Solar Telescopes

why are they built as towers?

A Week Above The Clouds 2019

Prof. Dr. Wolfgang Schmidt

Solar observer's challenges:

Seeing gets worse with increasing aperture!

- The angular resolution of a telescope is proportional to wavelength (i.e., less resolution in the IR): $\phi = \dfrac{\lambda}{D}$
- The seeing quality improves with wavelength, the Fried parameter is proportional to $\lambda^{6/5}$; effective resolution is: $\phi_s = \dfrac{\lambda}{r_0}$
- Effective angular resolution is nearly independent of telesccope size, once D >> 30 cm
- Large solar telescopes without AO do not make too much sense!

More solar observer’s challenges:

The Sun is not bright enough!

1. The spectral flux (photon flux per wavelength band and per m^2) from the Sun is constant.

2. The photon collection are increases with the square of the telescope aperture

3. The area of a diffraction-limited pixel (=„resolution element“) decreases with the square of the telescope aperture

4. **The number of photons per wavelength band per resolution element is independent of the telescope aperture.**

5. The characteristic time scales decrease inversely proportional to the telescope aperture -> i.e., T**he larger the telescope, the smaller the resolved spatial scale, the faster the pixel crossing time, …**

6. **Shorter integration time are needed to keep up with the faster processes on the Sun, but (4) still holds!**

7. **Example: ->>VTF**

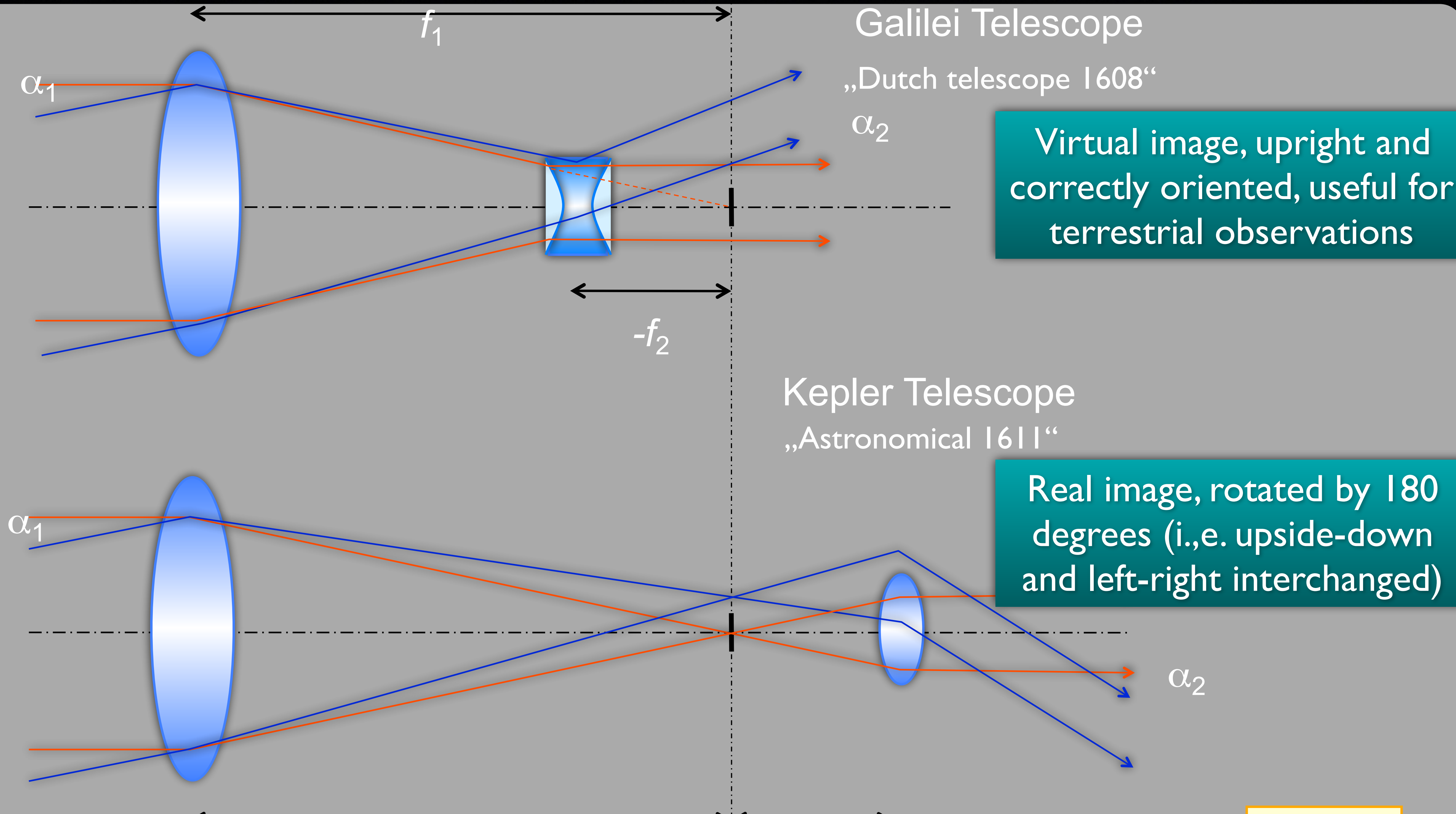
Some historical remarks

- Long before the Galilean and the Keplerian telescopes were invented, astronomers used long tubes without any optics to observe celestial bodies. The tubes served to eliminate or to reduce stray light.
  - This historical fact can be seen in the German word for telescope: „Fernrohr“, it combines the Greek „Tele“= „fern“ with the Latin „Tubus“=„Rohr“.
- The first optical telescopes were built in 1608 by the Dutch lensmaker Hans Lipperhey. Shortly after him, Galiei built a telescope of the same type. Since Galilei was famous, and Lipperhey was not, this type of telescope is known as Galilean Telescope.
  - The main motivation for Lipperhey was military use (80-year war between the Netherlands and Spain, where the Netherlands finally, in 1648 became independent from Spain.) Fortunately, Lipperhey also considered astronomical use.

More historical remarks

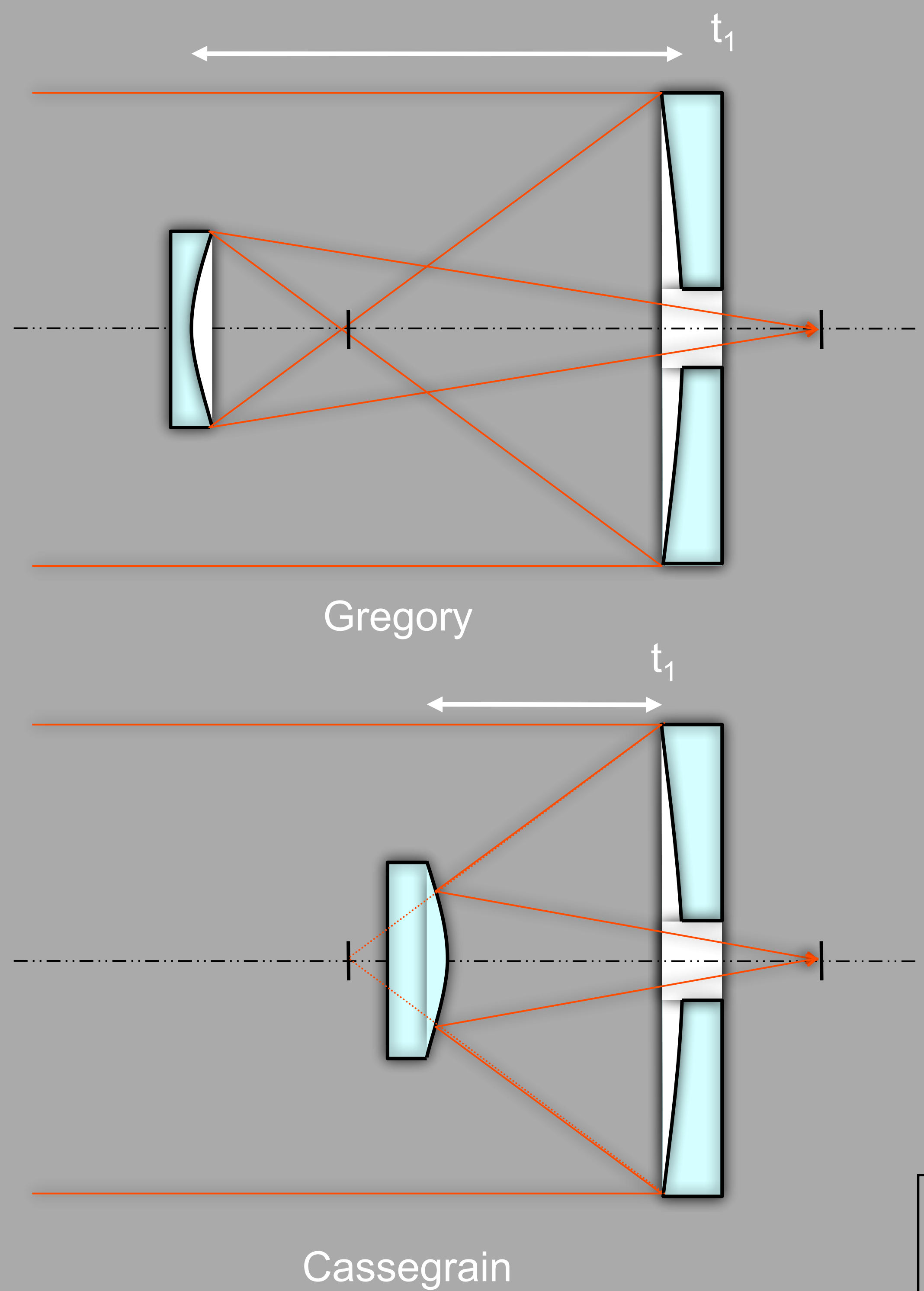
- Besides the Moon and some planets, the Sun has been a very important object for observation (by projecting a solar image, of course!). Therefore, the history of telescopes is also the history of solar physics
  - Sunspot observations started right after telescope invention
- The optical designs of telescopes for night-time observations and for solar observations are the same (e.g., Newton, Gregory, Ritchey-Chretién).
- The buildings are quite different, since solar observations are, not surprisingly, made during sunshine. Negative side effects of that sunshine (stray light, heated surfaces, bubbles of hot air („seeing“) are reduced by using tall and slim towers, white paint, thermal insulation, active cooling, …)

