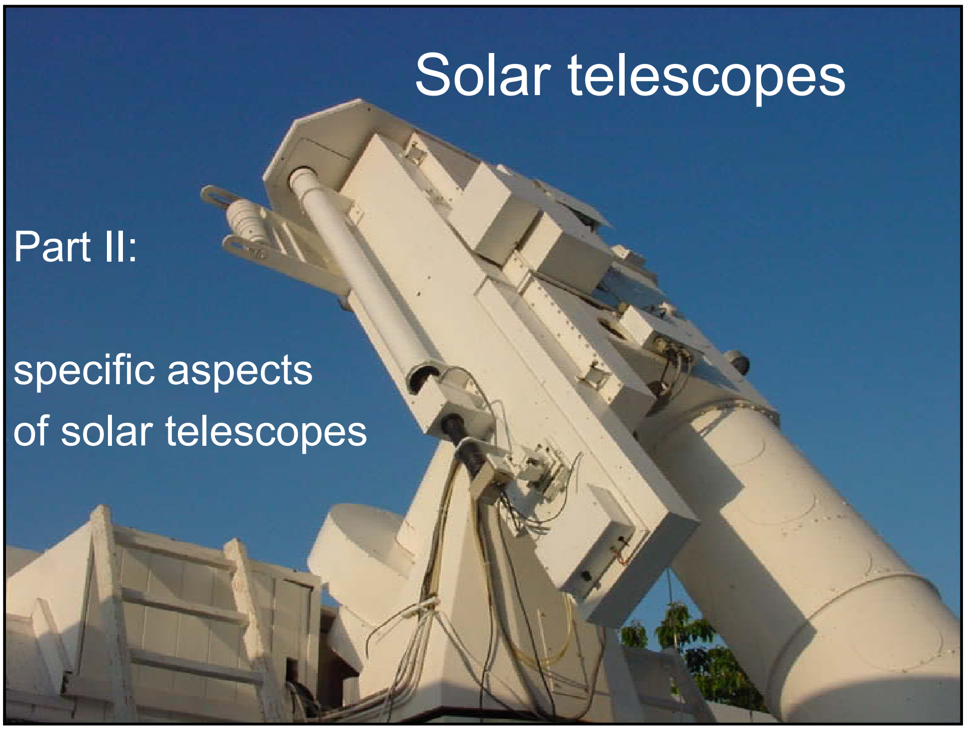
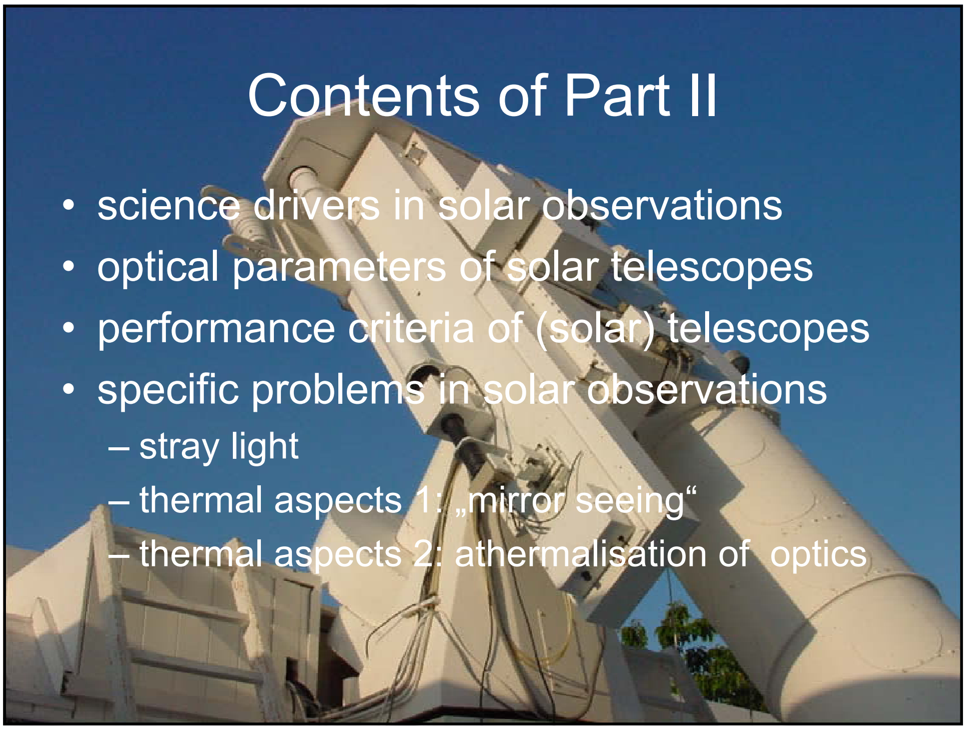
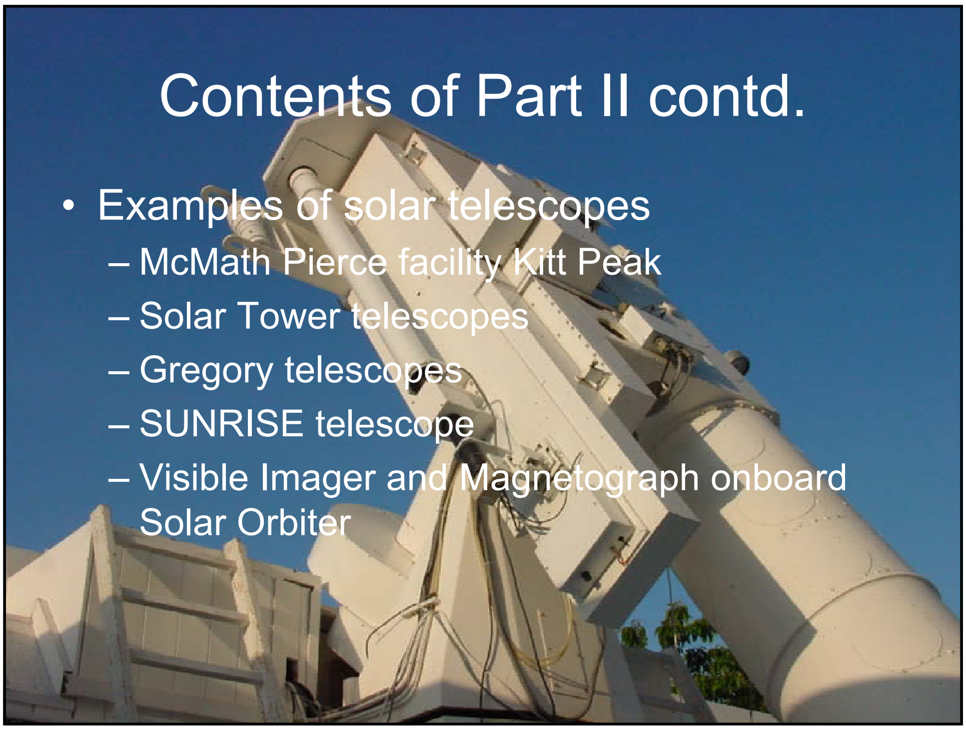

