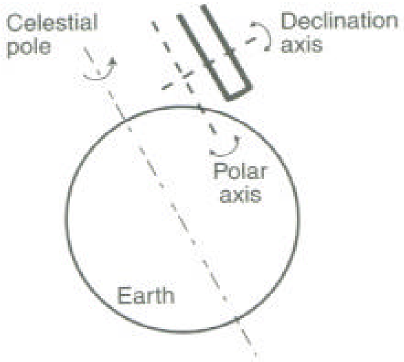
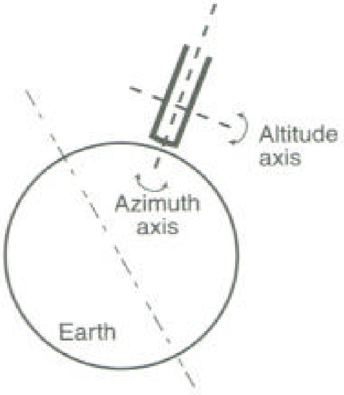
Observational Astronomy

Different mounts of ground-based telescopes

- Purposes of the mount: support telescope tube and allows rotation during pointing and tracking



Equatorial



Altitude-azimuth

Equatorial mounts

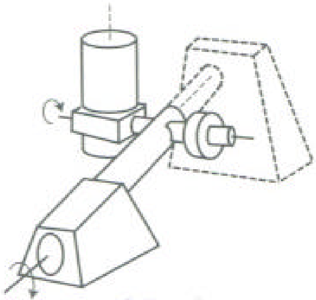
- All optical telescopes built before 1980

- Neutralize the rotation of the Earth by moving the tube around an axis parallel to the Earth axis rotation

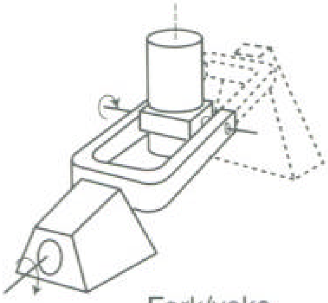
- Once pointed, the tracking is done by rotating the polar axis

- Advantages: simplicity and absence of field rotation

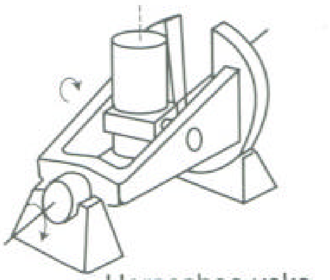
- Disadvantages: telescope varied angle position in gravity field – intrinsically heavy (antilever or beams necessary);



Off-axis



Fork/yoke



Horseshoe yoke

Altitude-Azimuth (alt-az) mounts

- Tube oriented by rotation around vertical axis (azimuth axis) and horizon axis (altitude axis)

- Advantages: neither of two axes changes direction with gravity; sturdier and simpler mounts

- Disadvantages: three axes of rotation are needed: 2 to oriented the tube and 1 to compensate for rotation of the field

- For tracking, each of the 3-axes must be rotated at variable speeds (no problem with fast computers)

- Drives rates:

$$\text{Altitude: } \frac{dh}{dHA} = \sin A \cos j$$

$$\text{Azimuth: } \frac{dA}{dHA} = \sin j - \tan h \cos A \cos j$$

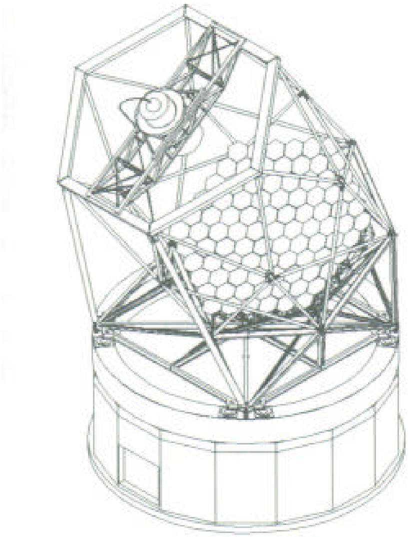
$$\text{Parallactic angle: } \frac{dq}{dHA} = -\frac{\cos j \cos A}{\cos h}$$

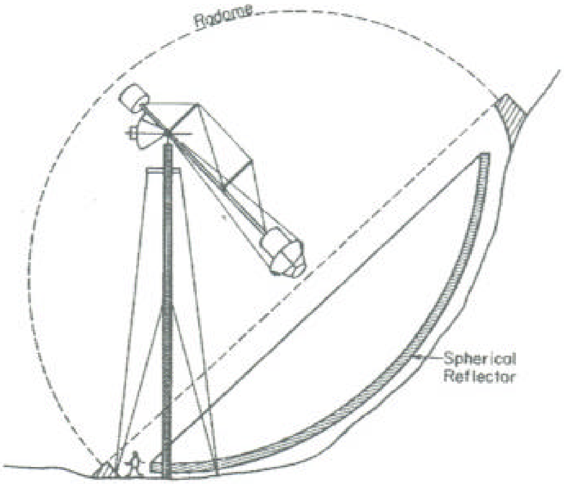
- Parallactic and Azimuth angle drives become infinite at the zenith ($h = 90^\circ$)
  - the maximum allowable velocity depends on inertia of the mount and tube and on torque capabilities of motors
  - for 8-10m drive rates are limited to 2° per second so there is a blind spot at the zenith with semi-angle of 0.5°

Fixed-altitude and fixed-primary-mirror mounts

- For very large telescopes may be advantageous to simplify the mount at the expense of the observational capability

- Ex. fixing primary in altitude with rotating or fixed in azimuth (Hobby-Eberly telescope HET)





- Main advantages:
  - primary does not change direction in gravity field – simplify support structure and control system
  - no need for tube or altitude axis
  - primary is spherical (inevitable because as the secondary sweeps across the primary, it must always face a primary with a vertex on its axis and with the same figure)
  - spherical primary segment are easier to build; less expensive than at-az mount;

- Disadvantages:
  - **a.** Small FOV (few arcminutes), due to correction for aberration;
  - **b.** Reduced sky coverage – function of angle between main optical axis and polar axis (ex. for 35° sky coverage is 73%);
  - **c.** Limited exposure time – 40 min to 2.5h depending on declination;
  - **d.** Numerous reflecting surfaces (2-4 mirrors to correct for aberrations);
  - **e.** Complex instrument feeds (Cassegrain impossible because axis is always moving);
  - **f.** Instruments at prime – limit size and mass of instrument (fiber optics can be used but with loss of throughput and field rotation)

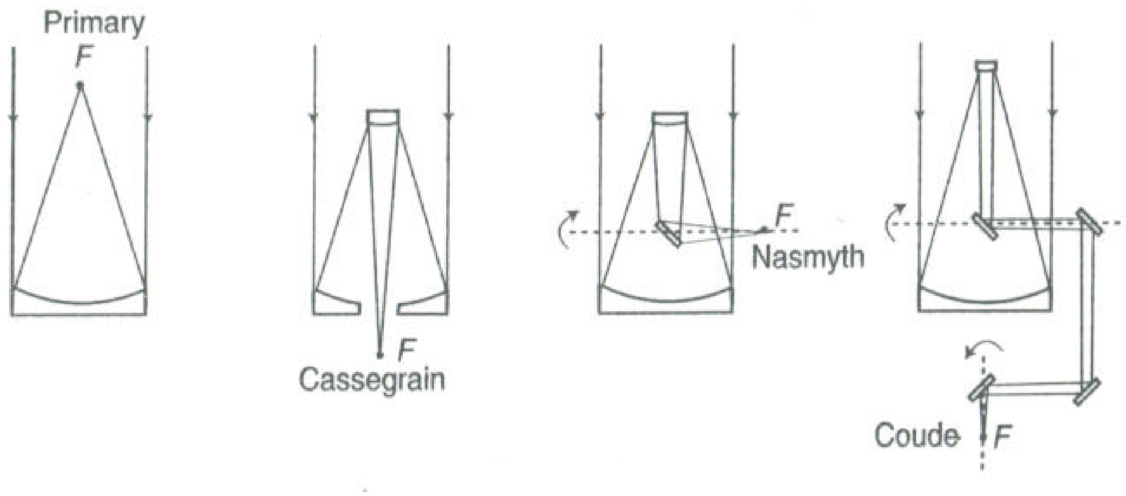
System issues

A) Focus selection

Space telescopes: equipped with only one focus (operational simplicity) Cassegrain focus offers best correction and plate scales

Ground-based telescopes: several foci increase the flexibility choice of f-ratios, instrument mountings interface and sizes, allows instruments to remain mounted on telescope while using another one

