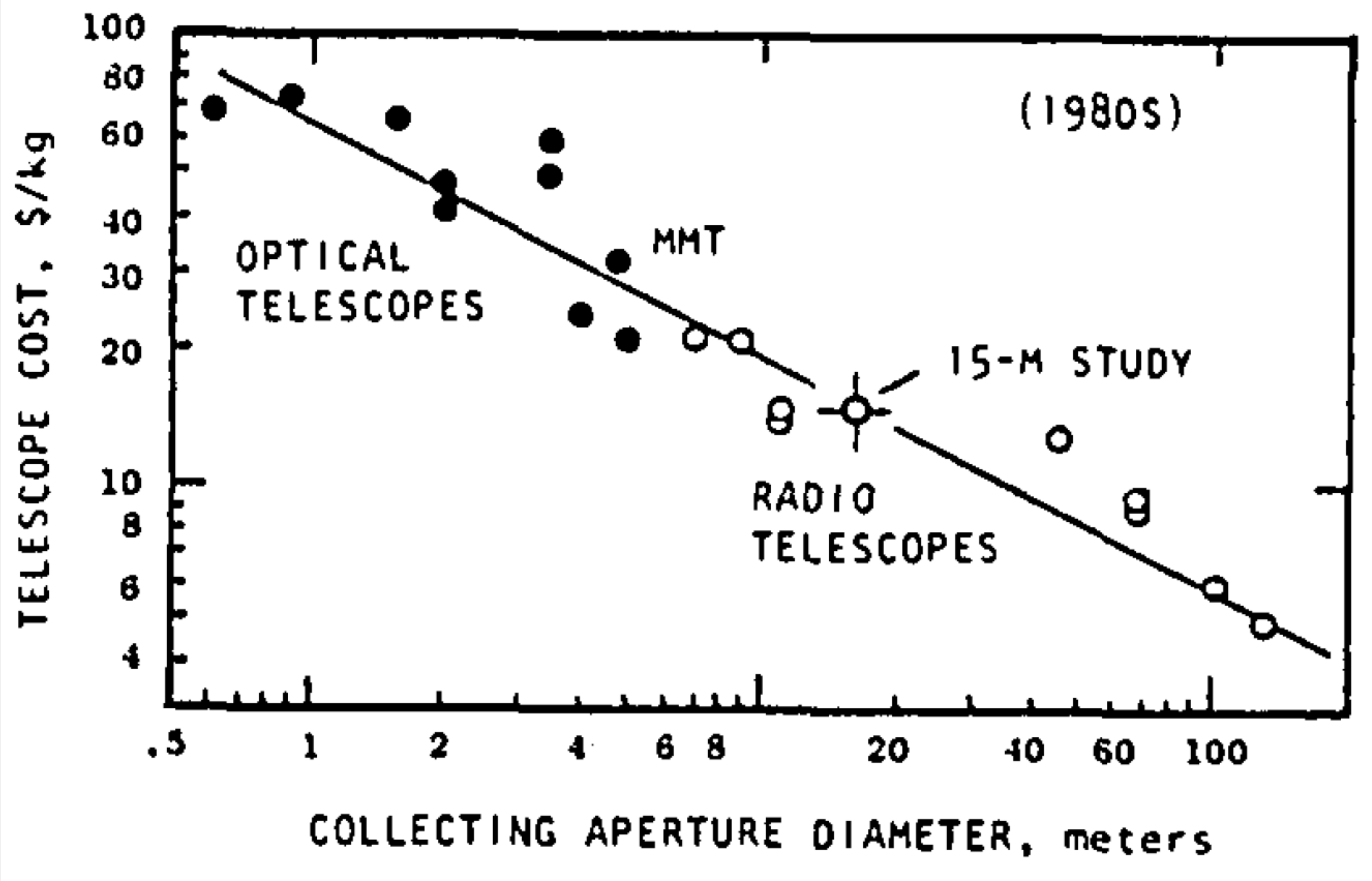
Examples from Baader Planetarium

What are the (Relative) Costs of Telescopes?

- With infinite resources (money), it would be possible to construct the "perfect" telescope for any science case
- All realistic projects need to fit within a budget, and so it's useful to understand the tradeoffs between different design considerations
  - What if the most critical driver is point spread function over a wide field of view (e.g., for gravitational lensing)?
  - What if the most critical driver is collecting area (primary aperture size)?
  - What if the most critical driver is control of stray light (baffling)?
- Within this context, let's consider some possibilities

What Sets the Overall Cost of a Telescope?