Solar telescopes
Part II:
specific aspects
of solar telescopes


Contents of Part II
• science drivers in solar observations
• optical parameters of solar telescopes
• performance criteria of (solar) telescopes
• specific problems in solar observations
– stray light
– thermal aspects 1: „mirror seeing“
– thermal aspects 2: athermalisation of optics



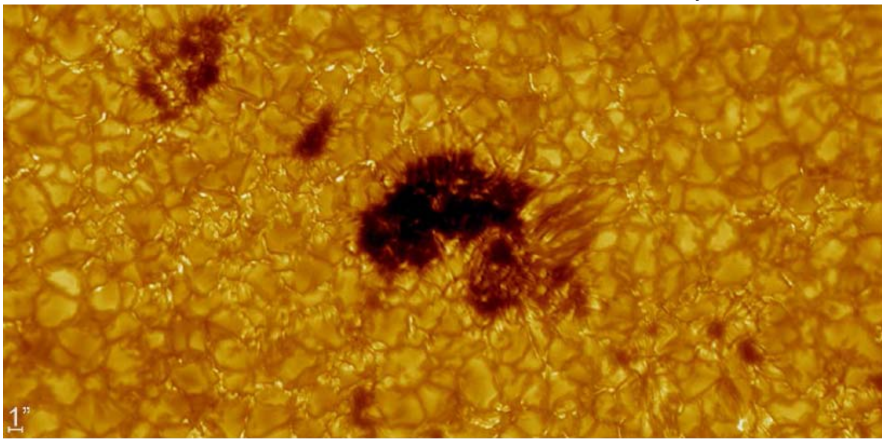
Solar Telescopes II

specific aspects of solar telescopes

science drivers in solar observing

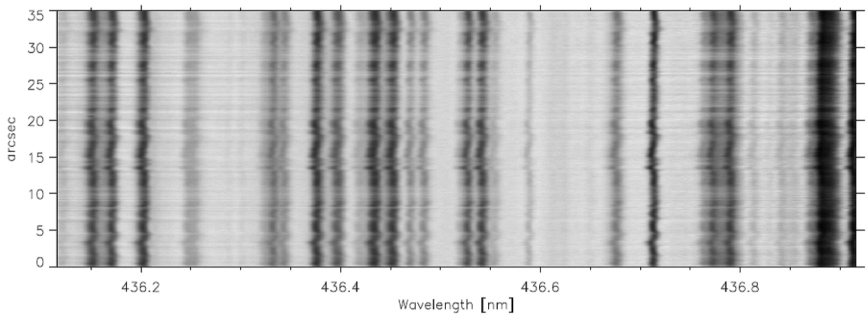
- Sun is only star that can be studied in detail → **highest spatial resolution** (angular resolution) in a relatively **small FOV**

from Vasilys PhD thesis



science drivers in solar observing

- **physics encoded in shape of spectral lines: highest spectral resolution** in a **small spectral range → quasimonochromatic observations**



from Vasilys PhD thesis

optical parameters of solar telescopes

- typical scale of solar surface phenomena on the order of 100km → fraction of arcsec
- typical detector element (pixel) 10µm

→ required plate scale ~ 5“/mm

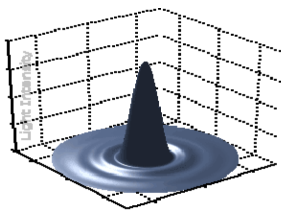
→ effective focal length ~40m!

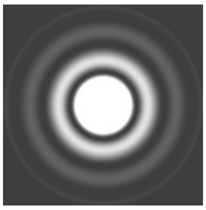
Which aperture diameter is needed?

(to broil a chicken)

performance criteria of (solar) telescopes

- diffraction sets upper value of image „sharpness“
- classical view: diffraction at entrance aperture creates intensity pattern in focal plane (Airy disc); angular radius 1.22λ/D (for circular unobscured aperture)
- Airy pattern: „point spread function“ PSF

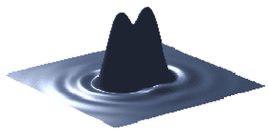


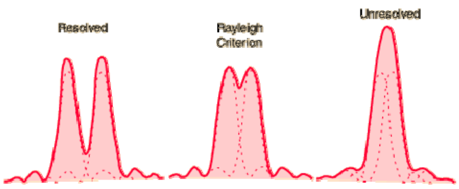


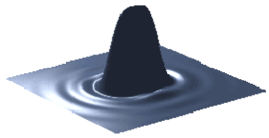
pictures from http://www.cambridgeincolour.com/tutorials/diffraction-photography.htm

Resolution of a (night time) telescope

- Rayleigh criterion: two point sources can be separated if Max (Airy Star 1) is imaged at Min (Airy Star 2)





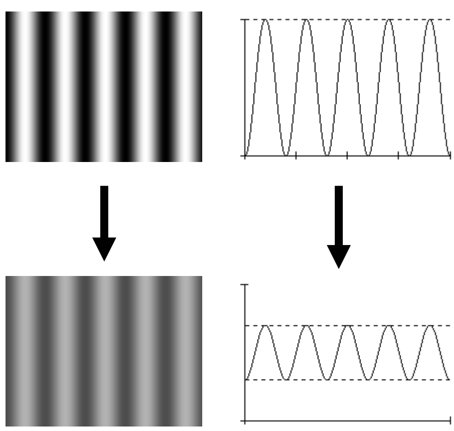


http://www.cambridgeincolour.com/tutorials/diffraction-photography.htm

Resolution of a solar telescope

- Rayleigh criterion not adequate for Sun: extended object!
- define resolution via ability to image intensity contrast