Refractors



$$m = \frac{\alpha_2}{\alpha_1}$$

Reflectors



Effective focal length *f'*:

$$\frac{n'}{f'} = \frac{n_1'}{f_1'} + \frac{n_2'}{f_2'} - \frac{n_1'}{n_1} t_1 \frac{n_1' n_2'}{f_1' f_2'}$$

n_i, n'_i: indices of refraction in front and behind *i*

t_i: Distance between planes *i* und *i*+1

f_i, f'_i: focal lengths of ith plane

$n_1 = n'_2 = n' = 1$

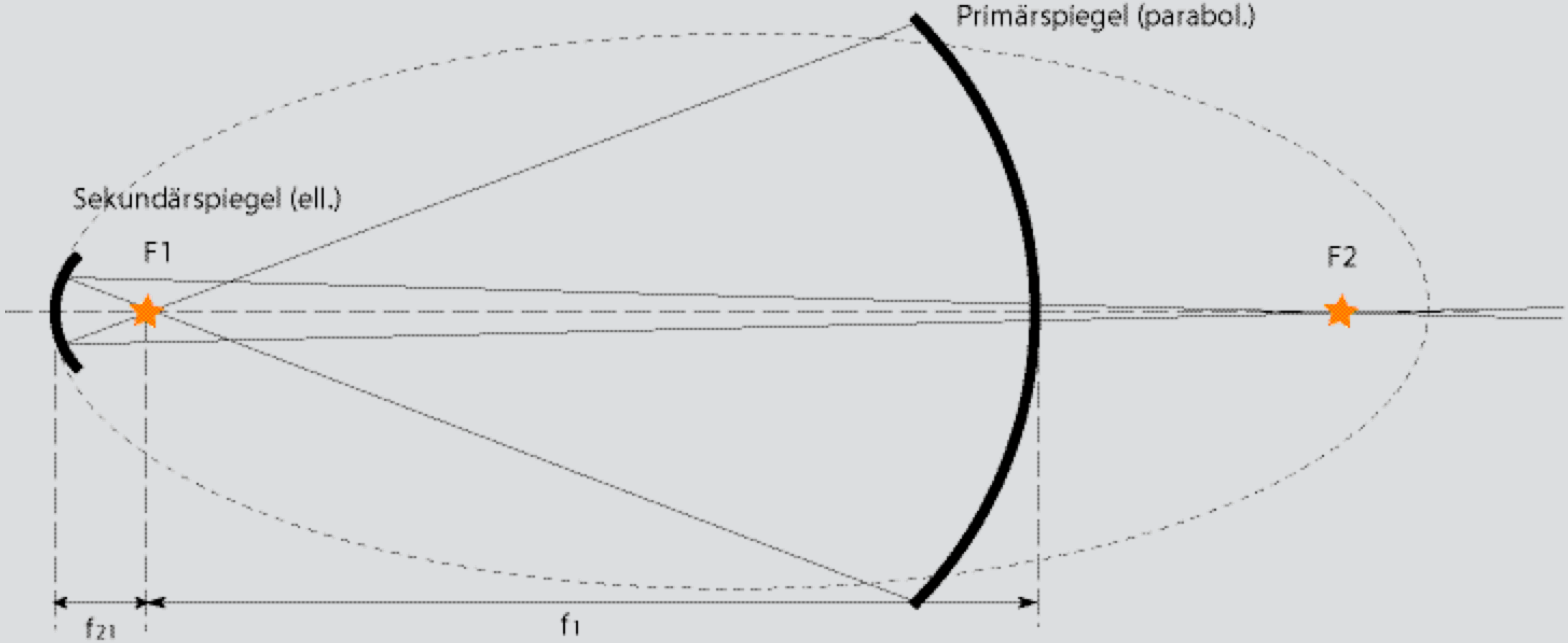
$n'_1 = n_2 = -1$

$f'_1 < 0, \quad t_1 < 0$

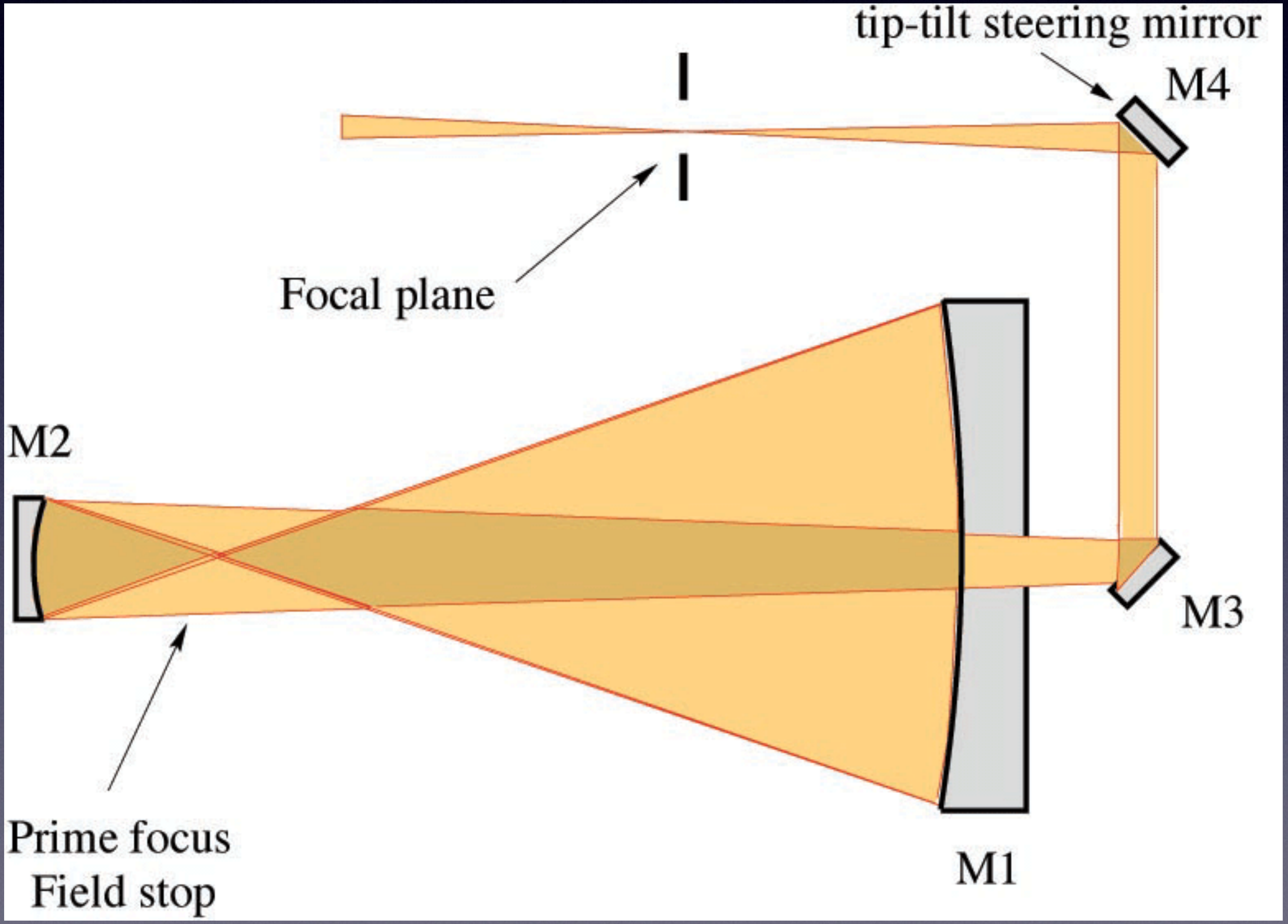
$f'_2 > 0$ (Gregory), < 0 (Cassegrain)

$$\frac{1}{f'} = -\frac{1}{f_1'} + \frac{1}{f_2'} - \frac{t_1}{f_1' f_2'} = \frac{-f_2' + f_1' - t_1}{f_1' f_2'}$$

Gregory optical design



Example: Sunrise 1m telescope



Refractors

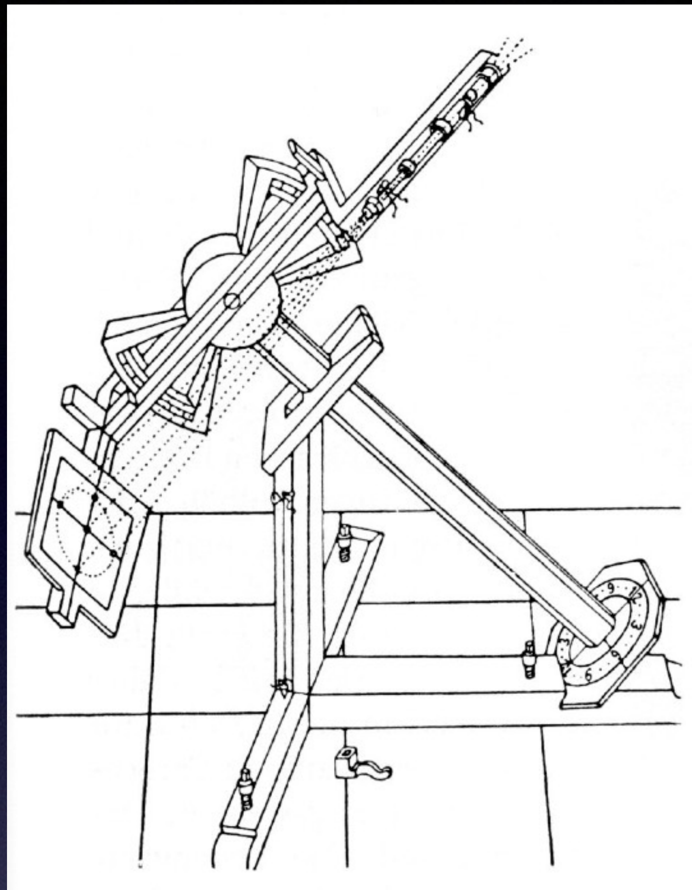
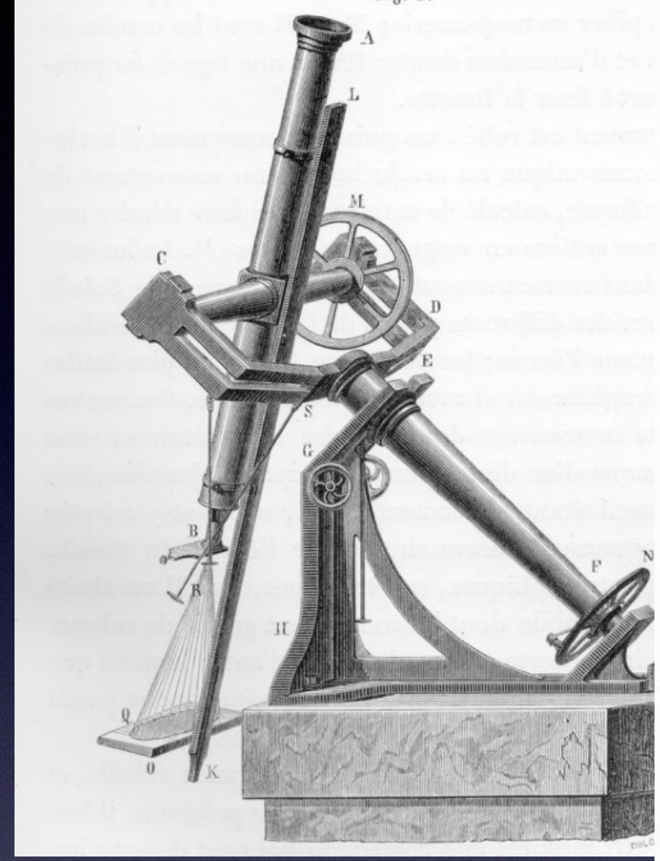