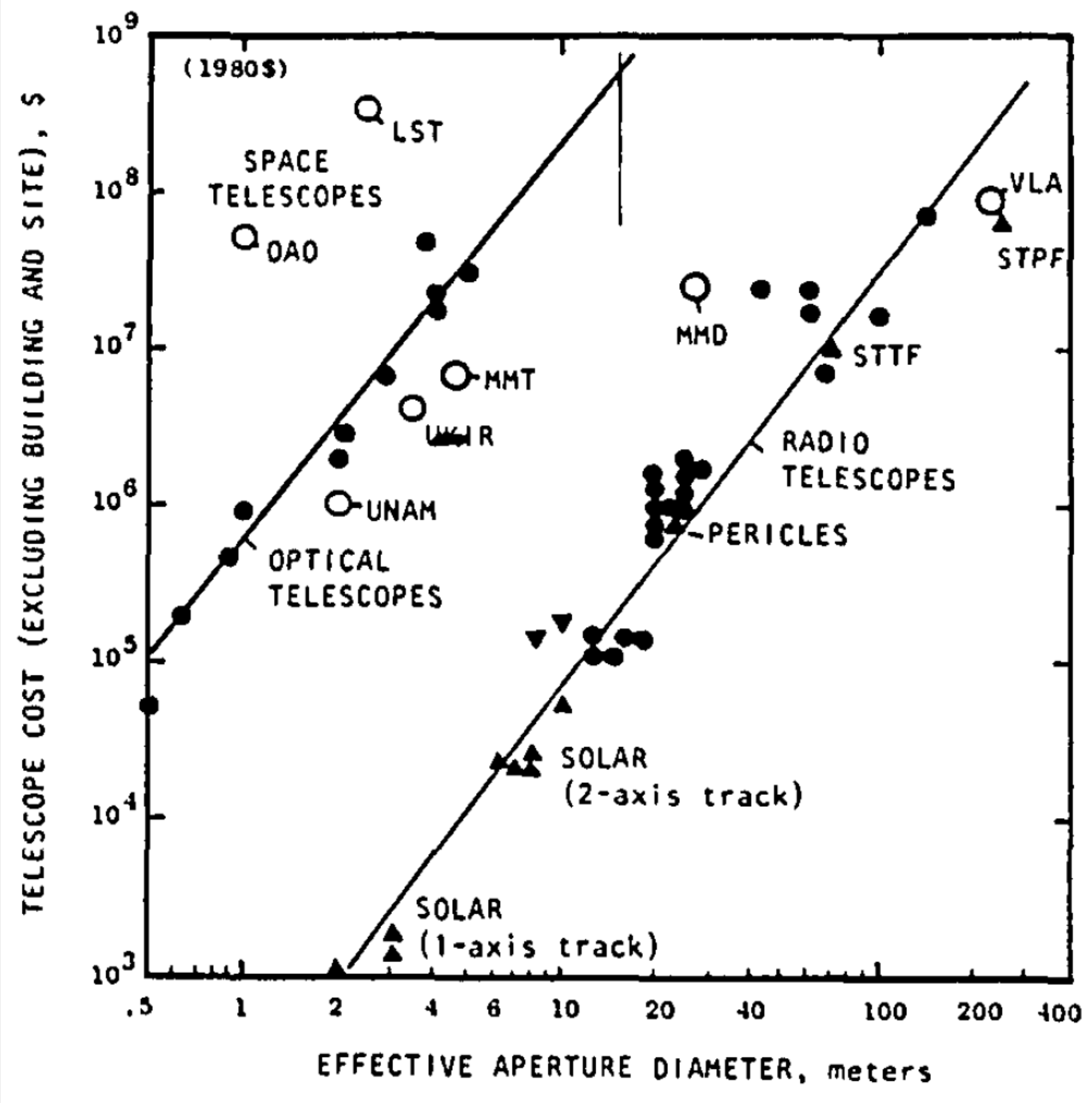
- The best indicator is total mass
- The correlation isn't perfect… But,
  - For a given design (e.g., RC Cassegrain)
  - And a given wavelength regime (e.g., optical)
  - And a given mount/enclosure (e.g., alt/az with dome)
  - Then reasonable cost scalings versus diameter can be obtained