→ „Modulation transfer function“ MTF

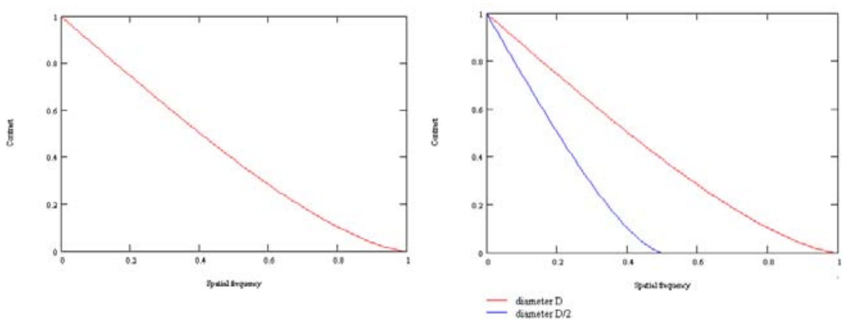


pictures from http://www.astrosurf.com/legault/mtf.html

physical meaning of the MTF

- extended object shows intensity pattern that can be Fourier analysed in spatial frequencies
- low frequencies (large scale structures) will be imaged through telescope without problem
- high frequencies will be more and more „damped“ by diffraction
- cut-off frequency: the sin-pattern at f_{limit} is completely smeared to uniform grey
- $f_{limit} = D/\lambda$

MTF curves (circular, unobscured entrance apertures of different sizes)



pictures from http://www.astrosurf.com/legault/mtf.html

advantage of the MTF representation

- MTFs can be multiplied! The optical performance of the system can be regarded as the product of the individual contributions:
- (seeing)*Telescope*instrument*detector

- at a frequency corresponding to 1.22λ/D (Rayleigh diffraction limit for circular aperture) a perfect telescope transmits only ~10% of the original contrast! A CCD has an MTF of ~50% near the sampling frequency. The solar photosphere has typical rms contrasts of 12%.........

→ measured contrast below 0.6% ! Compare to photon noise!!

a „diffraction limited“ optical system

- diffraction sets theoretical limit to image contrast
- geometrical optical aberrations also reduce contrast
- optical systems are usally considered „diffraction limited“ as long as the contributions of geometrical aberrations do not exceed the ones due to diffraction

Specific problems in solar observations

Stray light

- stray light (scattered light) decreases contrast (the minima of the Airy pattern are not zero any more!)
- not a problem for observations in white light in quiet solar regions (bright object)
- real problem in observations in spectral line in sunspot umbra (5% continuum intensity times 5% residual intensity in the line core!) → see lecture on magnetographs
- dominating problem in coronographs

methods to minimize stray light

- avoid direct illumination of focal plane (focal plane has illumination of

(100/F#)^2 solar constants vs. 1 solar constant

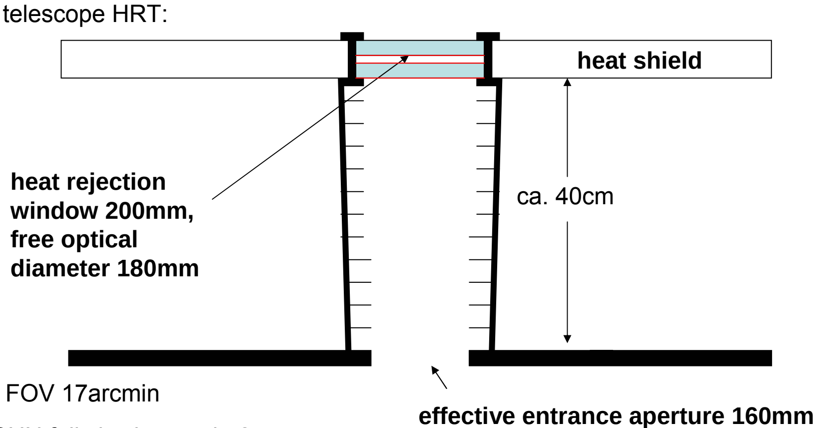
examples:

f/100 (Arosa horizontal telescope): 1 solar constant → direct illumination **desastreous**

f/10 () : 100 solar constants! → **forget direct illumination** (1%; compare to photometric noise, MTF!)

Stray light baffle of Solar Orbiter VIM (conceptual design)

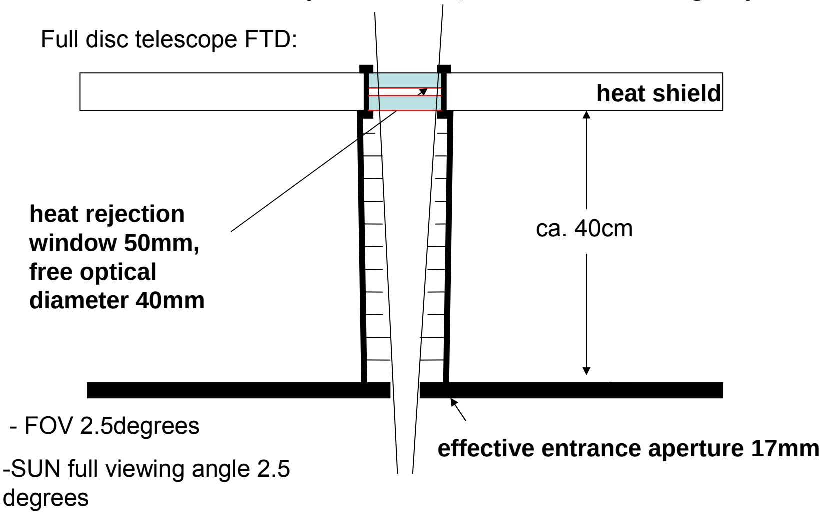
High resolution telescope HRT:



- FOV 17arcmin

-SUN full viewing angle 2.5 degrees (Solar Orbiter operates at 0.2 AU)!