Abb. 260. Scheiners Fernrohr zur Projektion der Sonnenflecken

Fig. 2.



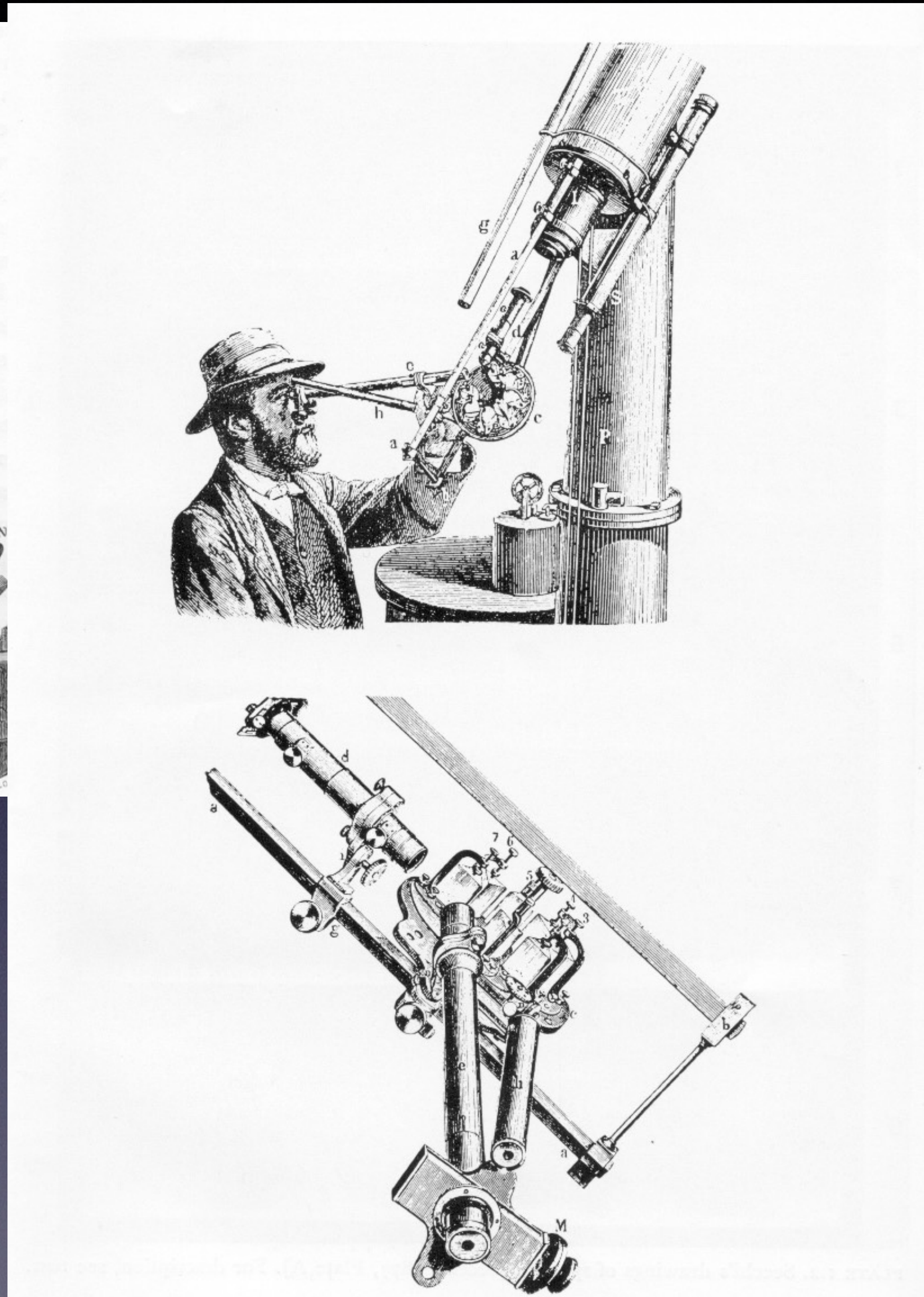
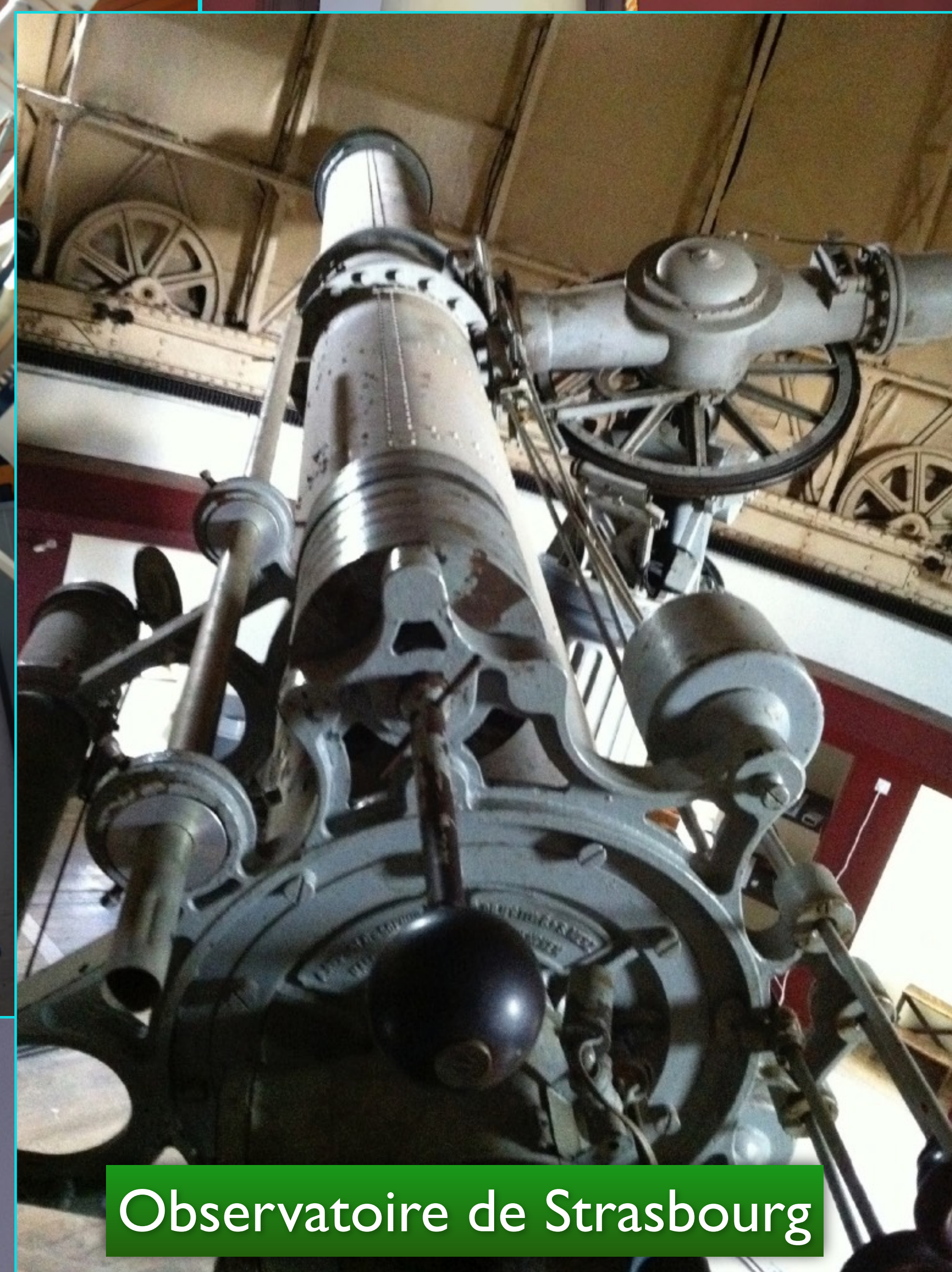


PLATE 1.1. Spectroscope built in 1868 for J. N. Lockyer by Browning of London for observation of prominences and the chromosphere outside of an eclipse. d is the collimator, e the viewing telescope, and h a small telescope for reading the prism assembly micrometre scale.