From Meinel 1982

Cost vs. Aperture

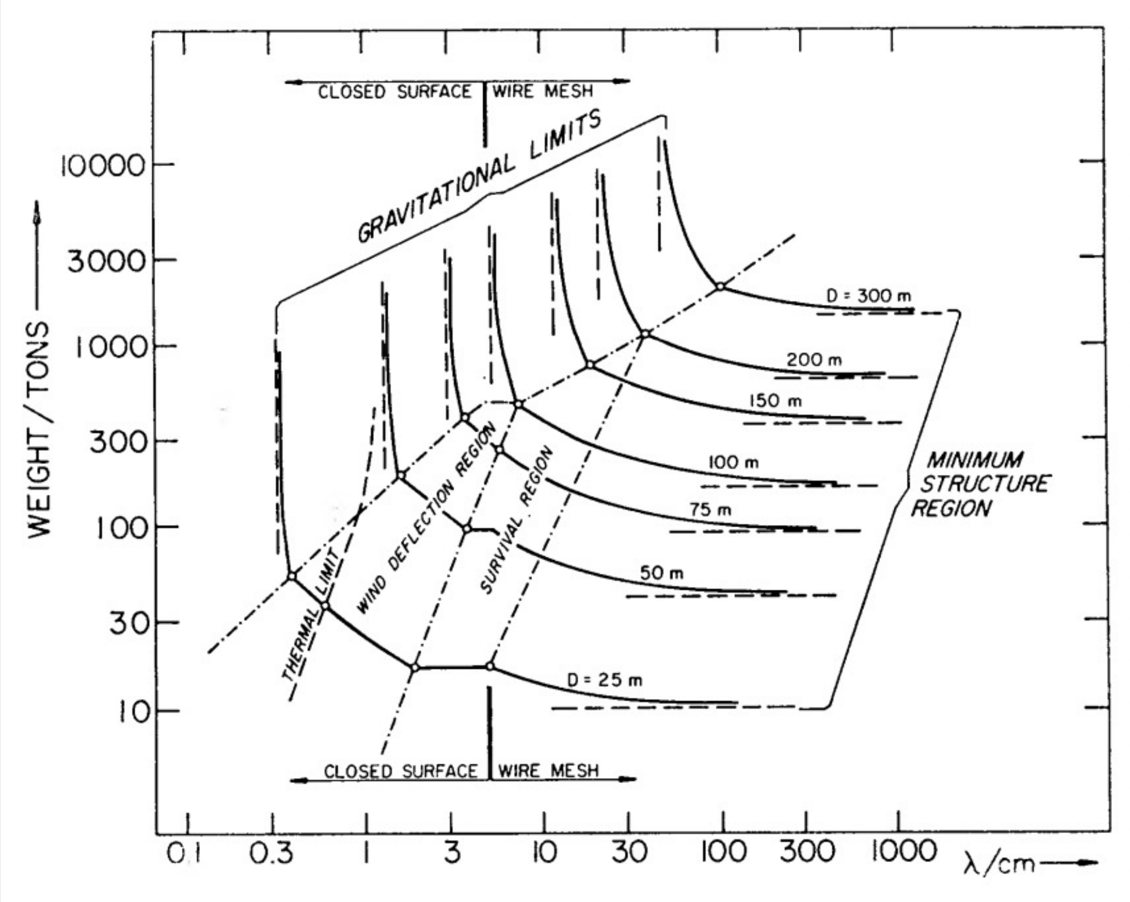
- From a detailed study of the actual costs of various optical and radio telescopes, Meinel 1982 found that
  - Cost ~ Diameter$^{2.6}$
- The normalization of this relation changes significantly based on wavelength, but the trend is similar



From Meinel 1982

What Sets the Overall Cost?

- While Meinel 1982 examined the issue using as-built empirical data, others have taken a first-principles approach (e.g., Van Hoerner 1967)
- There are a range of conditions that can set the required mass (thus cost)
  - The "minimum structure" (i.e., self-supporting)
  - Limited by surface deflections due to wind
  - Limited by surface deflections due to thermal contraction
  - Limited by surface deflections due to gravity
- These various conditions scale total mass between diameter^2 and diameter^3
  - Consistent with the empirical approach