Drawback: the larger the number of focus available and the more complex (expensive to build and use) the telescope structure



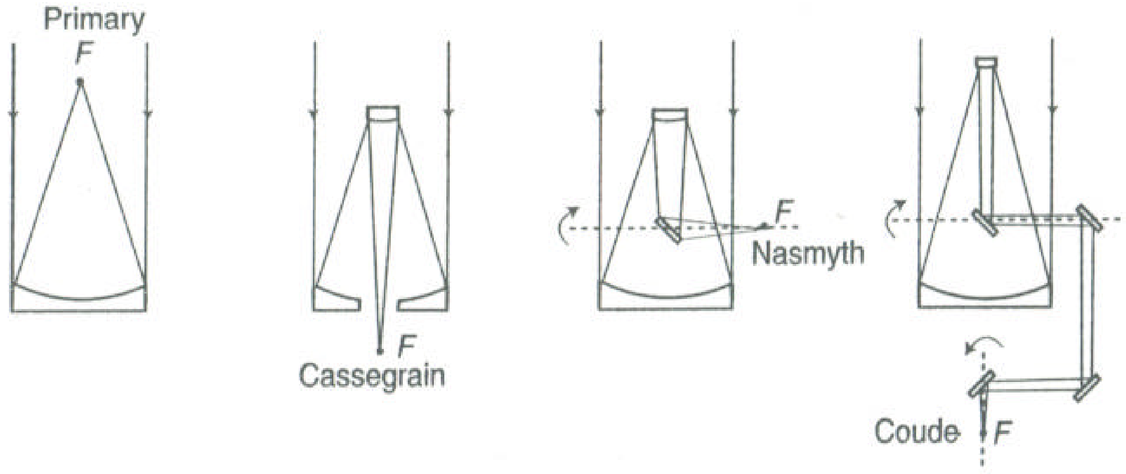
1. **Prime focus**:

    - Minimum number of surfaces (minimize the scatter and thermal emission, while maximizing the reflectivity)

    - Typical f-ratios: f/1.5 to f/3

    - Appropriate plate scale for seeing-limited wide field observations, but too small for many instruments

    - Require corrector and difficult to access

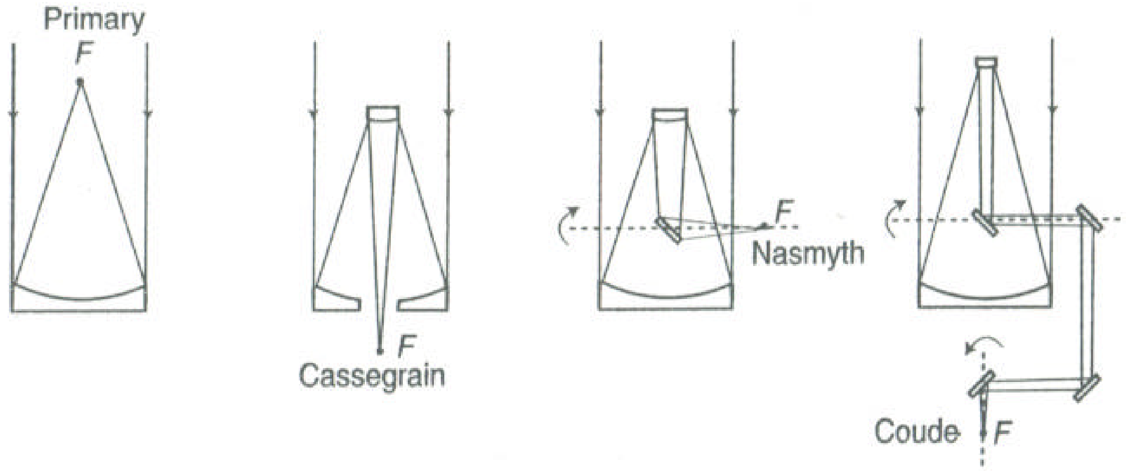


2. **Cassegrain focus**: preferred in majority of observatory

    - Easy accessibility, good field without transmitting elements and small number of surfaces
    - Typical f-ratios: f/8 to f/15
    - Plate scale well adapted for high spatial resolution imaging
    - Can accept fairly bulky instruments

3. **Nasmyth focus**:

    - This is a Cassegrain focus that remains fixed on the rotation (elevation) axis of the tube tanks (with 45° field mirror)
    - Same advantage as a Cassegrain, but with even more flexibility
    - Instruments remain fixed with respect to gravity field provided that an optical field rotator is used (if not the instrument must rotate around the axis to follow the field)
    - The telescope tube does not need rebalancing when changing the instrument
    - Various instruments can be attached and used with minimum changing efforts

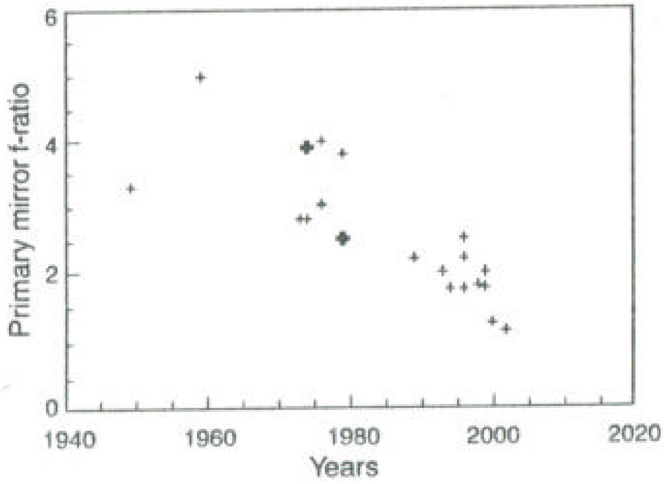


4. **Coudé focus**:

- Long focal length Cassegrain focus remains fixed in space with folded mirrors located on the tube and mount rotation axis
- Typical f-ratio: f/30 to f/100 to reduce beam size, since it has to be piped over relatively long distance
- FOV is quite small (~ arcsecond)
- Accept very bulky instruments, like very high resolution spectrographs
- Field rotates – which is not a problem for stars or extended object taken as a whole (or used with optical derotator)
- Large plate scale – well adapted for high spectral resolution spectroscopy (too large for imaging)
- Large number of mirrors (5-7) ⇨ throughput is low (means need to observe only bright objects)
- Non normal incidence of light, introduces phase changes complicate polarization measurements (alternative is to use fiber-optics)

B) f-ratio selection

- The choice of f-ratio affect the entire observatory system: optical train, telescope structure, control system, instruments, dome and building
- Since the cost of the observatory increase with the length of the tube, primary as fast as possible are cheaper
- Over the last 30 years, due to new techniques, producing fast primary mirrors is not a problem anymore



- The limits on fast primary mirrors is driven by the tolerance on the position of the secondary mirror misalignment is a strong function (varies as the cube) of f-ratio this is tempered by two facts:
    a. For given final f-ratio, the mass and size of secondary is smaller
    b. Fast telescopes are shorter, gaining in stiffness and reduction of wind-buffeting torques

- Selection of final Cassegrain or Nasmyth f-ratio involves important trade-offs: because the f-ratio must matches the focal plate scale of the instrument (which also depends if the telescope is seeing or diffraction-limited), a final slower f-ratio will:

  1. Decrease the size of the secondary
  2. Lengthen the tube slightly
  3. Increase the size of the instrument entrance optics
  4. Increase the focal length of the spectrograph collimator (bulkier and heavier)
  5. Increase the size of the beam steering mirrors for image-motion compensation

C) Matching the plate scale to the detector resolution

- To optimize the sensitivity or spectral resolution the focal plane plate scale must be adapted to the detectors spatial and size characteristics

- Problem: for a given pixel size of detector what is the optimal plate scale, or, that is, the optimal f-ratio? Answer it depends on class of observation

- General case: ***to maximize the sensitivity without losing the spatial information in the object*** sampling too finely, for example, would increase the noise and accumulate redundant data generally at the expense of the field ⇨ Optimized or critical sampling (**Nyquist's sampling**)

Nyquist's theorem (law that is the basis for sampling continuous information): *The frequency of data sampling should be at least twice the maximum frequency at which the information might vary. This condition preserves patterns in the information or data, without introducing artificial, lower-frequency patterns (aliasing)*

- Rule: virtually all the information can be recovered by sampling the image with an angular pixel size on the sky equal to half of the resolution element of the optics as defined by the Sparrow's criterion (l/D)

- Since the angular pixel size on the sky is p/f, where p is the linear pixel size and f is the final focal length $\Rightarrow$ the plate scale matching the condition of critical sampling of diffraction limited image: $\frac{2p}{f} = \frac{l}{D}$