Schauinsland, Freiburg


Sternwarte Göttingen


Observatoire de Strasbourg

Solar telescopes (I)

Solar telescopes (II)

Solar telescopes:
Basic design considerations

- The era of modern solar observations started around 1940, well before the availability of electronic computers.
- The solar community was small, therfore, inexpensive solutions were important
- Solar telescopes were designed as mainly passive devices (no cooling), with a minimum of moving parts, and simple guiding systems (=hour drives).
- Sky coverage limited to the ecliptic ± 24 degrees
- Field of view ~0.5 degrees (= angular diameter of Sun)
- Reduce internal seeing -> Vacuum telescopes
- Reduce influence of local seeing -> tall towers
- High-resolution telescopes need long focal lengths

Vacuum tube in tower (VTT)

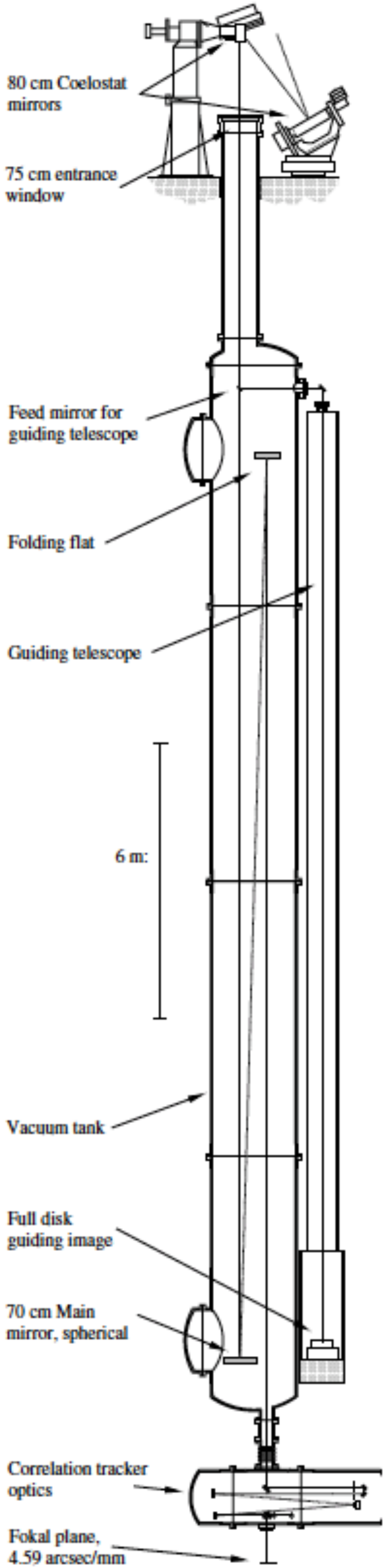
(Nearly) empty tower (Schauinsland)

Hi-Res Solar telescopes

at the OT (I)

- Vacuum Tower Telescope (70 cm, designed 1972, FL 1987):
  - Coelostat („equatorial mount“), open dome, simple guiding, few moving parts, telescope optics in vacuum, computer-controlled fine-pointing using agile M2, primary mirror with 45 meter focal length, off-axis design. No image rotation during the day. Orientation of image depends on Coelostat azimuth. Equipped with adaptive optics in 2002
- Telescope Télescope Héliographique pour l'Etude du Magnétisme et des Instabilités Solaires (THEMIS, 90 cm, designed 1981, FL 1996)
  - Ritchey-Chretién, Helium-filled telescope tube, alt-az mount, closed dome moving in sync with telescope, fully computer-controlled, cooled secondary, low instrumental polarization, spectrograph rotates with telescope. Adaptive optics under construction 2018-2020

These telescope, together with the Swedish Solar telescope on La Palma, mark the end of the era of Vacuum telescopes



The VTT

VTT Handout

Hi-Res Solar telescopes

at the OT (II)

❖ GREGOR (145 cm, designed 1998, FL 2012)

- Gregorian optical design, Alt-az mount; open design; folding dome; cooled primary & F1 field stop; image rotator to compensate image rotation produced by telescope; 57 m effective focal length. High-order adaptive optics from the beginning (but with extra mirrors). Polarization calibration unit for all optics downstream of M2.

GREGOR is the first telescope of the new generation of solar telescopes:

- Open telescope structure
- active cooling of the primary, to reduce or avoid internal seeing
- Adaptive optics included from the beginning
- Tower building mainly needed to avoid ground-layer seeing

- BUT:
  - No active support of primary
  - Open design with restrictions due to re-use of existing building (dome does not completely fold away; M1 and M3 not always in „free air“)

Insider's comment: In retrospective, an active mirror cell would have been important, but at the time of that decision, we still planned to have a CSiC mirror with much better stiffness compared to Zerodur.