From Van Hoerner 1967

More Sophisticated (Modern) Scalings

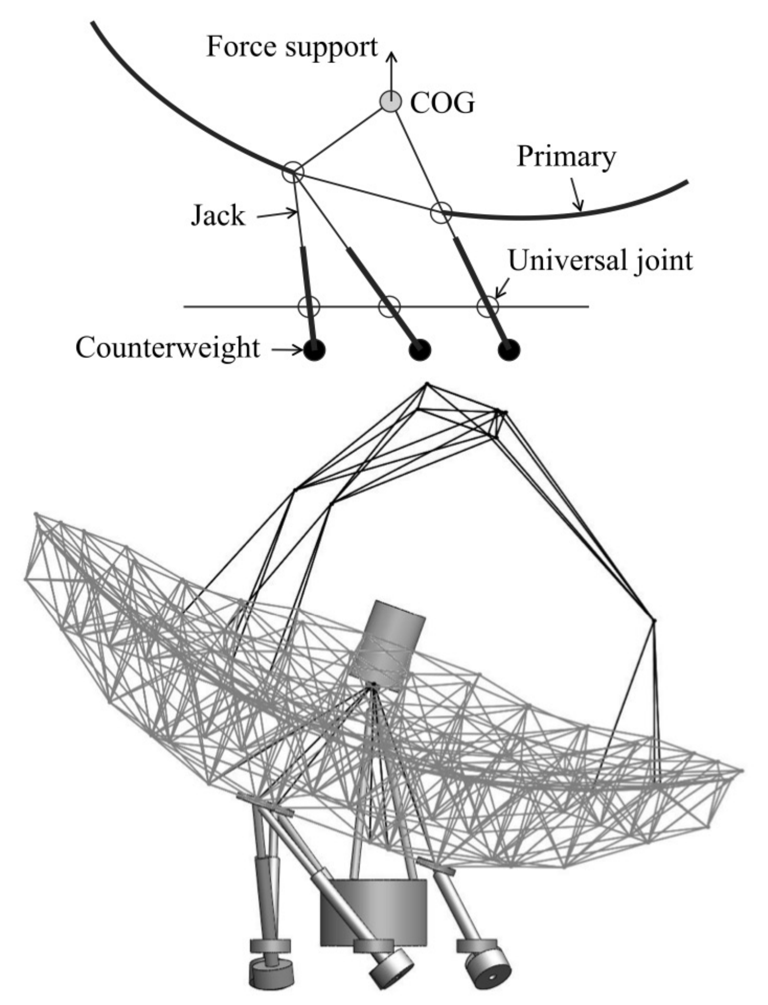
- Stahl and Allison 2020 performed an empirical analysis of a range of telescopes based on actual costs
- With a range of additional terms including: space versus ground, wavelength, operating temperature, and year of construction
- The found a milder scaling of:
  - Cost ~ Diameter$^{1.7}$

$$\mathrm{OTA\$\ (FY17)} = \$20\mathrm{M} \times 30^{(S/G)} \times D^{(1.7)} \times \lambda^{(-0.5)} \times T^{(-0.25)} \times e^{(-0.028)\,(Y-1960)}$$

From Stahl and Allison 2020

Are Lower Cost Telescopes Possible?

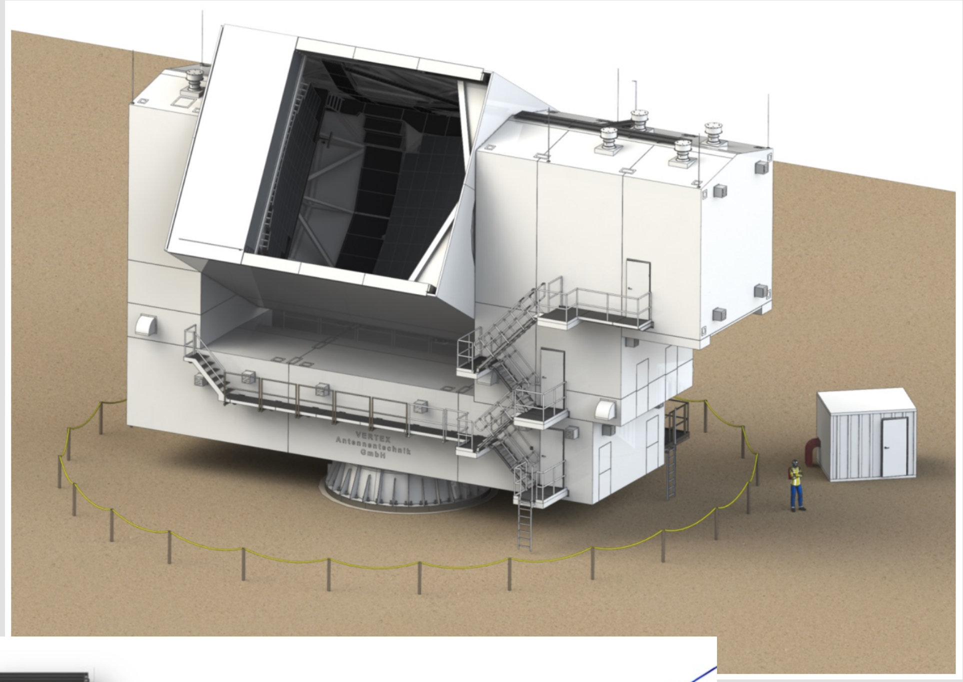
- Yes!
- If the science allows for some kind of compromise, then lower mass (less expensive) designs are possible
- Padin 2014 explored a Cassegrain design with a single-point support
    - x4 reduction in mass (and x2 reduction in cost) compared to traditional alt/az mount
    - Can only access 1 rad of sky (compared to 2π for alt/az)
- Such a design is thus viable for a large-sky survey (using sky rotation from a mid-latitude site), but not viable for a GO facility that needs to access targets at a range of sky positions on a given night