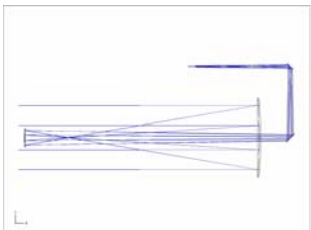
Stray light baffle of Solar Orbiter VIM (conceptual design)



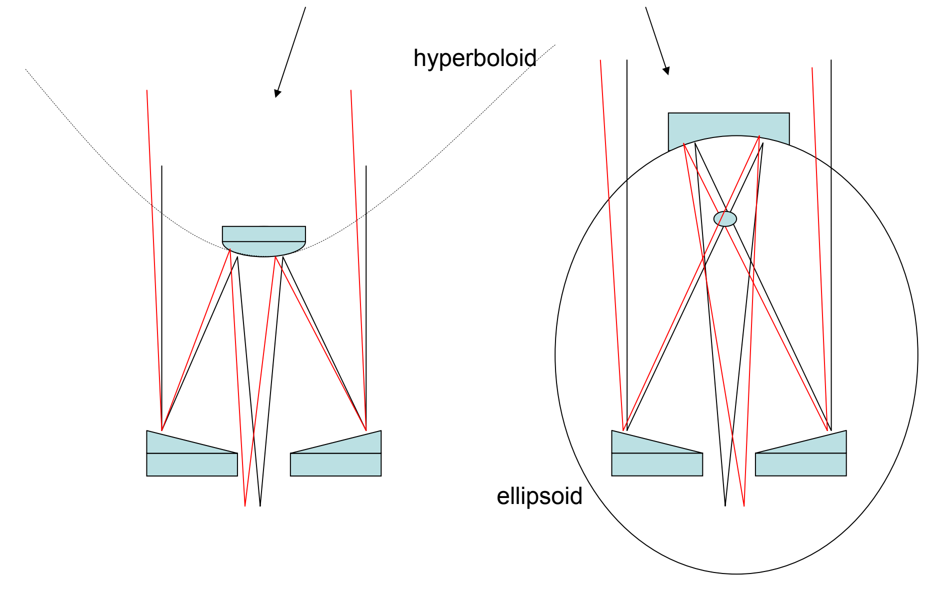
stray-light killing: the Gregory telescope with primary field stop

- first experimentally used in Hainberg observatory Göttingen, then GCT Locarno, Tenerife, Big Bear, Hida

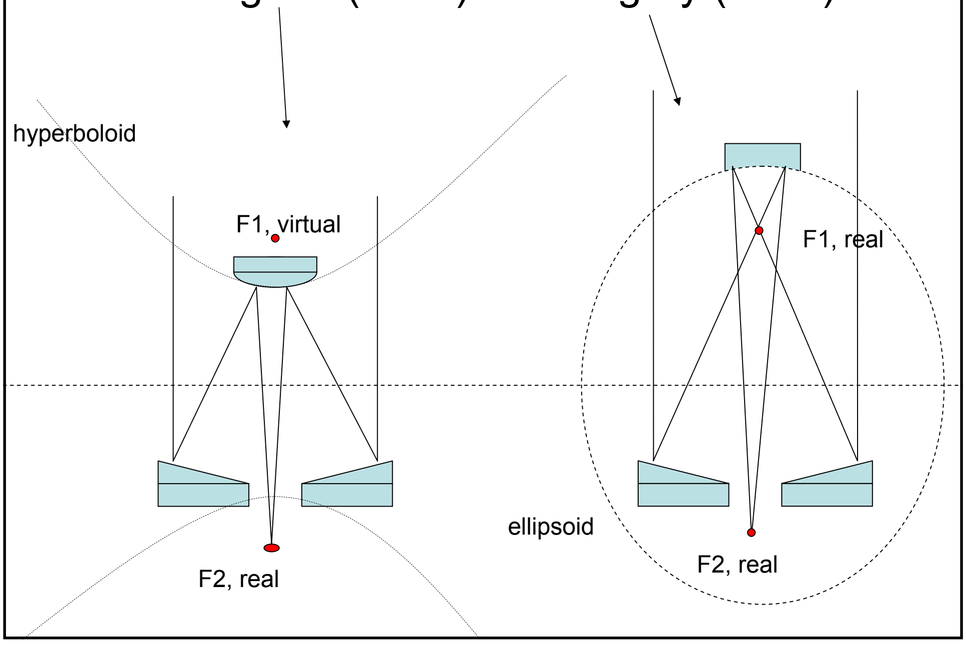
- today: GREGOR, SUNRISE ; in space: HINODE (SOLAR-B) SOT