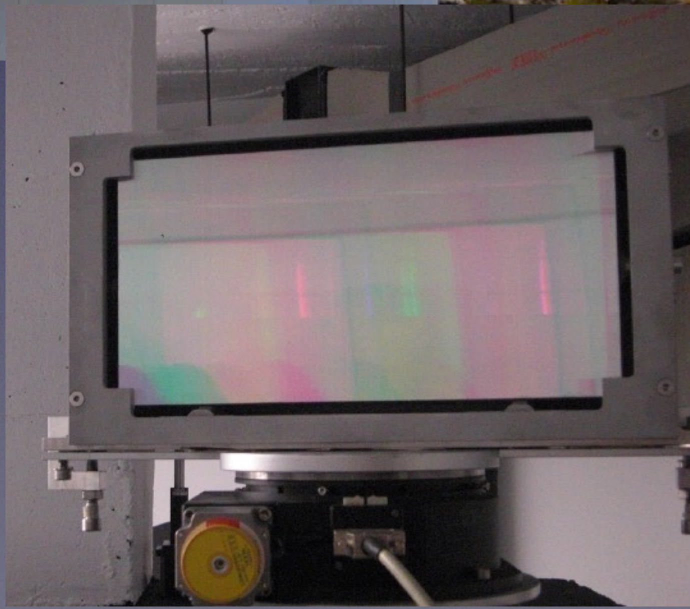
GREGOR

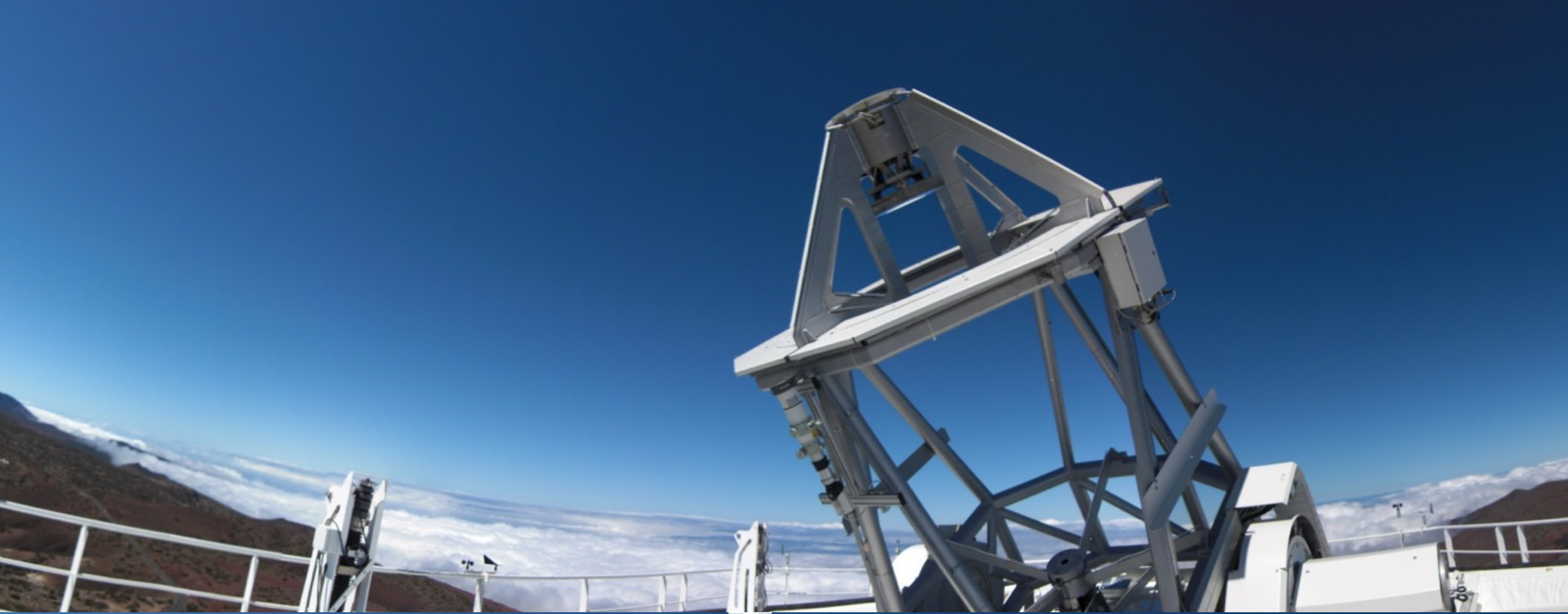
Largest solar telescope in Europe

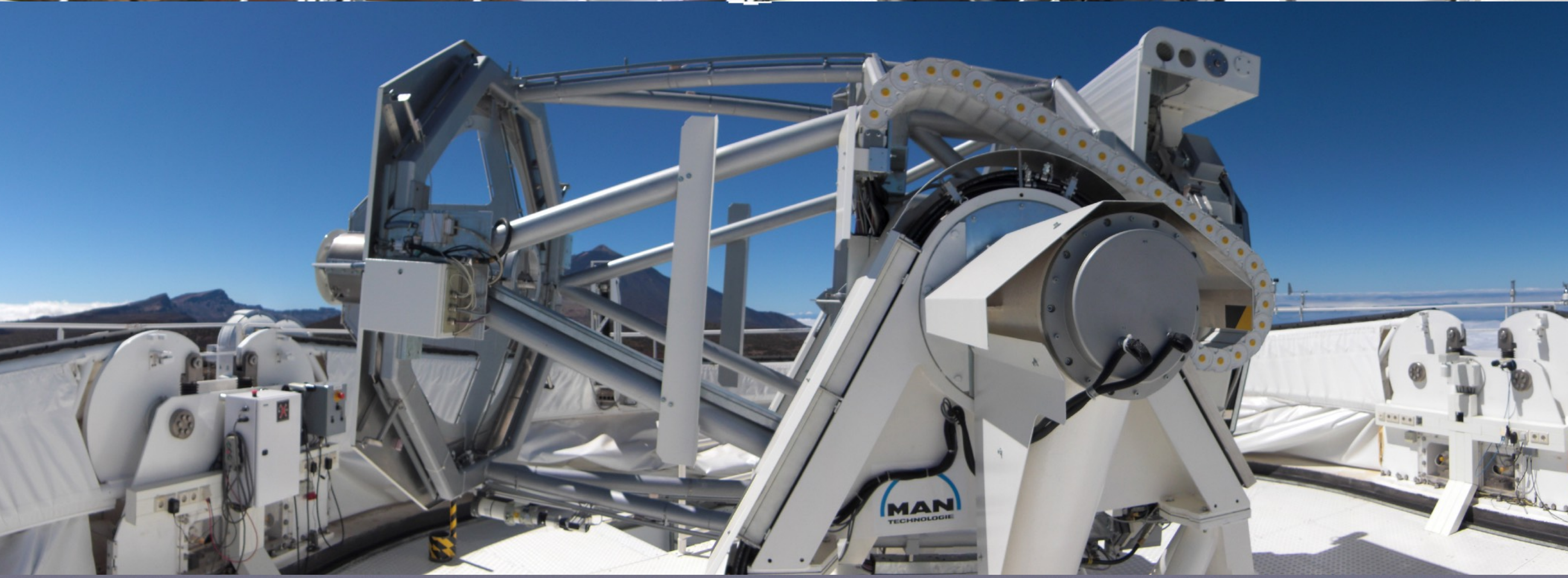
Leibniz-Institut für Sonnenphysik & Partners AIP, IAG; with contributions from the IAC and AIAS

- ✤1.5 m Aperture
- ✤ Gregory Design (3 mirrors)
- ✤ Alt-Az-Mount
- ✤ Folding dome
- ✤High-order AO

- ✤Grating spectrograph with IR polarimeter (GRIS)
- ✤Filter-Spectro-Polarimeter
- ✤Filtergraph
- ✤New instruments under development:

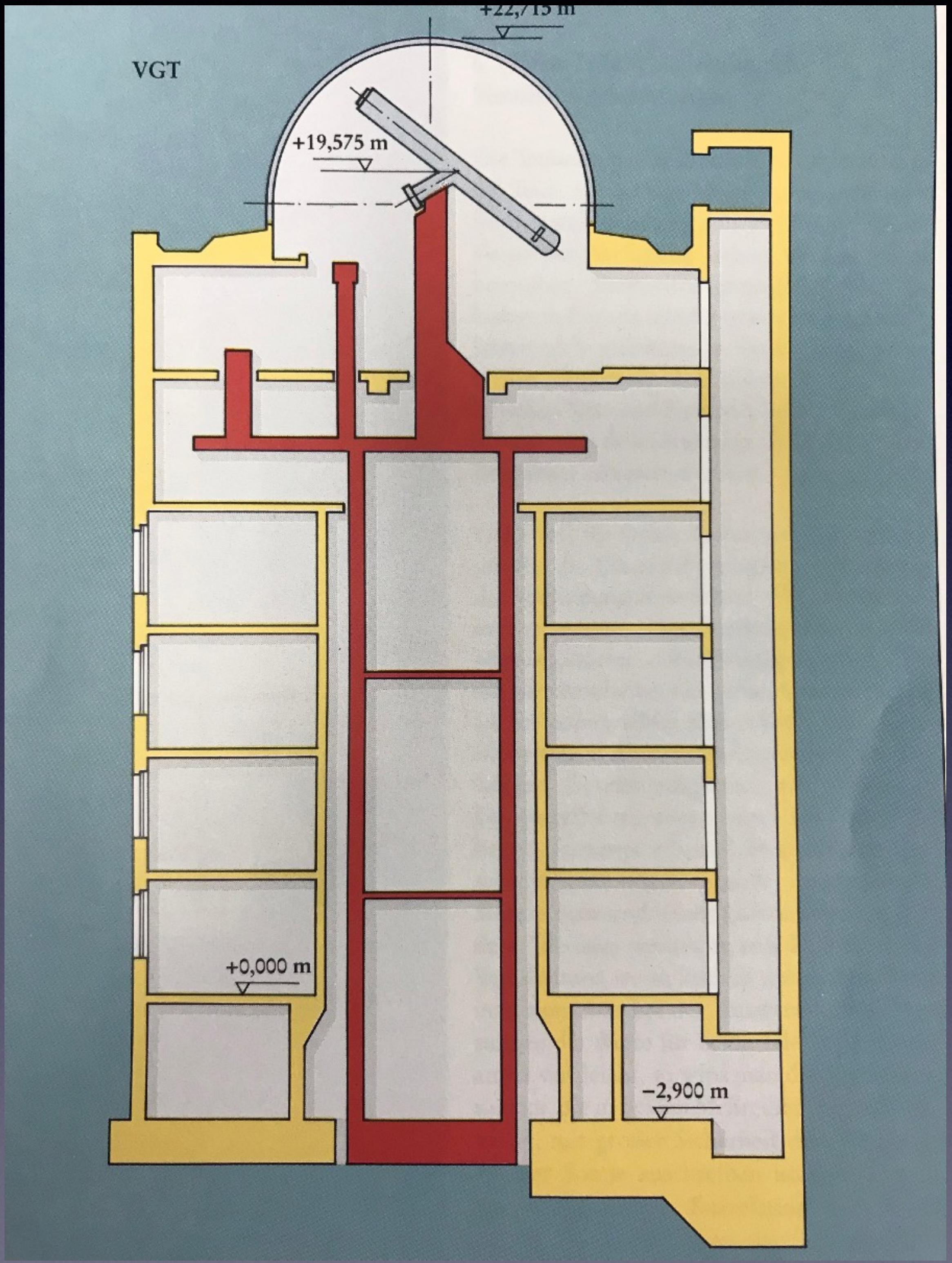





MAN
TECHNOLOGIE

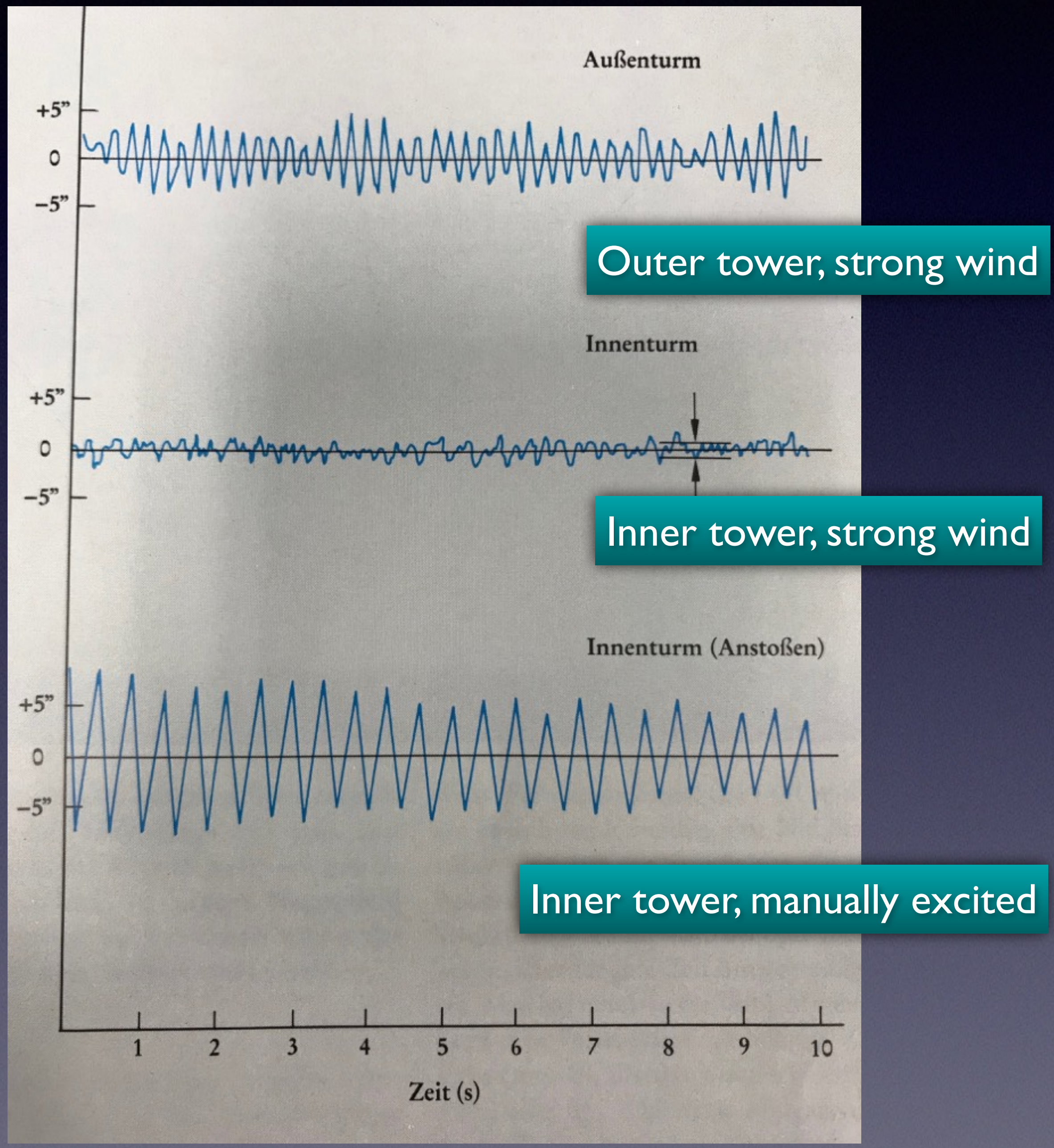
Remarks about solar towers

- ✤ Many solar telescopes are built as double tower constructions
- ✤ The idea is, to structurally isolate the part with the telescope from the „busy“ areas, where people move and work, from machinery, and from wind load.
- ✤ The eigenfrequency of the inner tower must be different from that of the outer one to avoid crosstalk



The effect of double towers

- The outer tower has a better stiffness and therefore a higher eigenfrequency, i.e., the inner tower has a lower stiffness than the outer one.
- Works well, when dome is closed
- Reduced stiffness also means that the inner tower is more easily excited to oscillate than the outer one. The excitation happens by wind load on the telescope through the open dome shutter.
- The problem is more severe for the VTT, with its folding dome and the coelostat M2 fully in the open.