- $\Rightarrow$ The optimal f-ratio is independent of D: $\left(\frac{f}{D}\right)_{opt} = \frac{2p}{l}$

Table 4.5. Typical f-ratios for critically sampled detectors

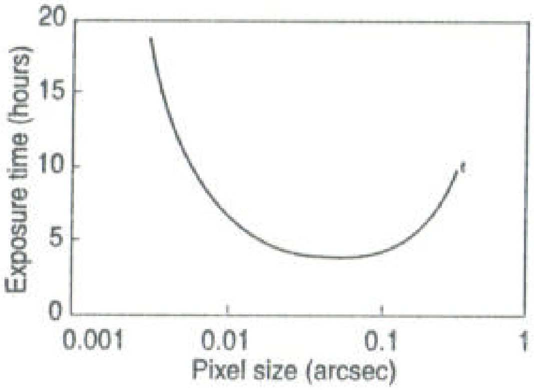
Wavelength (μm)	0.5	2	2	10
Pixel size (μm)	7	18	28	28
Optimal f-ratio	28	18	28	5.6

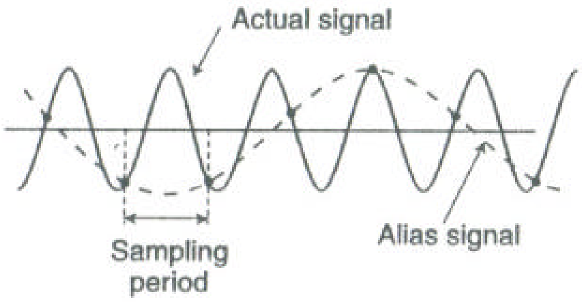
- In case of high spatial resolution imaging of bright objects the detector noise is not a problem and one gains by **oversampling** the image, at the expense of the field

- When sensitivity is primordial, the optimal plate scale minimized the exposure time for a desired S/N (depends on solid angle of the source, the detector dark current and the readout noise) ⇨ **undersampling** two problems related to this:

    - ⇨loss of spatial resolution mitigate by doing **dithering**: taking several exposures of the field with line of sight stepped by fraction of pixel Sub-exposure are re-centered and added recovering most of the spatial resolution

    - ⇨ **Aliasing**: occurs when sampling is less than Nyquist limit
        - Detector cannot distinguish between several possible spatial frequencies
        - Increase the noise in signal at low spatial frequencies





Historical note: The optimal f-ratio for photographic plates was not based on grain size, but on photographic speed

The problem was poor sensitivity, which was suggesting prohibitively long exposure time

Principal for choice of optimal f-ratio: exposed sky background to optimal density within a reasonable time (4-6 hours)

In the early 1900, this was implying f/4 or f/5

During the 60-70’s faster photographic plates were developed and the standard for f-ratio becomes for Cassegrain telescope f/8 to f/10

Mirror types

Substrates

Conditions that mirror substrates must satisfy:

- Dimensionally stable retain their figure over decades
- Low internal stress retain forms during figuring process or over time due to stress relaxation
- Insensitive to temperature changes
- Possible to cast them in large size
- Sufficient mechanical rigidity and strength for handling and mounting
- Fine surface polish must be coatable
- Cryogenic: keep their structural shape when cooled

With current technologies, the choices come down to very few material (Table 4.6)
Glass-like material have better polish compared to metal, with micro roughness of 5-12 Å rms (compared to 10-20 Å rms for metal)

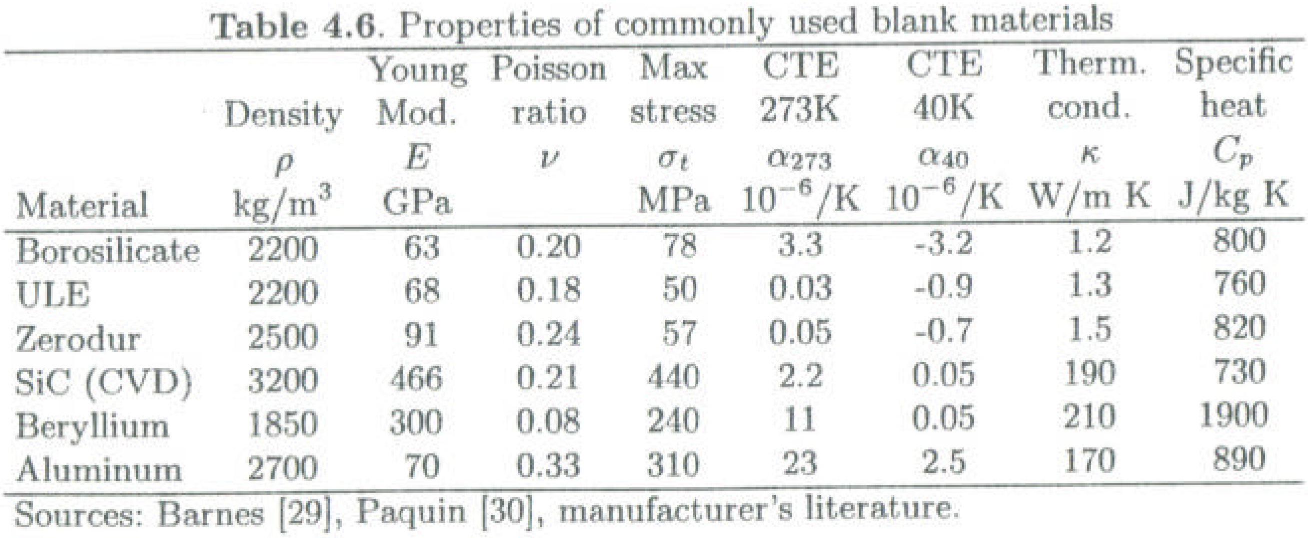


Table 4.6. Properties of commonly used blank materials

Material	Density ρ kg/m^3	Young Mod. E GPa	Poisson ratio ν	Max stress σ_t MPa	CTE 273K α_{273} 10^{-6}/K	CTE 40K α_{40} 10^{-6}/K	Therm. cond. κ W/m K	Specific heat C_p J/kg K
Borosilicate	2200	63	0.20	78	3.3	-3.2	1.2	800
ULE	2200	68	0.18	50	0.03	-0.9	1.3	760
Zerodur	2500	91	0.24	57	0.05	-0.7	1.5	820
SiC (CVD)	3200	466	0.21	440	2.2	0.05	190	730
Beryllium	1850	300	0.08	240	11	0.05	210	1900
Aluminum	2700	70	0.33	310	23	2.5	170	890

Sources: Barnes [29], Paquin [30], manufacturer's literature.

Physical characteristics

1. **Stiffness:** $\frac{E}{r}$ where E is the Young modulus, r the material density
   - For grounded telescope, mirror must minimized mass

   - For space telescope, resist vibrations (acoustic loading at launch and in space) ⇨ have highest possible natural frequency higher the stiffness ⇨ less deformation ⇨ higher frequency

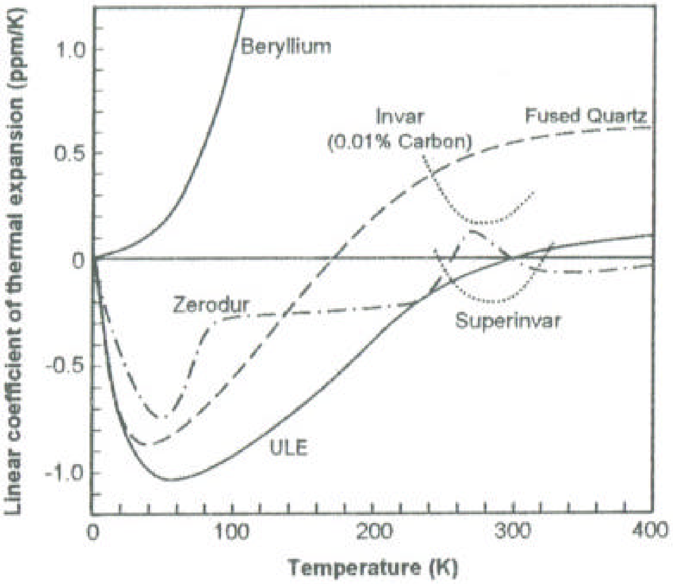
2. **Thermal behavior:** in general the mirrors must show the lowest sensitivity to thermal variations
   - For grounded telescope: early at night – mirror try to reach equilibrium with air temperature throughout the night – temperature drops

   - For space telescope: periodic eclipse of the Sun by Earth or changes in orientation respect to the Sun during repointing

   - Bulk of temperature changes (homogeneous and isotropic material) affect the focal length but not the figure