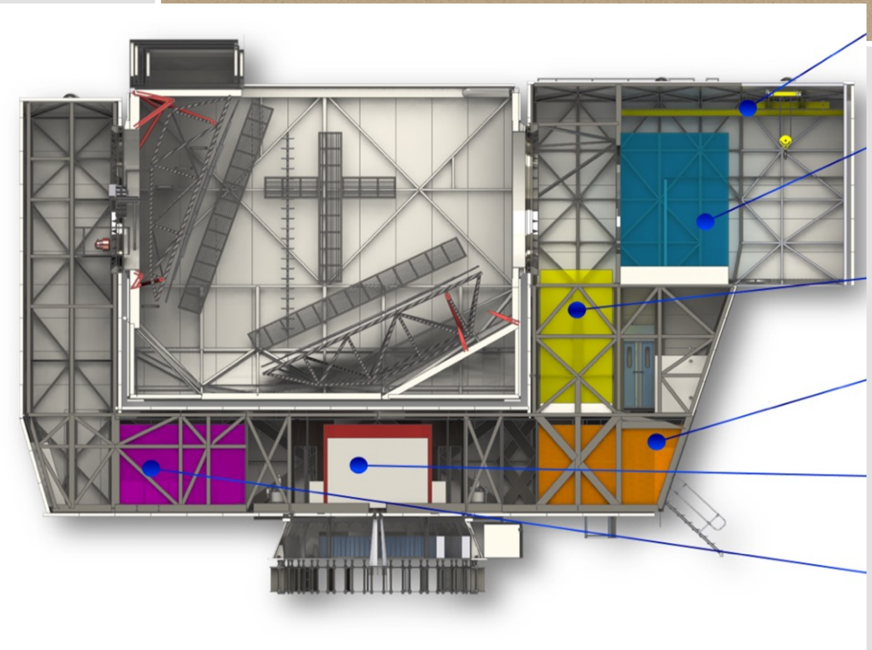


From Padin 2014

Higher Cost Telescopes?

- Yes!
- If the science requires special considerations
- For example, many CMB telescopes require exquisite stray light control, thus motivating off-axis telescope designs
  - As a rough guideline, an off-axis system of a given diameter is twice the cost of an on-axis system
  - Although larger increases in cost are possible (e.g., Fred Young Submm Telescope with extensive baffling, non-conic surfaces, etc.)
- On or off axis, TMA designs are generally much more expensive than two-mirror designs
- Also, even modest enclosures can increase the overall cost by 10s of percent





Summary

- Many telescope designs are possible with a range of performance characteristics and costs
- The most important consideration is *your* science driver
  - Determine which performance characteristics are most important to your particular project
  - If those characteristics fit within your budget, then great!
    - This is generally the case when something other than the telescope is limiting the budget (e.g., the detector arrays are much more expensive)
  - If not, then determine which compromises are most efficient for reducing cost while retaining as much of the science as possible
- It is generally best to go with the simplest concept that satisfies your project's current (and future) needs
  - Don't add additional optics and/or complicated surfaces just because you can
  - Perfection is the enemy of good enough