GST

- New Jersey Institute of Technology & Big Bear Solar Observatory
- 1.6 m aperture
- 0ff-axis Gregory design
- Equatorial mount
- Nasmysth & Coudé focal planes
- 0.39 - 1.6 µm range
- lo AO (76 actuators)
- Spectropolarimetric instrumentation: IRIM, VIM

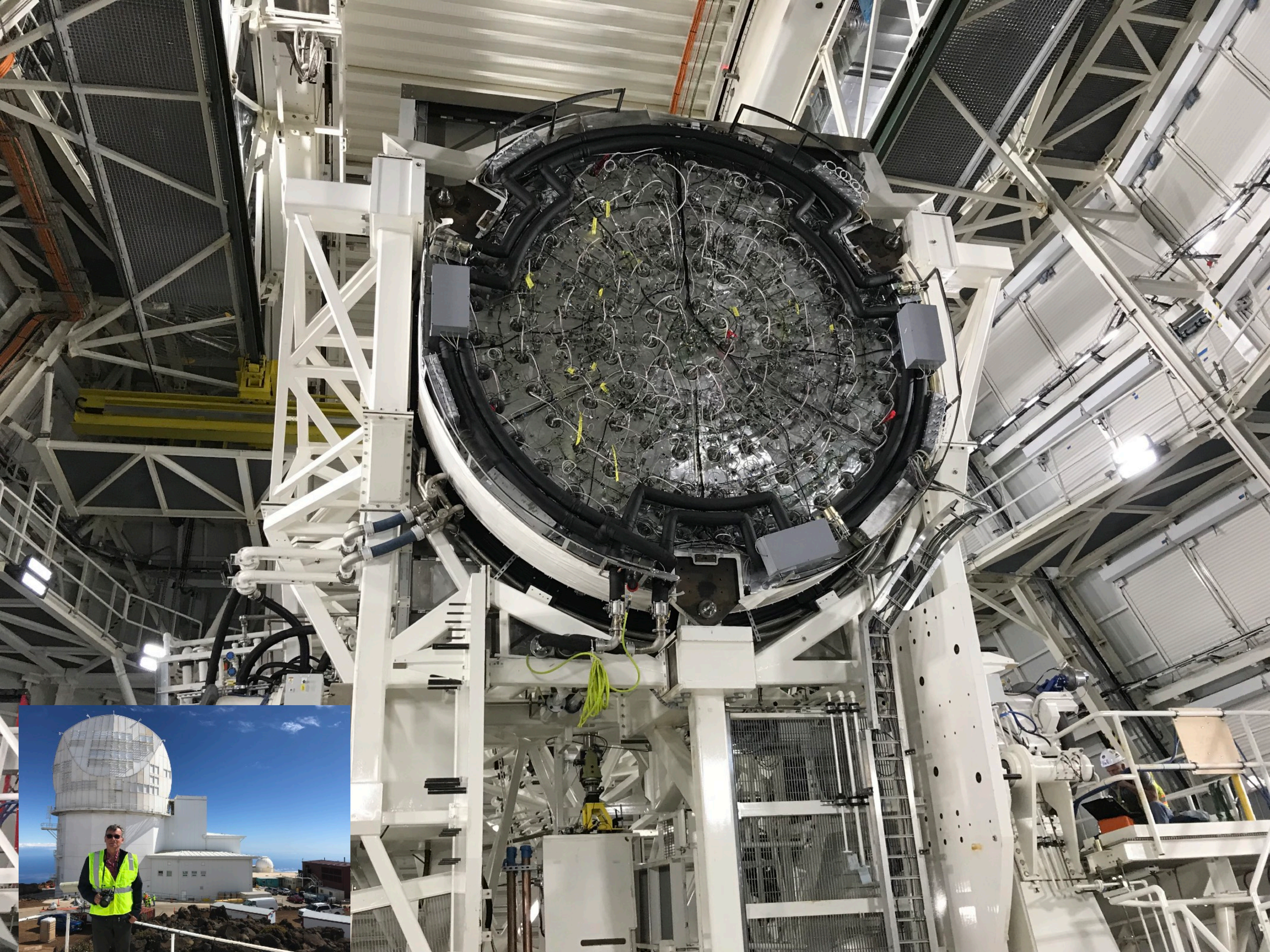
Largest solar telescope in the world

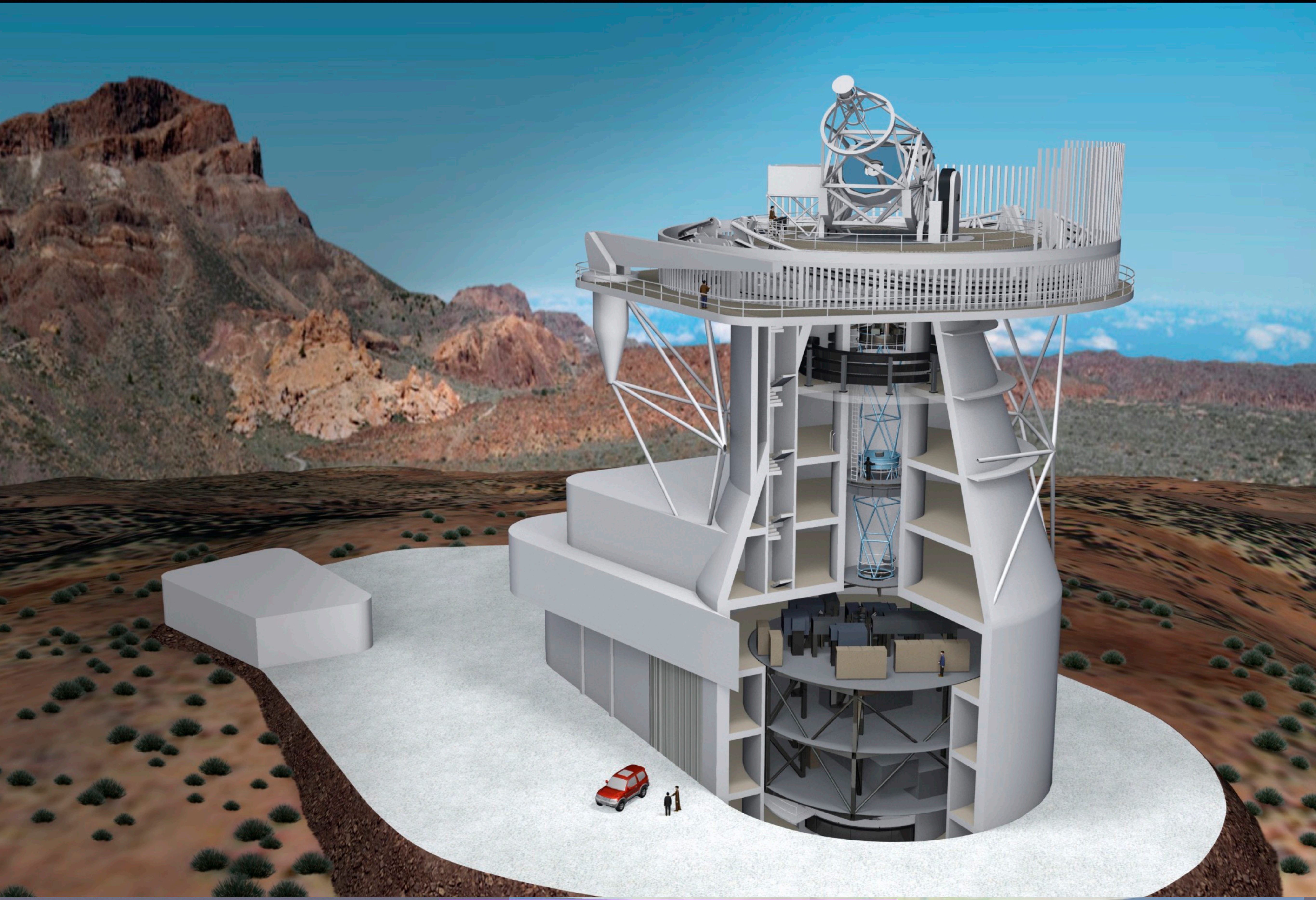
DKIST in a nutshell:

- Fully funded by NSF
- US project, with participation from KIS and from the UK
- Under construction at Maui (Hawaii)
- Four meter aperture, off-axis optical design
- Closed dome, actively cooled
- 5 Instruments (2 grating spectro-polarimeters for VIS and NIR, 1 broadband imager, 1 spectrogaph for IR, 1 filter spectro-polarimeter
- KIS: Filter spectro-polarimeter VTF (11 M€)
- Total cost 345 M$ (w/o VTF)
- First light Autumn 2019 (Telescope + imager)
- Critical Science Plan established