   - Gradient between front and back of mirror or across diameter affect both focal length and figure

   - To minimize thermal effects, a the **Coefficient of Thermal Expansion** (**CTE**) must be as small as possible

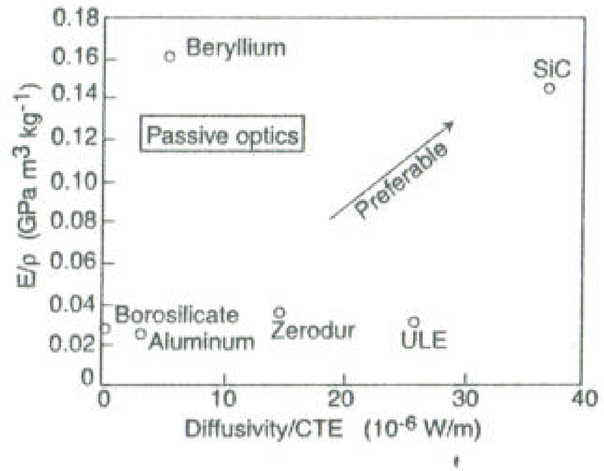


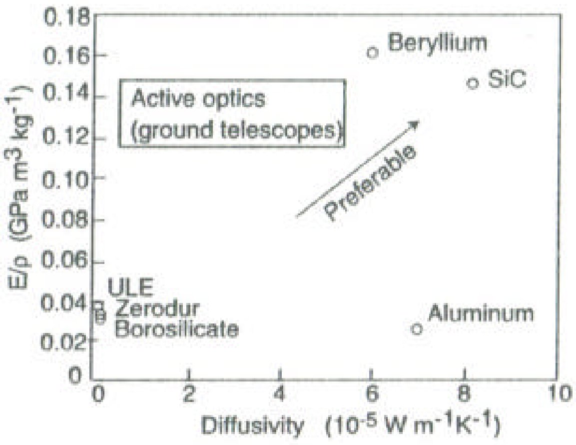
- Alternatively, low gradients must be achieved $\Rightarrow$ **thermal diffusivity** (determine how quickly material comes at temperature equilibrium) *must be as high as possible* important to elude mirror seeing

  i. **Passive optics**: thermal diffusivity $=\frac{k}{a C_p r}$ where k is the thermal conductivity, C_p is the specific heat

  ii. With **active optics** (ground only) requirement is less stringent, because thermal effects are slow and well within bandpasses of active optics systems thermal diffusivity $=\frac{k}{C_p r}$

- Advantage of thermal diffusivity is enhanced by equipping the mirror with a thermal control system to keep the mirror bulk temperature close to the actual night temperature





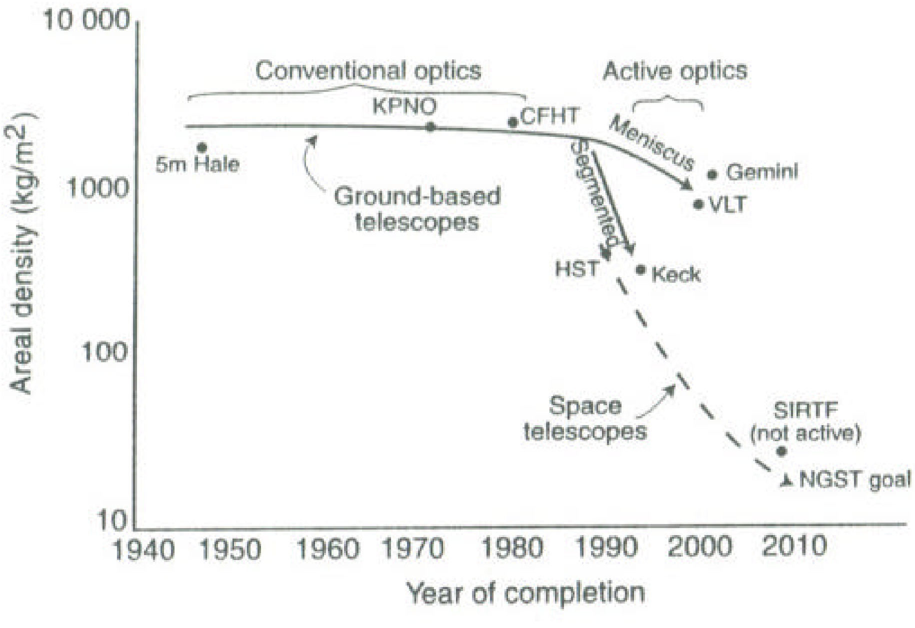
Mirror structural design

- Once installed in the telescope the mirrors must keep their form up to a fraction of the optical tolerance when subjected to gravity + wind loading or spacecraft disturbance

- Mirror must also be strong enough for safe handling during manufacture and assembling (or launch loads in case of space telescope)

- **Rigidity** $\propto \frac{h^3}{D^2}$ where h is the thickness
- **Deflection under self weight** $\propto \frac{D^4}{h^2}$
- **Natural frequency** $\propto \frac{h}{D^2}$
- Ground-based telescope can be floated in a compensation system to eliminate the gravity effects (passive system) ⇨ mirror must have high rigidity

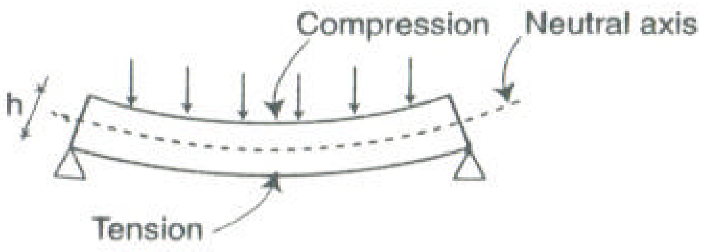
- For large mirror, mass as to be decreased without changing rigidity ⇨ **Lightweighting:** removing mass from inside the mirror

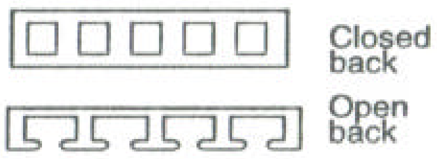


Lightweight mirror

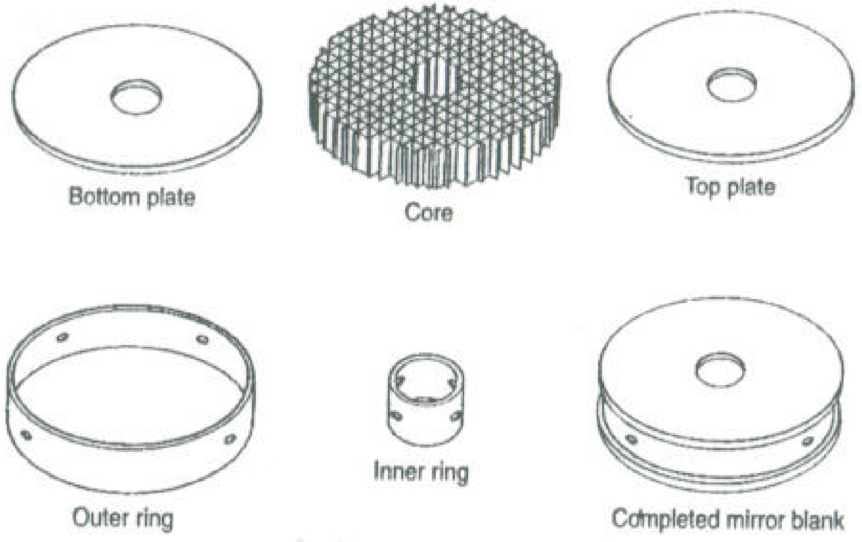
Basic idea: reduce mass without affecting rigidity

In a beam supported at the two extremities, the upper surface is in compression, while the lower surface is in tension. In the middle (neutral axis) the normal stress falls to zero. Other than carrying shear loads, material near the neutral axis contributes little to bending stiffness ⇨ most of it can be removed – smaller mass implies lower deflection under self weight (principle of I beam)





Honeycomb structures: material is emptied during casting of mirror (closed back) or by drilling the back (open back) alternative is to build the structure from plate elements and fuse them together (HST)