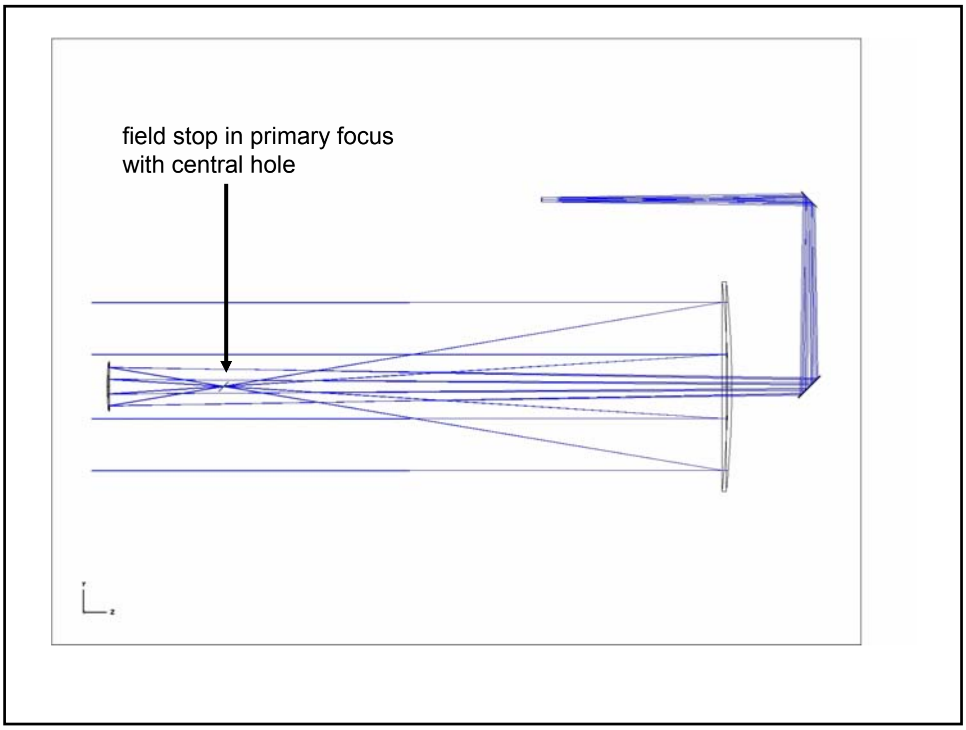


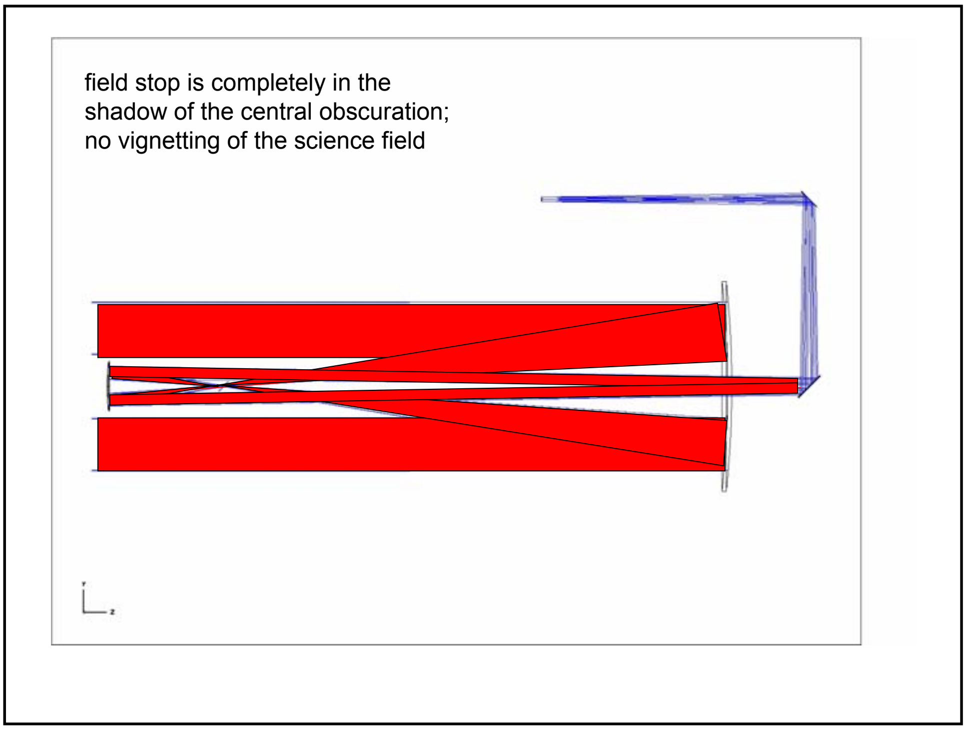
Cassegrain vs. Gregory:

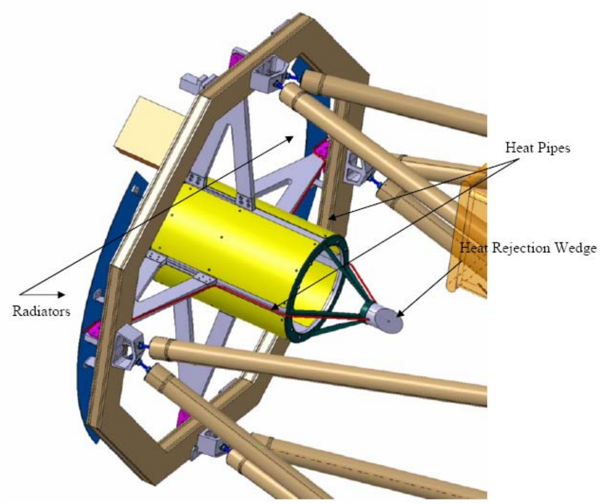


Cassegrain (1668) vs. Gregory (1663):

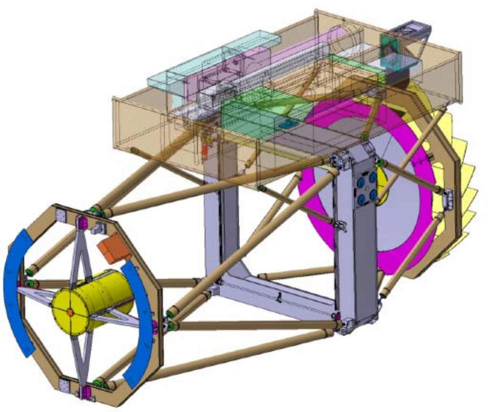



field stop in primary focus
with central hole

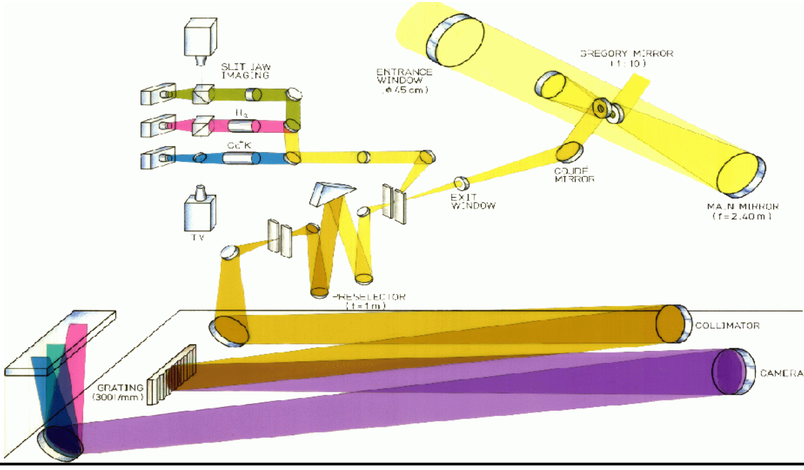

field stop is completely in the
shadow of the central obscuration;
no vignetting of the science field



Heat Pipes
Heat Rejection Wedge
Radiators



Gregory-Coudé-Teleskop



Thermal problems in solar observing

Once again, Schröders colleagues secretely pointed the telescope to the Sun....