DKIST

DKIST - begin of construction

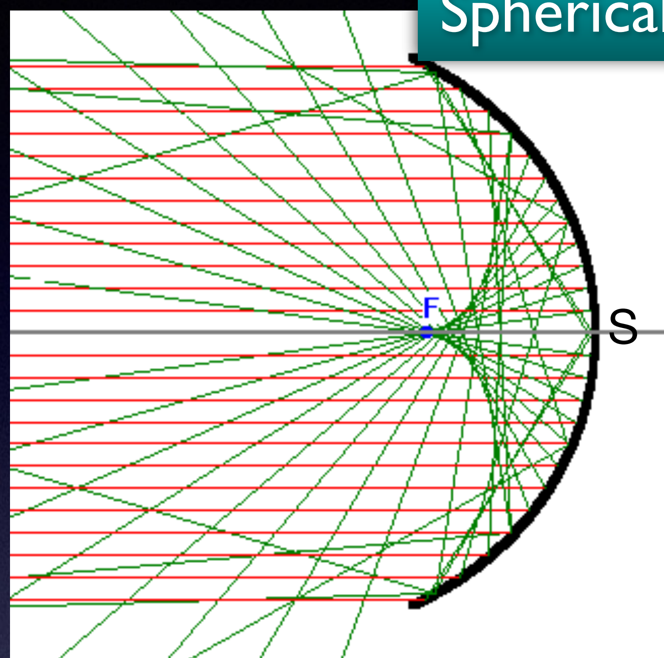




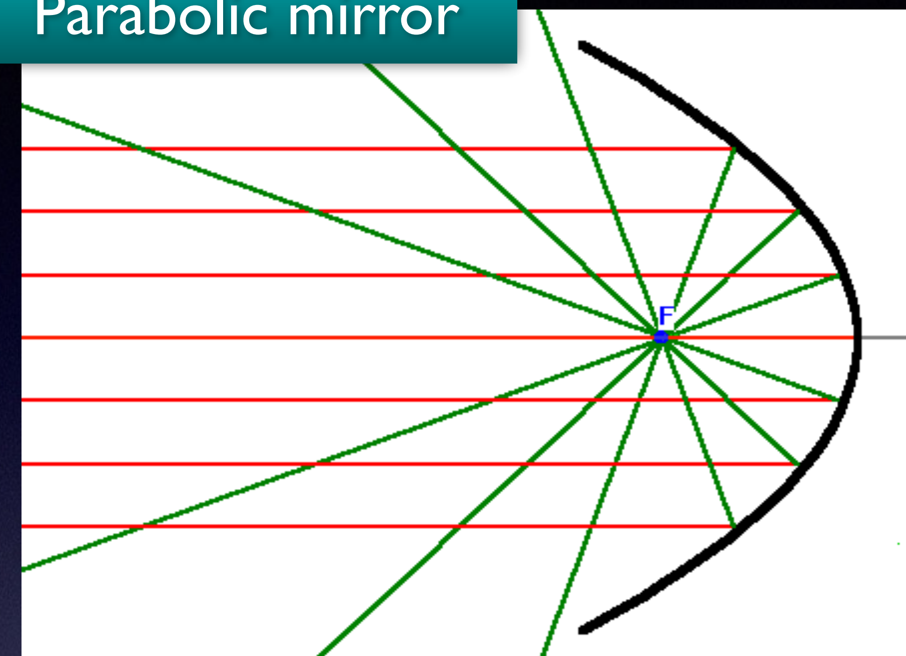
http://www.est-east.eu/est/

Spherical aberration

Spherical mirror



Parabolic mirror



- Rays parallel to the optical axis hitting a spherical mirror: reflected rays close to the optical axis meet in the focal point, whereas rays further away from the OA intersect in a curved envelope called „caustics“ (Katakaustik in German). This behavior is called „spherical aberration“. The tip of the caustics envelope coincides with the focal point of the mirror.

- A parabolic mirror has no spherical aberrations, i.e., it reflects all incoming rays in the focal point. Instead, it suffers from astigmatism and coma. (All single mirror systems suffer from at least one kind of aberration)

Aberrations (contd.)

- Aberrations are not imperfections of optical systems, which could be eliminated or avoided in a perfect system. They are intrinsic properties of optical systems
- Correction or compensation is partially possible (e.g., achromatic lenses, aspherical lenses, …)
- Practical description: Seidel Aberrations of 3rd grade (tip, tilt, focus, coma, astigmatism, …)
- Mathematical description of aberrations uses suitable polynomials (Legendre, Bessel, Fourier, Zernike, Karhunen-Loeve)
    - Low-order Zernikes coincide with Seidel aberration

Adaptive optics needed!

Only AO enables high angular resolution (better than 0.3 arcsec)!
The raw images of a 2 meter telescope have the same angular resolution as those of a 40 cm telescope!

Solutions:

(I) Avoid Earth atmosphere: Hubble, Sunrise

(II) Use adaptive optics

The idea

Babcock, 1953, „The possibility of compensating astronomical seeing“

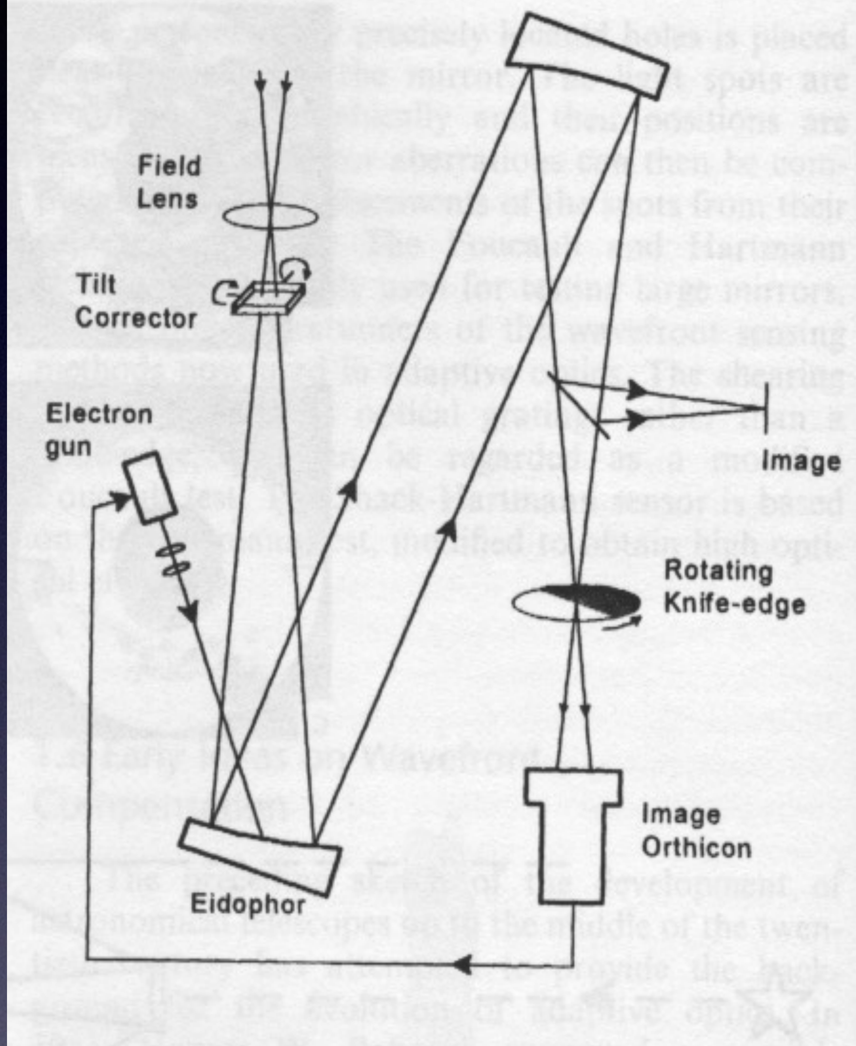


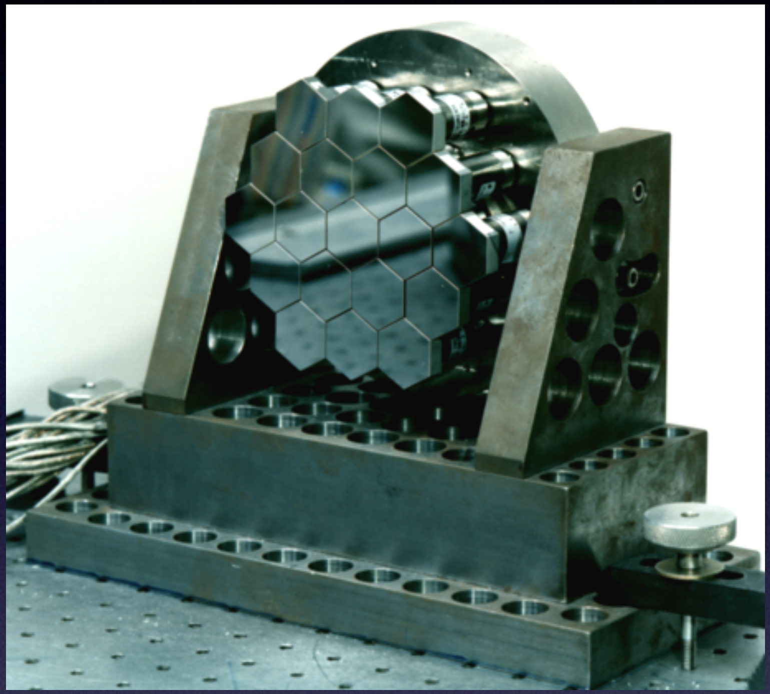
Figure 1.6 Seeing compensator proposed by Babcock [1953]. The wavefront received from a star is analyzed by a rotating knife-edge and an image orthicon detector tube. Correction signals are fed back in real time to change the optical thickness of an electronically deformed oil film on the Eidophor mirror, thereby compensating the wavefront disturbances.