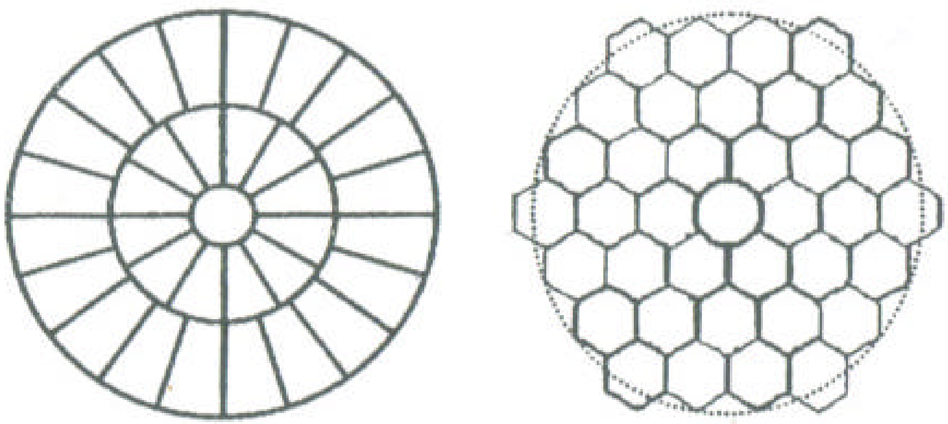
The limits on lightweighting mirrors are set by manufacturing and handling constraints optimizing rib height (limited by shear), rib thickness (danger of breakthrough if to thin ~1 mm) and face plate thickness (too thin will deflect under weight of figuring tools then bounce back once tools are removed (**print-through** or **quilting**)

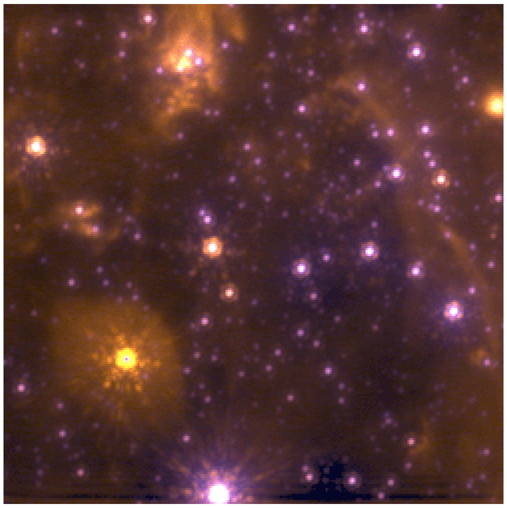
Segmented mirrors

- The size of monolithic mirrors for ground telescopes is limited in practice to 8 meters due to current capacity of furnaces, size of polishing machines and transport techniques
- Although larger mirrors are not impossible, the cost of required facilities is a breakeven point for segmented systems
- In space currently available launch vehicles have fairing diameters limited to 4m

- 1930: Horn d'Arturo (1m composed of 61 hexagonal)
- 1970: military space applications: LAMP, A LOT, Pamela similar technology 2 Keck and Hobby-Eberly 11m telescope

- Disadvantages: no surface continuity 1) segments must be figured so that they are all part of the same overall parent shape 2) once installed at the telescope, the segments must be positioned exactly and maintained in their exact position against gravity, thermal effects and wind disturbance
- Fabrication of off-axis optics is challenging and expensive (2-meter segments are now possible at reasonable low costs)





Example of image taken with Keck with adaptive optics system

One can see the diffraction pattern introduced by the hexagonal form of the aperture

This image is much lower in quality than what can be achieved with a monolithic mirror like Gemini or Subaru (below)

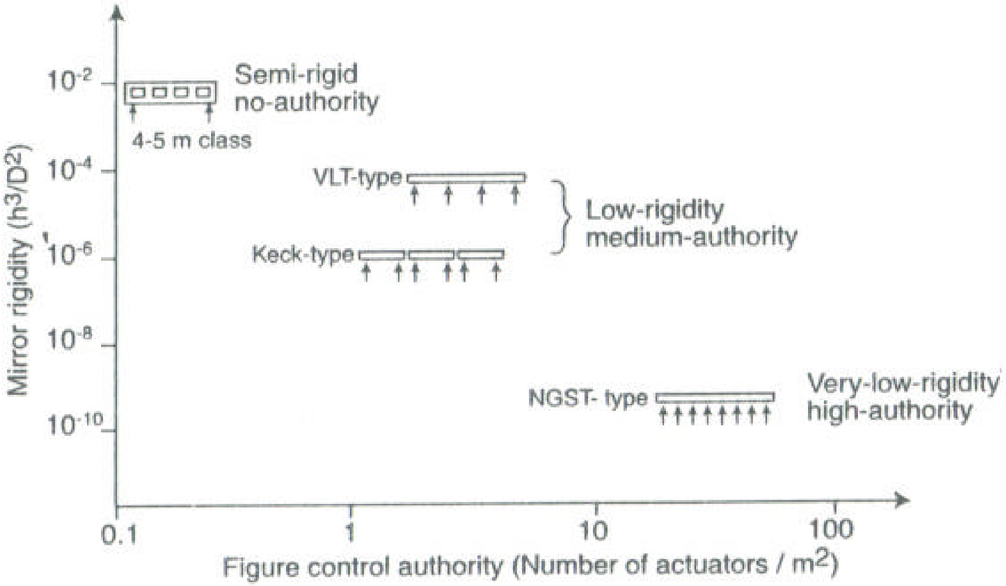
Active optics

Replace the gravity compensation system support points by actuators which are commanded to maintain mirror figure at all time

Mirror blank structures:

Rigid	Maintain shapes under gravity or external disturbance without support	**No authority**
Semi rigid	Maintain shapes with gravity compensation systems	**Low authority**
Low rigidity	Need backup supports	**Medium authority**
Very low rigidity	Need backup supports	**High authority**

- Advantage of low rigidity: figure can be corrected level of authority describe how much shaping (reconfiguring) is possible



- Rigid telescopes: HST D = 2.4m, h = 0.3m SIRTF (Spitzer) D = 0.9m

- Semi rigid no authority type: Solid 4m (Tololo – Blanco) and 5m (Palomar – Hale)

- Semi rigid medium authority: D = 8.0m, VLT, Gemini, Subaru (meniscus) LBT (honeycomb)

- Low rigidity medium authority: D =10m, Keck

- Very low rigidity: NGST (James Webb telescope)
- On ground, no authority type are limited to 4-5m larger telescopes require medium authority supports

- Other advantages of lightweight mirrors: resist wind loading better short thermal time constant

- Disadvantages: risk of print through challenging thermal control

Mirror coatings

- Best coatings: good reflectance in visible and infrared: **aluminum**, **silver**, **gold**

- General purpose: **aluminum** - best for ground based telescope good reflectance from UV to IR easy to be deposited and removed ideal coat ~ 100 µm (- less mirror is transparent - more non-uniform) variation of thickness ~ 5%

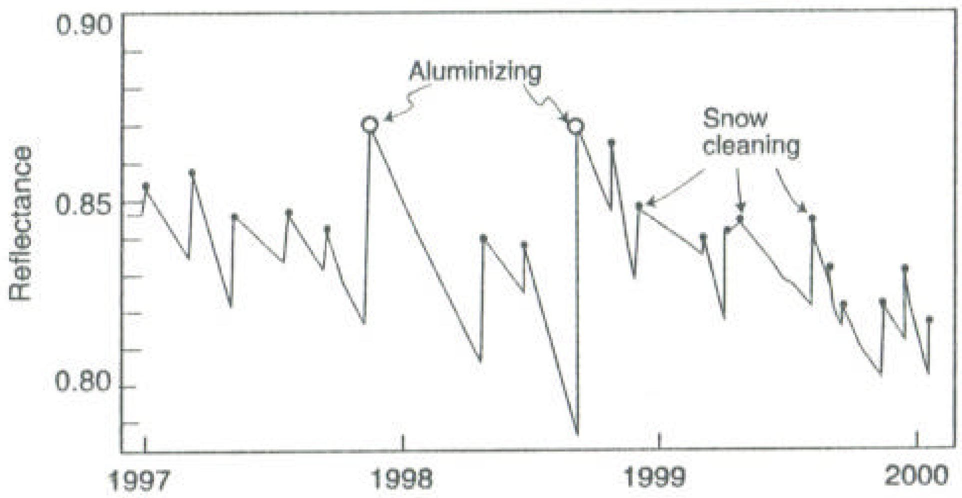
- **Silver** – reflectance higher for $l > 4000$ Å, but must be protected against oxidation, loss of reflectance at some l due to destructive interference in overcoat and need special coating tools

- **Gold** – perfect for IR (secondary) disadvantages: soft, easily damaged and need special cleaning techniques

- Mirror coatings degrade over time due to dust + pollen + molecular contaminant (oil + water drops) on ground telescope reflectance can decrease by as much as 0.5% per month, with increase in scatter and infrared emissivity

Coating plants

- Space telescopes are coated only once – orbit degradation is negligible
- Ground based telescope – coating degrades after a few years and must be redone frequently