Thermal problems of solar telescopes

- solar energy input not negligeable (~1kw/m^2)
- is absorbed near telescope (ground seeing) or in telescope:
  - near telescope: local turbulence: ground seeing
  - in telescope: „mirror“ seeing
- can heat up optical system: performance decrease (→„athermal optics“)

Seeing: the enemy

- seeing the dominant problem in ground based solar observations
- solutions:
  - site selection: mountains on islands
  - air knife: laminar flow along mirror
  - evacuation: no air – no problem?
  - helium filling

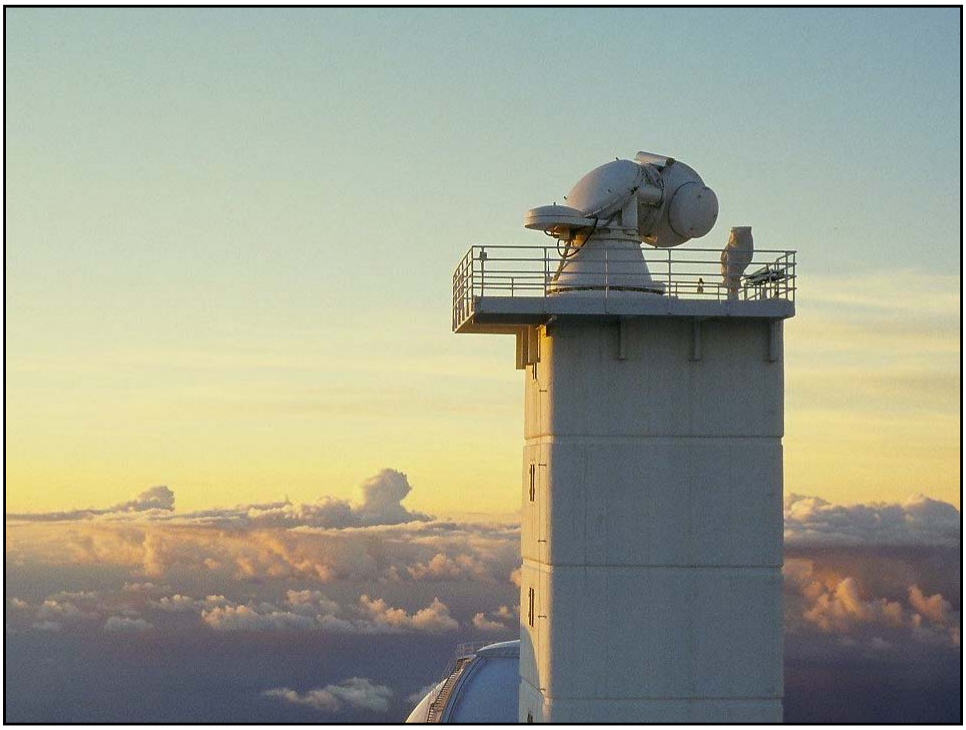
Mirror seeing

- Excurs: Mirrors
  - mirrors are coated with bare Al or „protected silver"
  - residual absorption ~4-10% !
  - substrate: ZERODUR, has high thermal resistance, deposited energy cannot be drained away from the mirror surface
  - mirror surface will heat up, air becomes convectionally unstable → turbulence
  - refractive index of air depends on density

  →„air lenses"

open telescopes

- DOT (Dutch Open Telescope)
  - Experimental telescope
  - open construction: wind avoids „internal“ seeing
  - Site: Observatorio de los Roque de los Muchachos, La Palma



evacuated telescopes

- SST (swedish solar telescope on La Palma) is an evacuated refractor
- objective lens serves as vacuum window
- internal optical path is seeing free

64.000$ question: WHY DOESN´T THE ABSORPTION IN THE LENS (also a few %) POSE THE SAME PROBLEM AS THE ABSORPTION IN THE MIRROR?

helium filled telescopes

- large vacuum windows must withstand enormous forces
- stress detoriates image quality and polarization properties („stress induced birefringence“, see lecture on magnetometry)
- solution: pressurize telescope with helium
- examples: THEMIS, SOLIS VSM

effects of helium

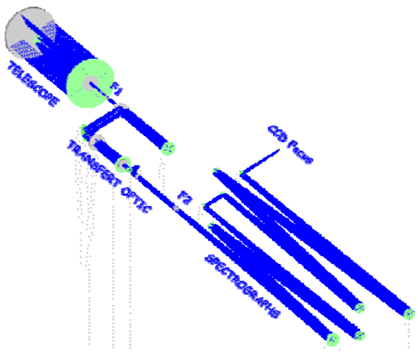
- very high thermal conductivity

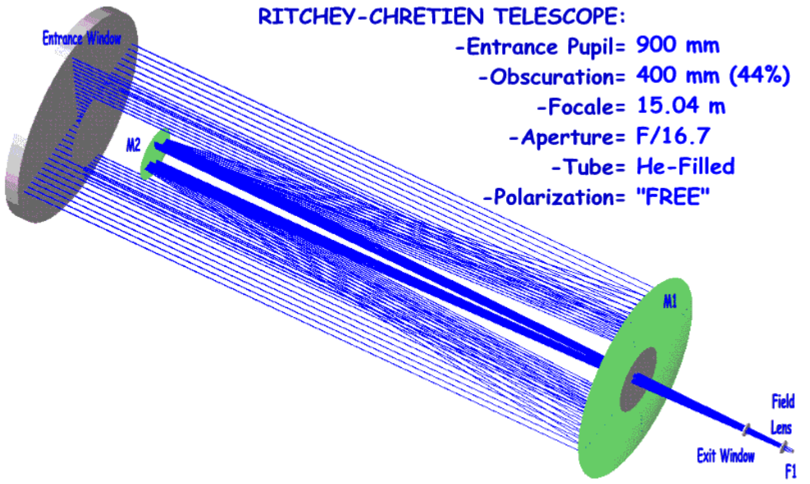
→ instantaneous equilibration of local temperature (density) inhomogeneities

- very low refractive index

→ no „(air) lenses“

THEMIS

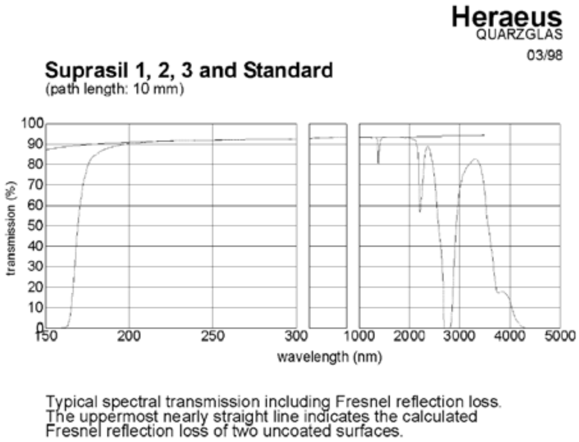




Thermal control of solar space telescopes

- on ground: most effective thermal balance mechanism is convection
- in space: purely radiation based
  - minimize absorption
  - maximize emission in mid-IR wavelengths (thermal infrared)
  - examples:
    - White paint (TiO) vs. gold (mirror!)
    - glass

transmission curve of fused silica



http://www.heraeusoptics.com/uploads/100005_datasheets/100034.pdf

Example: Solar Orbiter VIM

- optical instrument orbiting Sun (perihelion distance 0.22 AU)
- 16cm aperture, polarization sensitive monochromatic (high spectral resolution) high resolution camera (f=4.25m)
- optical design driven by thermal aspects!

VIM baseline design

- closed telescope with entrance filter
  - narrowband interference filter, reflects complete spectrum except narrow band pass at science wavelength
- uncritical simple optical scheme
  - off-axis Ritchey Chrétien telescope, instrument optics purely refractive

Entrance window / Filter

- entrance window to reduce flux into instrument
  - highly reflective over solar spectrum
  - narrow notch in reflectivity curve to transmit science band pass
  - very low absorption at visible and near IR
  - maximize emissivity at thermal IR: window should be „black“ in thermal IR

solution: highly reflective backside coating, front surface uncoated to use high emissivity of substrate material (fused silica)

Solar orbiter VIM optical layout

- off-axis Ritchey Chrétien
- secondary in shadow, no spider necessary
- secondary mirror still hot element, needs thermal drainage to radiator
- ZERODUR mirrors
- needs carbon fiber optical bench
- lens optics must be athermal
- focus mechanism necessary to cope with thermal lensing of the entrance window

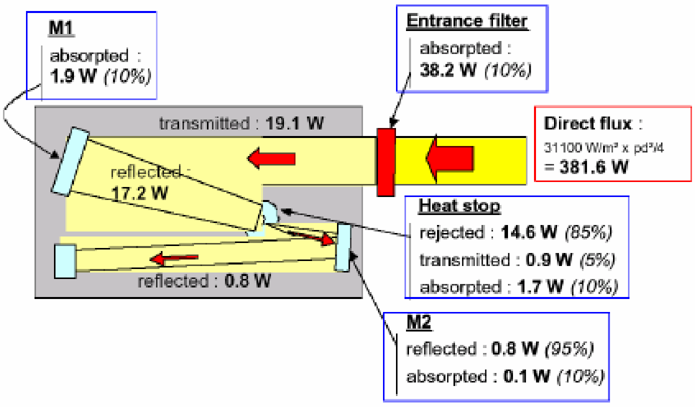


Figure 2.6.2: VIM thermal architecture concept.

taken from ESA SCI-A/2004/175/AO, issue 3, revision 0

Solar Orbiter Payload definition document

Thermal effects on optical performance

- temperature (gradients) can have different effects on optical components:
  - change in position (thermal expansion of mechanical mounts, tube length)
  - change in shape (thermal expansion of glass)
  - change in refractive index („thermal lensing“, worst offender!)

methods in building „athermal“ optical systems

- material choice: Mirrors can be made from ZERODUR (Astrositall, ULE) with negligeable thermal expansion
- lenses must change their position to compensate for changing refractive power!
- mounts must be made of material with well selected thermal expansion coefficient (CTE)

Athermal design using ZERODUR mirrors

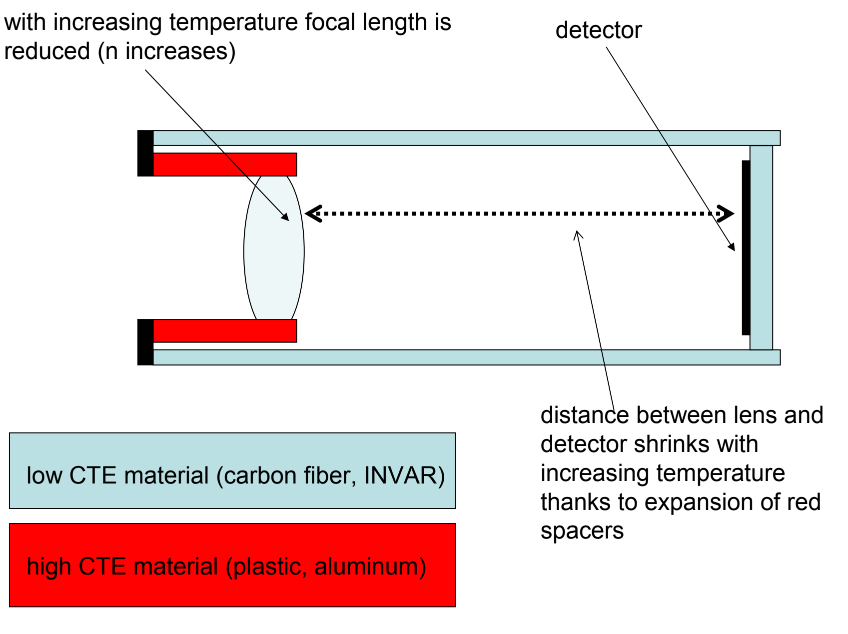
- since the mirrors will not change their properties, also the rest of the telescope must not change! DON´T MAKE THE (COMMON) MISTAKE OF BUYING (MAKING) EXPENSIVE ZERODUR MIRRORS AND USING ALUMINUM AS THE TELESCOPE TUBE! The expansion of the tube will spoil your focus!