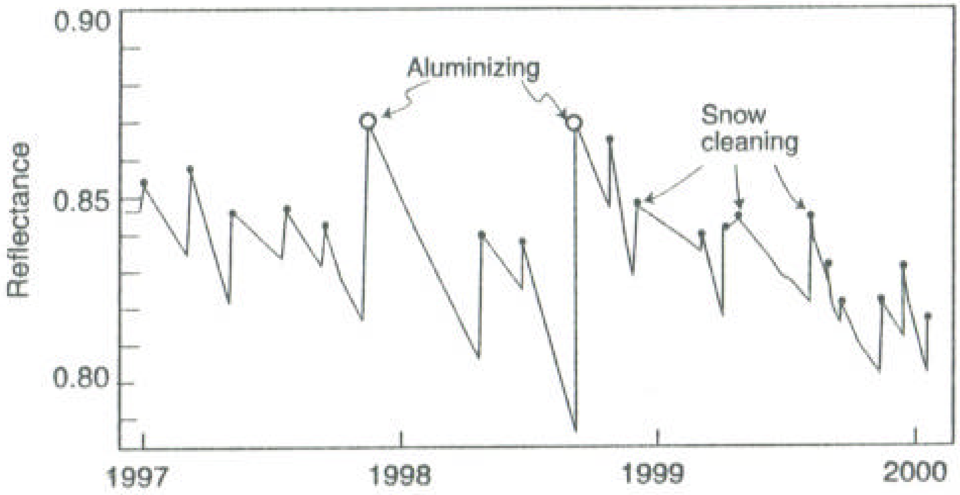
- Because of time, cost and danger of transport coating usually done in-situ
- All coating are applied in vacuum tank with vacuum of the order 10^{-6} torr (1 torr = 1mm of mercury = 133 Pa)

- 3 methods are used:

1. **Thermal evaporation**: heating coating metal (aluminum) to sublimation a short distance from mirror surface – molecules condensed on mirror surface advantages: simple and good coating uniformity disadvantage: to avoid molten drops mirror place vertically or face down
2. **Electron beam method**: coating metal is evaporated using a beam of electrons to heat it advantages: greater control of evaporated metal
3. **Ion sputtering**: bombarding coating with a ion beam of inert gas – some of the particle of the coating metal detached and accumulated on surface advantages: a) mirror placed face-up, b) small vacuum tanks c) better adherence d) allows multicoat

Cleaning techniques

- **Washing** (distilled water + mild detergent – removes dust + molecular contaminant)
- **Plastic film peeling** – brushing mirror surface with polymer liquid which dry to rubbery film the film is peeled away – remove dirt + deposit at molecular level
- **Blowing gas** – jet of filtered air or nitrogen – only particle longer than 20μm (larger particle need higher velocity jet – dangerous to damage surface)
- **CO2 snow cleaning** – sprayed across surface with fire extinguishable like apparatus – liquid CO2 released through fine nozzle become a mixture of gaseous CO2 + dry ice 1) snowflakes collide with dust and force them away 2) dust particles freeze contract and break away from surface efficient and safe (done once per month)



Background control

Stray light (sidelobes) control

- **Stray light** is any light (visible or infrared) that does not come from the celestial source of interest and yet illuminates the detector ⇨ background that lowered the sensitivity acceptable level must be lower than other natural background sources that cannot be controlled (on the ground = sky space = zodiacal light)

- **Two origins:**

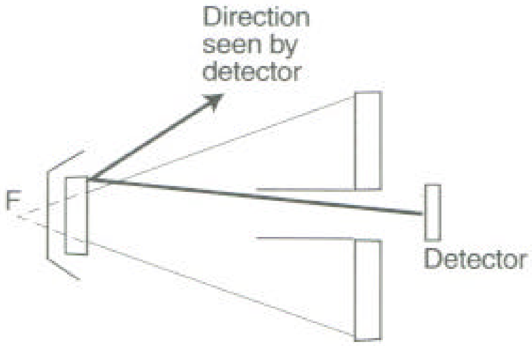
1. Celestial sources out of the FOV (off-axis sources) – light scattered or diffracted from various observatory surfaces
    - Curtailed by installing baffles and stops to prevent direct illumination

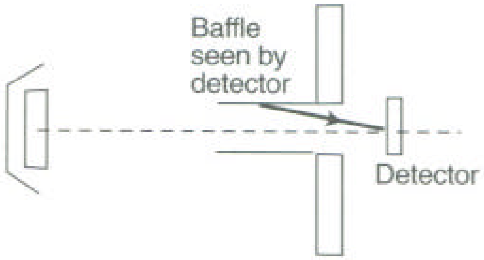
2. Thermal emission of telescope and surrounding surfaces – directly or scattered
    - Cooling surfaces seen by detector or minimizing the view of surface that cannot be cooled

Baffles and stops

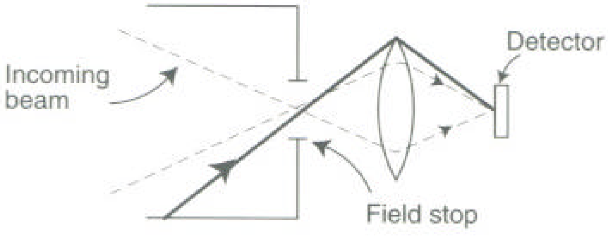
- Mechanical walls and aperture that block the propagation of unwanted light from a source to a detector ➔ must be properly placed and sized

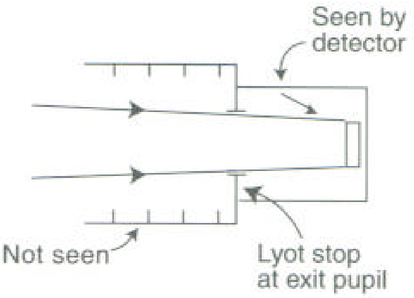
- **Aperture stops (entrance pupil):** limits the size of the incoming beam that converge to the focal plane ⇨ objects in the space preceding the aperture stop outside of the desired beam are not seen by the detector objects downstream may be seen (secondary mirror oversized for image – inside of lower baffle) aperture stop = periphery of primary mirror in chopping infrared systems = secondary mirror





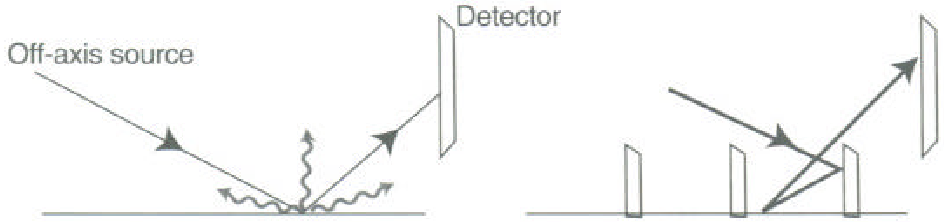
- **Field stop:** prevent off-axis sources at infinity from reaching the detector do not block closer sources placed at the first unused focus to block diffracted light produced by the front light-baffle slightly oversized field stop prevent light diffracted at the stop itself to reach the detector



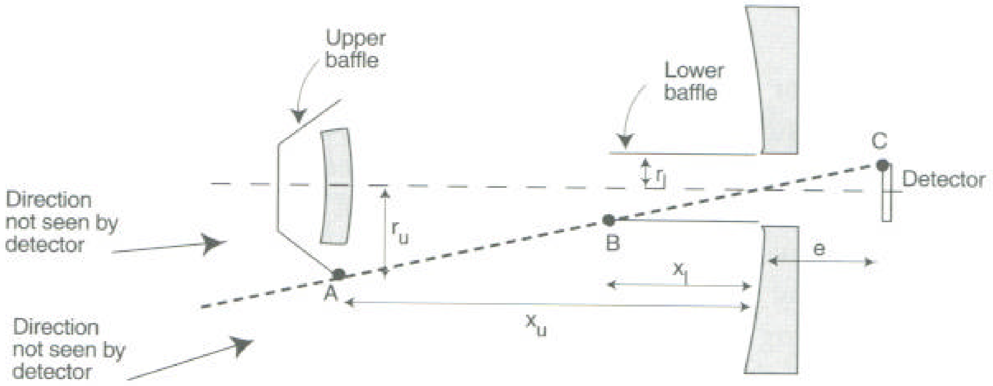


- **Lyot stop:** limit the beam at the exit pupil prevents the detector from seeing any surface preceding the stop other than the optics itself critical for IR instruments – cooling the stop and relatively small environment immediately around the detector minimizes thermal emission In demanding high contrast observations, Lyot stop is placed at intermediate pupil, to stop the light diffracted by the edge of the entrance pupil (coronograph)