ZERODUR ctd.

- ZERODUR must be used in combination with low (ideally zero) CTE structures: carbon fiber (attention, anisotropic expansion coefficient!), or INVAR (steel, difficult to machine, extremely heavy!).
- For titanium structures better chose DURAN as mirror material!

athermal lens design

- lenses will change their refractive index and their shape!
- to keep focus at right distance the tube length must shrink.....that would mean a negative CTE
- trick: Mount lens (or detector!) on thickness compensator:



Famous solar telescopes

a personal retrospective

Solar tower telescopes

- long focal length (primary focus telescopes) fixed pointed (to zenith)
- mirror arrangement to guide Sunlight into telescope

Never ask google about „Solar Towers“!





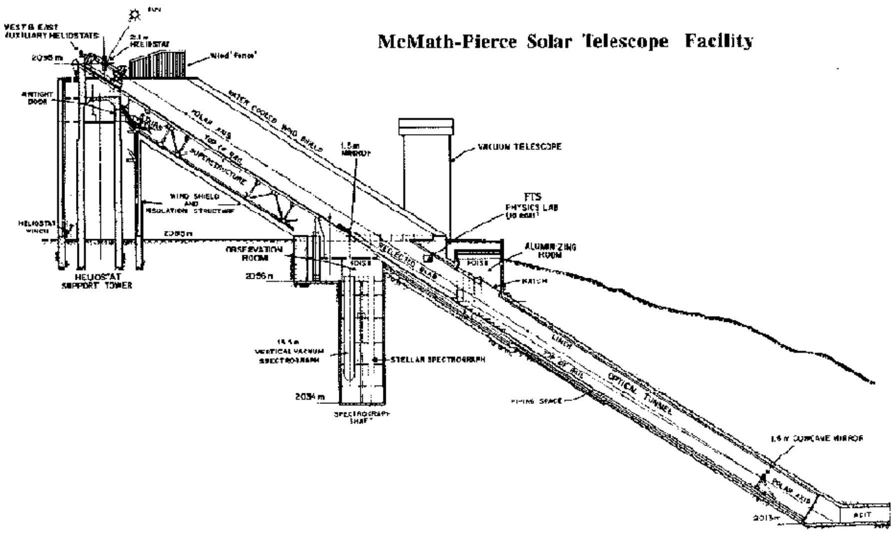

A Solar Tower Telescope

Einsteintower

- 70cm achromatic refractor with 12m focal length
- built in 1924 by Erich Mendelsohn (Architect) and Carl Zeiss Jena (optical arrangement) for experimental verification of gravitational redshift in solar lines
- most powerful spectrograph of its time
- an architectual and technological masterpiece!!

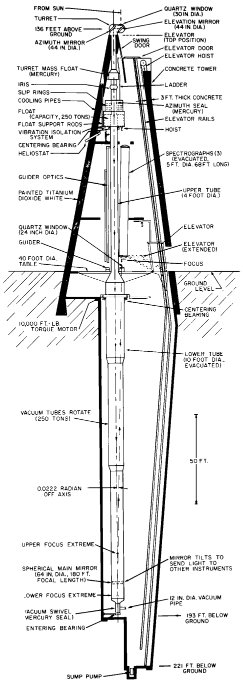
The Einsteinturm (Potsdam 1924)

McMath-Pierce facility (Kitt Peak National Observatory)



Dunn Solar Tower, Sacramento Peak, NM, USA

- built in the seventies as evacuated reflector
- for a long time highest resolution solar telescope
- now again scientifically productive thanks to first adaptive optics system in solar physics (followed by VTT AO on Tenerife)


FROM SUN
TURRET
136 FEET ABOVE GROUND
AZIMUTH MIRROR (44 IN. DIA.)
QUARTZ WINDOW (30 IN. DIA.)
ELEVATION MIRROR (44 IN. DIA.)
ELEVATOR (TOP POSITION)
SWING DOOR
ELEVATOR DOOR
ELEVATOR HOIST
TURRET MASS FLOAT (MERCURY)
CONCRETE TOWER
IRIS
LADDER
SLIP RINGS
COOLING PIPES
3 FT. THICK CONCRETE
AZIMUTH SEAL (MERCURY)
FLOAT (CAPACITY, 250 TONS)
ELEVATOR RAILS
FLOAT SUPPORT RODS
VIBRATION ISOLATION SYSTEM
HOIST
CENTERING BEARING
HELIOSTAT
SPECTROGRAPHS (3) (EVACUATED, 5 FT. DIA. 68 FT. LONG)
GUIDER OPTICS
PAINTED TITANIUM DIOXIDE WHITE
UPPER TUBE (4 FOOT DIA.)
QUARTZ WINDOW (24 INCH DIA.)
ELEVATOR
GUIDER
ELEVATOR (EXTENDED)
40 FOOT DIA. TABLE
FOCUS
GROUND LEVEL
CENTERING BEARING
10,000 FT.-LB. TORQUE MOTOR
LOWER TUBE (10 FOOT DIA., EVACUATED)
VACUUM TUBES ROTATE (250 TONS)
50 FT.
0.0222 RADIAN OFF AXIS
UPPER FOCUS EXTREME
MIRROR TILTS TO SEND LIGHT TO OTHER INSTRUMENTS
SPHERICAL MAIN MIRROR (64 IN. DIA., 180 FT. FOCAL LENGTH)
LOWER FOCUS EXTREME
12 IN. DIA. VACUUM PIPE
VACUUM SWIVEL MERCURY SEAL)
193 FT. BELOW GROUND
ENTERING BEARING
221 FT. BELOW GROUND
SUMP PUMP