- **Baffles:** conical or cylindrical object designed to block unwanted radiation paths baffle sides facing the region of unwanted stray light are provided with vanes, a series of concentric rings suppressing scattering (with variable geometry optimized for every design)



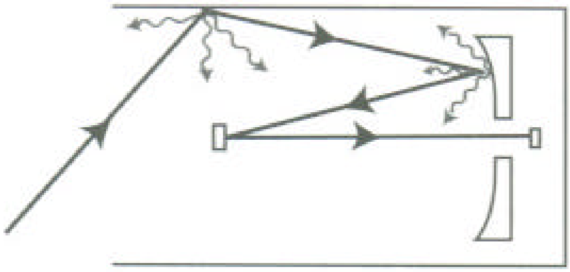
- **Baffles of Cassegrain system:** two sets of baffles, one around the secondary mirror the other above the primary, sized to align the edges (A and B) with the field stop at the focal plane (C):

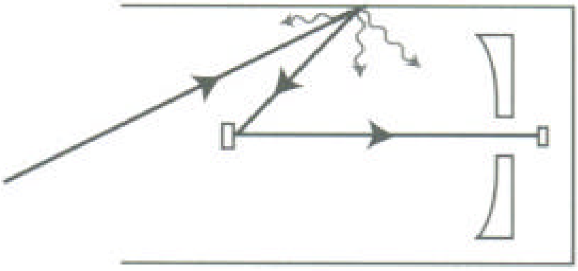


Scattering processes

- Light from off-axis sources can be scattered from the optical and surrounding surfaces, such a inside of baffles, and reach the detectors via single or multiple bounce

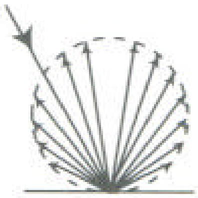
- Dominant sources: dust on optical elements (micro-roughness is usually very small (except in UV) ⇨ purely specular part is low)





- If an incident beam falls upon an ideal flat surface, the reflected beam is concentrated in specular fashion for a perfect diffuse reflector, light is scattered uniformly, the power of the scattered beam varying as the cosine of the angle when irradiance is independent of angle ⇨ surface is **Lambertian** real surfaces falls between these two extremes surface scattering is described by the **Bidirectional Reflectance Distribution Function** (**BRDF**)

Specular reflection



Lambertian scattering

Diffusely reflecting surface

- At IR scatter from dust particles or particulates is the dominant source of stray light – particulates are of random sizes and scatter has to be measured directly it is very difficult to maintain a dust coverage lower than a few percent in large optics

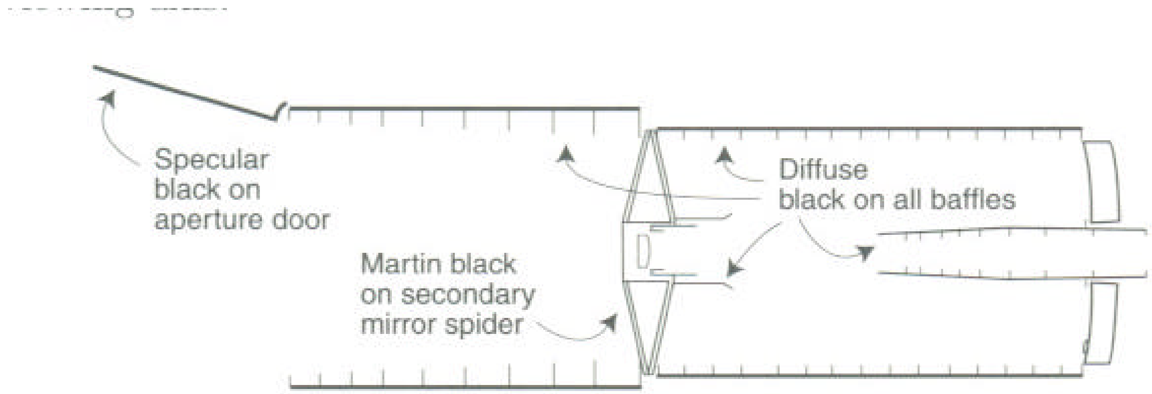
- In the UV mirror scatter is dominated by micro-roughness

- Baffles and surfaces in telescopes have a diffuse black coating to absorb most of the incident light black surfaces should be positioned so as to be illuminated at or near normal incidence ⇨ placing vanes on the surface

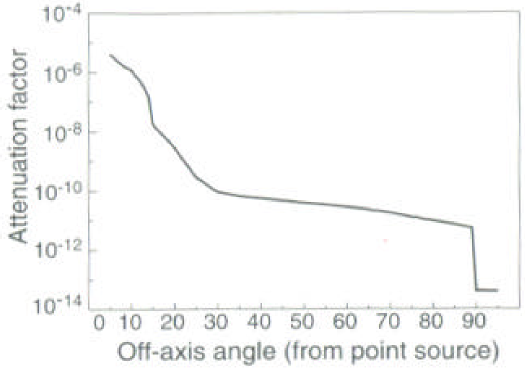
Example – the HST protection

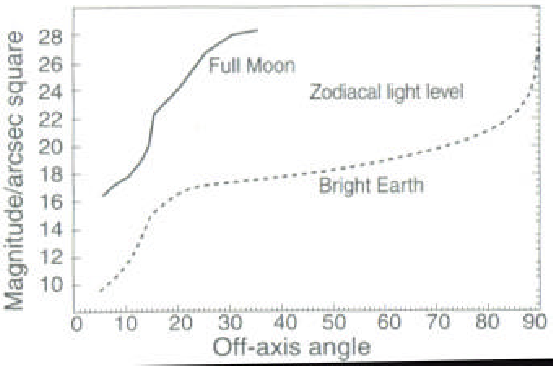
- Stray light environment particularly severe because of the Sun and Moon while flying only about 500km above bright Earth surface baffled in unusual manner – upper baffle around secondary and lower one around Cassegrain return beam – prevents any off-axis light stray light from hitting the focal plane directly inner sides of the tube and lower baffle have vanes to prevent direct bounces and all surfaces are coated black to reduce scatter

- In addition the telescope is preceded by an extensive light shield 4m in length coated black and provides with vanes The aperture door always kept on the Sun side is dimensioned such that the Sun cannot shine on the light shield entrance (as long as it is more than 50° away form the viewing axis



- **Attenuation factor:** described the effectiveness of the baffling system and stray light suppression - defined as the ratio of the flux density reaching the focal plane to the flux density impinging on the telescope aperture – the flux Φ impinging on the focal plane due to stray light from off-axis point source over a unit area of detector (one pixel) per given pass band Δl : $\Phi = EA(a) f_e^2 dw$ where E is the incoming flux density per Δl , A is the attenuation factor, a the angle of the source with respect to the axis of the telescope, f_e the effective focal length, dw the solid angle subtended by one pixel on the sky


10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
Attenuation factor
0 10 20 30 40 50 60 70 80 90
Off-axis angle (from point source)


28
26
24
22
20
18
16
14
12
10
Magnitude/arcsec square
Full Moon
Zodiacal light level
Bright Earth
0 10 20 30 40 50 60 70 80 90
Off-axis angle

Thermal Control

Thermal issue affects various aspects of observations:

- Temperature variations in optics or supporting structures ⇨ mirror figure and alignment

- Temperature difference between telescope or enclosure and ambient air ⇨degrades image quality (dome and mirror seeing)

- Thermal emission from optics and environment ⇨ thermal background in the IR

Thermal control:
Describes the ways of reducing residual thermal effects to an acceptable level

General purposes:
Control the temperature of critical systems - to keep them within their design temperature - to maximize the performance

- Maintain temperature of optics and supporting structures within design operational range

- Minimize seeing – temperature of systems near light path (particularly the primary) close to ambient air temperature

- Minimize instrumental background

Passive measures: coatings, insulation, radiators to control external heat or dump waste heat

Active measures: heaters, ventilation and coolants

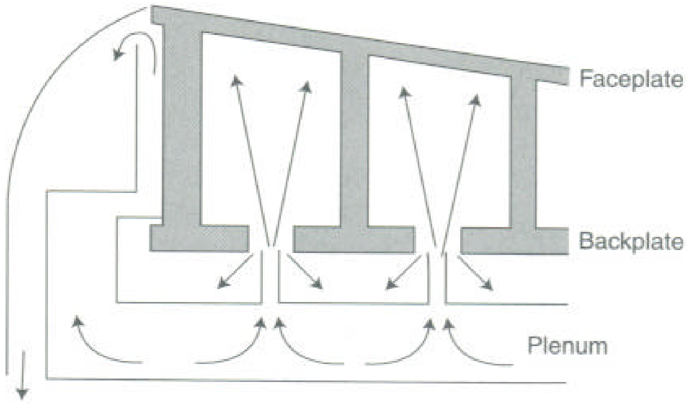
Mirror figure control:

- With ultra-low-expansion materials (ULE or Zerodur), thermally induced deformation of mirrors has essentially disappeared

- Not the case of borosilicate (LBT – 2 honeycomb 8-meter mirrors)

- Advantage of lightweighted mirrors = reduce seeing by lowering thermal inertia

- Temperature gradients can also be eliminated by ventilating the honeycomb cells with temperature-controlled air

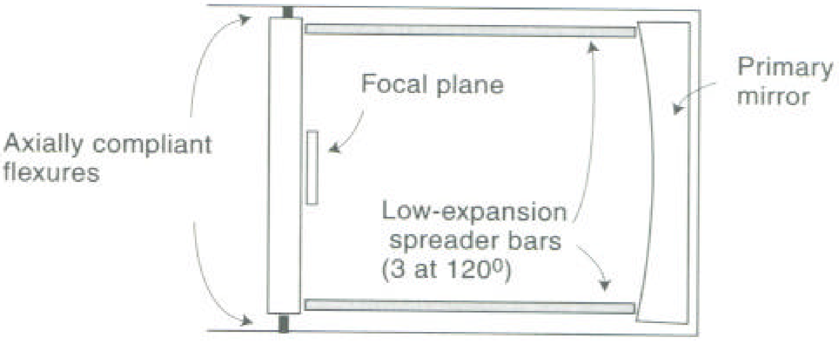


- Thermally induced mirror deformation is not a problem for large **meniscus mirrors** (VLT and Gemini) with active optics
    - Even low-order active optics can correct for thermal effects
    - Not the case of **segmented mirrors -** active optics corrects for errors between segments, but not within segments itself (mirror blanks with low CTE essential)

- Space telescope may or may not require temperature control
    - HST (ULE) is temperature controlled to 21 ± 1 °C
    - Designed temperature, cannot deviates more than 3 degrees without affecting image quality
    - Mirror submitted to strong gradients

- **Older telescopes**:
  - Infamous for their focus variations focus change on time scale of hour or less – due to deformation of mirror or changes of length of steel structure supporting the Cassegrain
  - Focus must be checked many times during the night (if temperature variation observed)
  - Simple solution is to use low-expansion-coefficient rods resting on the primary mirrors (Schmidt and SLOAN telescopes)

- In space, passive solution are preferred
  - Athermal design using same material for primary and supporting structures
  - Expansion of the tube compensate for change in radius of curvature (HST, SIRTF)



- HST – the primary and secondary are temperature controlled and the structure holding the secondary is made of ultra low-expansion graphite epoxy in spite of careful design HST change focus by ± 5 μm on an orbital time scale

- **Dome seeing:**
  Image degradation due to thermal instabilities generated by the telescope and enclosure seeing effects, being caused by temperature fluctuations
  - Decreases rapidly with distance from heat-exchanges surfaces (free convection)

- Sources of free convection:

1. Floor warmer than ambient air or telescope part which are colder than ambient air
2. Temperature differences between surface of primary or secondary and ambient air
3. Heat sources on the telescope or inside the enclosure

Thermal controlled of enclosure

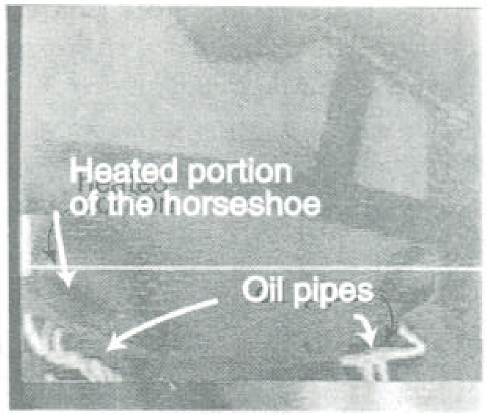
- Rejecting solar heat and insulating the air inside from the warmer air outside

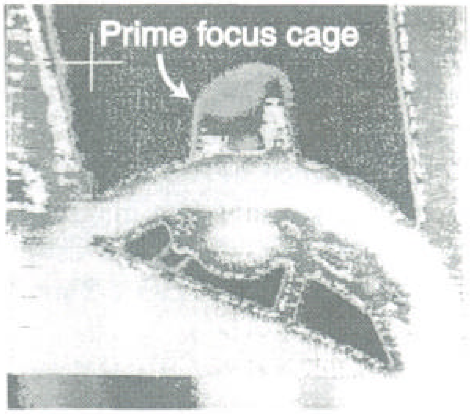
- Active cooling (air conditioning with dew point sensor to avoid condensation) of telescope chamber may be needed to keep air temperature near night time condition

- Controlling the temperature of the floor (used in several 4-meter class observatories in the 60s and 70s) to keep it near temperature of night air or insulating it

    - Disadvantages a good system is costly – may be better to rely on insulation

- All heat-generating equipment should be eliminated
    - ESO requirement – no heat source in the telescope chamber should generate more than 10W/m^2
    - Particular difficulties is secondary activators

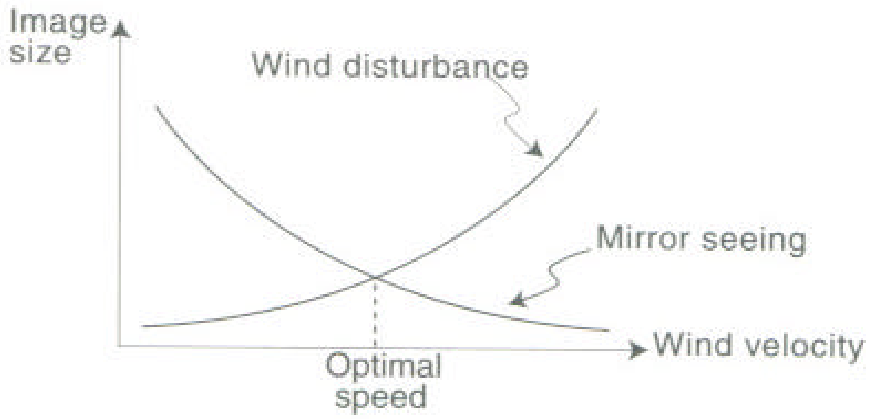




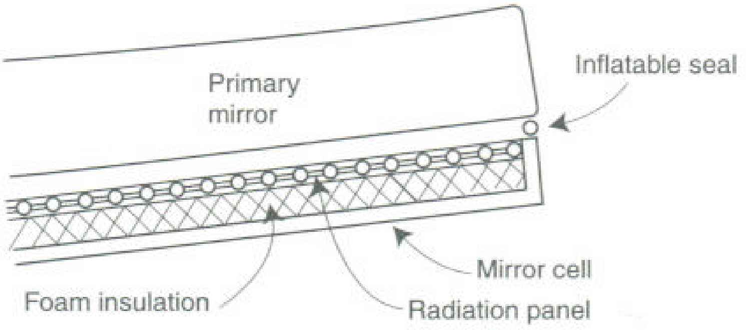
- **Telescope structures cold area:**

    - Upper tube ring, spider and secondary mirror or prime focus cage generate a slow flow of cold air which falls down the optical beam
    - Metal part not located in the beam can be coated with low-emissivity paint (aluminum flake pigment)
    - Metal part located in the beam must be coated with a product that is black in the visible to minimize scatter and has low emissivity in the infrared
    - Other solution is covering the telescope structure with insulation topped with aluminum foil (SUBARU)

- **Mirror seeing:**
  - Caused by natural convection over the optical surface whenever that surface is colder or warmer than the ambient air
  - Most of the degradation occurs in a thin but very turbulent layer floating a few millimeters above the surface mirror
  - Seeing diminishes when the mirror is ventilated (larger mirror produces larger seeing)
  - To benefit from natural flushing by wind entering the enclosure the primary mirror must be as free as possible from surrounding structures (Ex. GEMINI)



- **Active mirror cooling:**
  - Sites where temperature varied more than 2 degrees (Ex. VLT – GEMINI)
  - Radiative cooling (glycol-water mixture circulating in coils) of the back surface of the mirror during the day
  - Fans behind the mirror increase the convective exchange, which makes possible to cool the mirror by 2°C in 6 hours



- **Mirror surface heating:** GEMINI – during day the rear surface of the mirror is cooled to below the expected temperature of the coming night – at night the surface is heated by feeding a current (energy required 1kW)