Eidophor

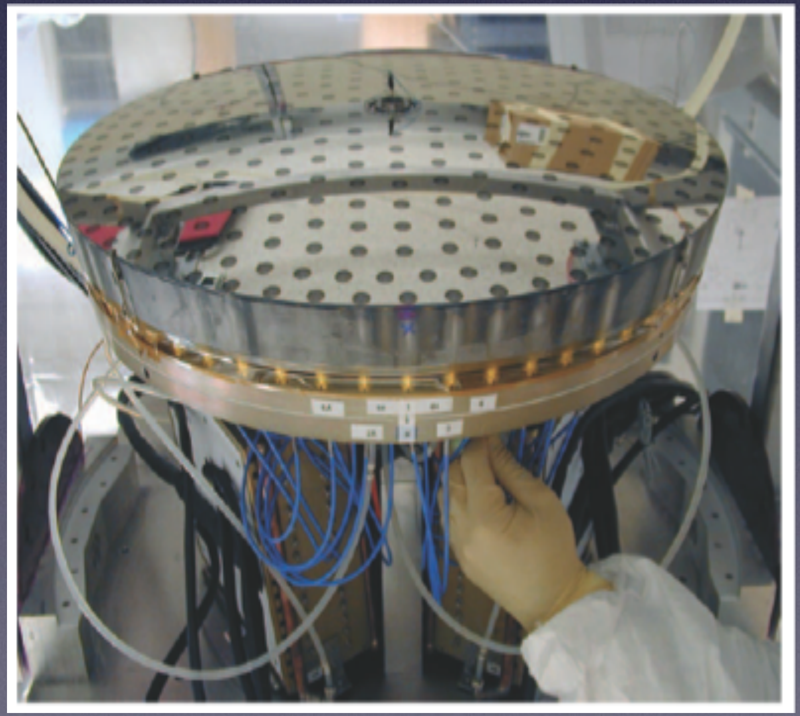
A few µm oil film on a mirror is locally deformed by fast electrons (Fritz Fischer, Swiss patent, 1939)

Eidophor for TV projection

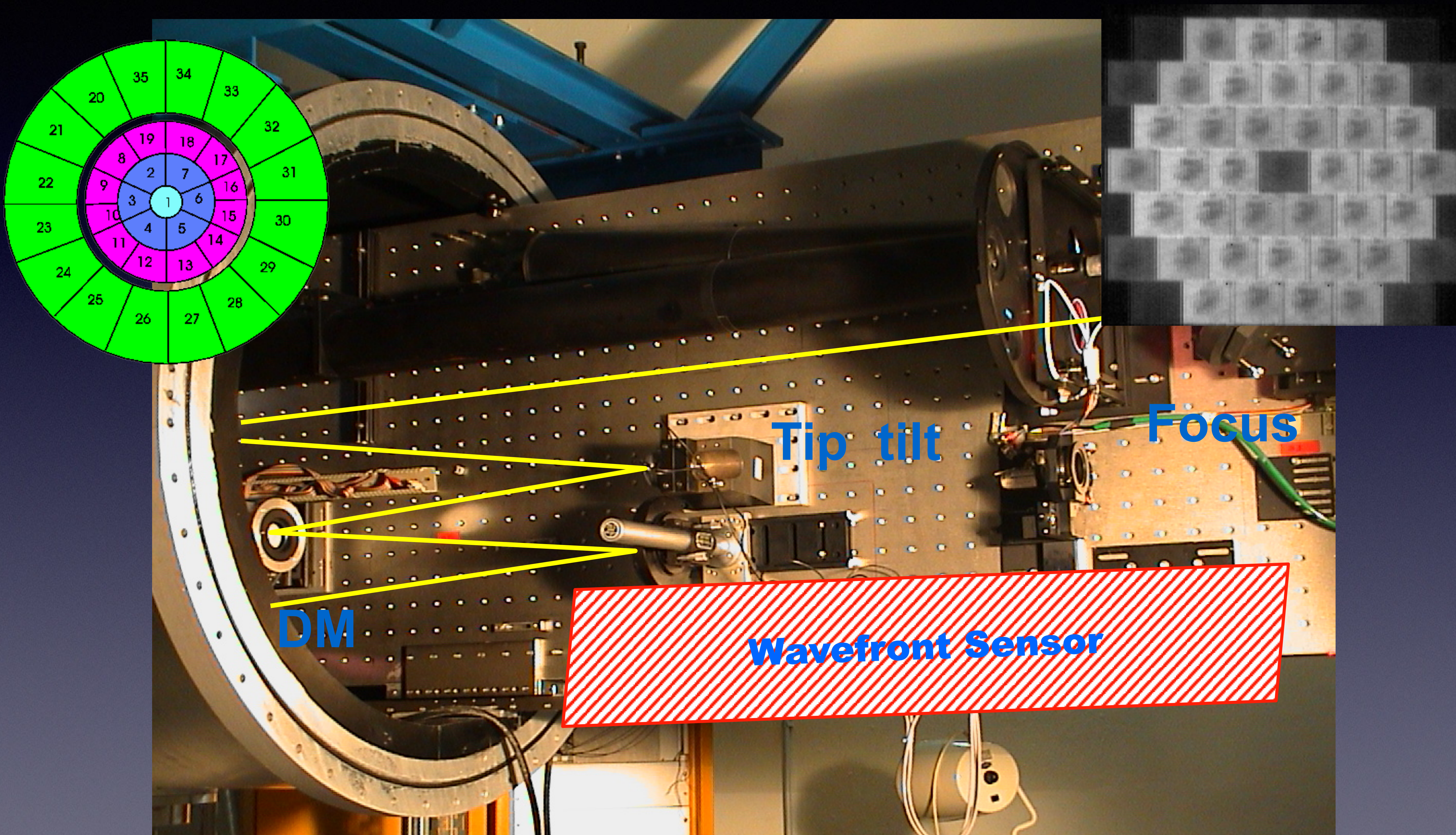
Hardware for wavefront correction

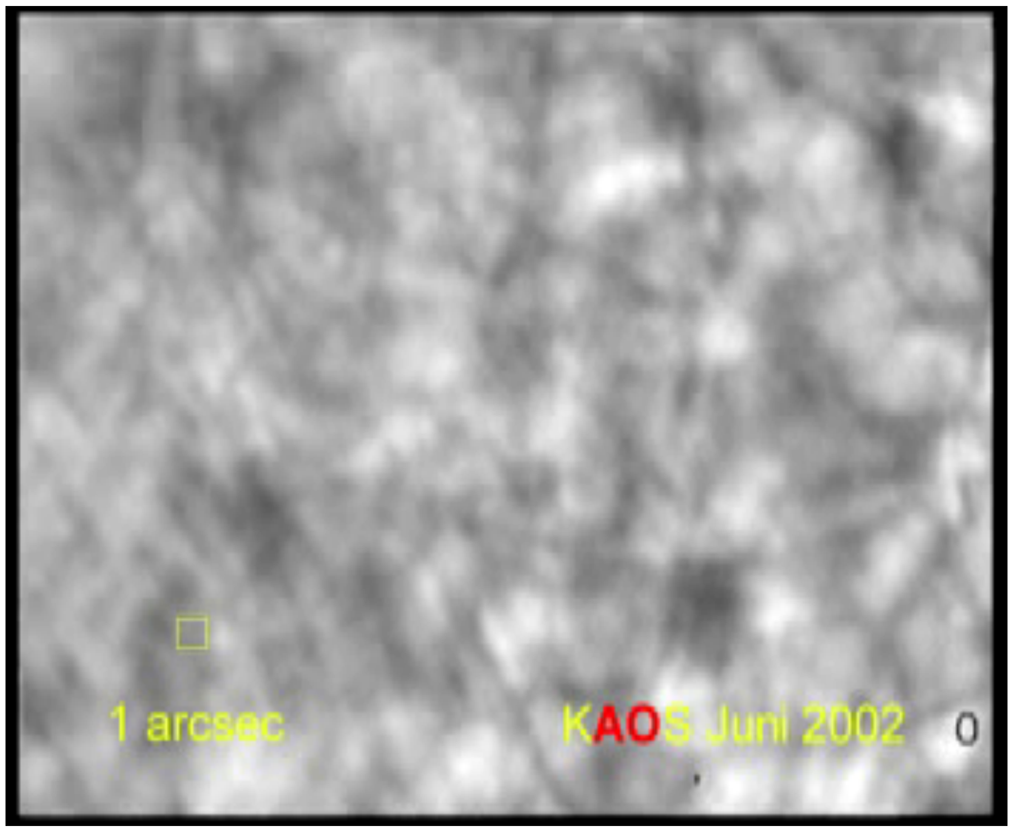


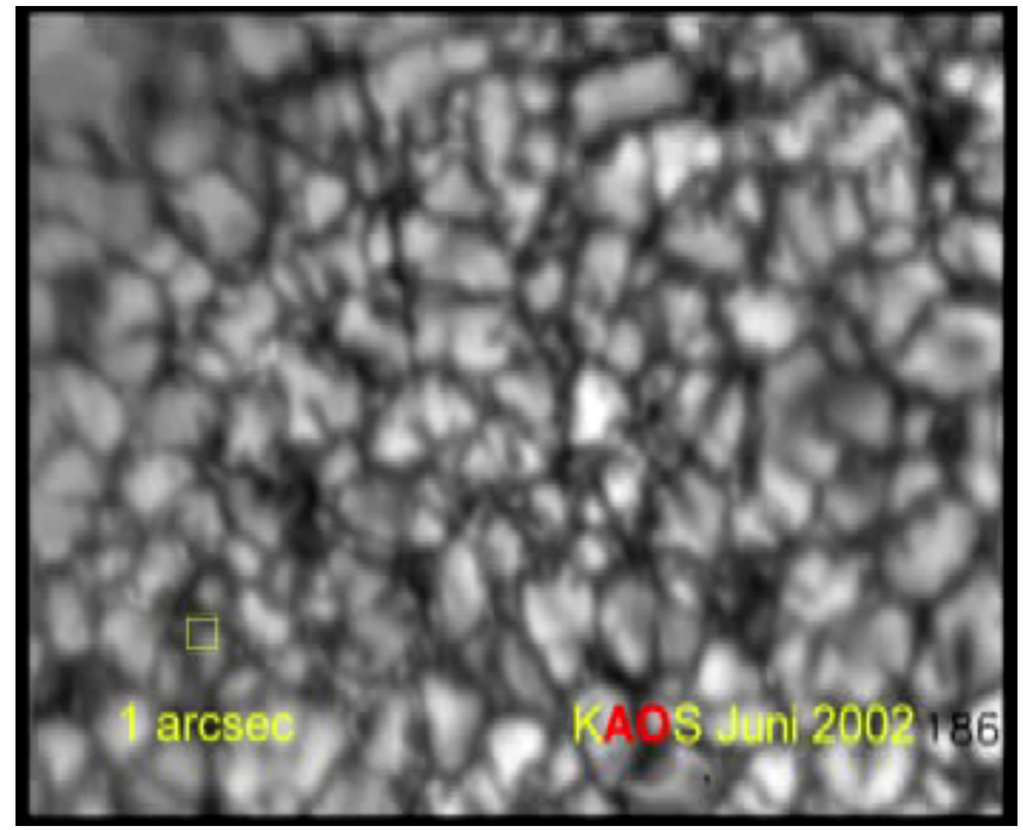
Lockheed 19-segment mirror, successfully used at the VTT in the early 90s (Acton, Soltau, Schmidt, 1996)



KAOS – Kiepenheuer-Institut Adaptive Optics System at the VTT







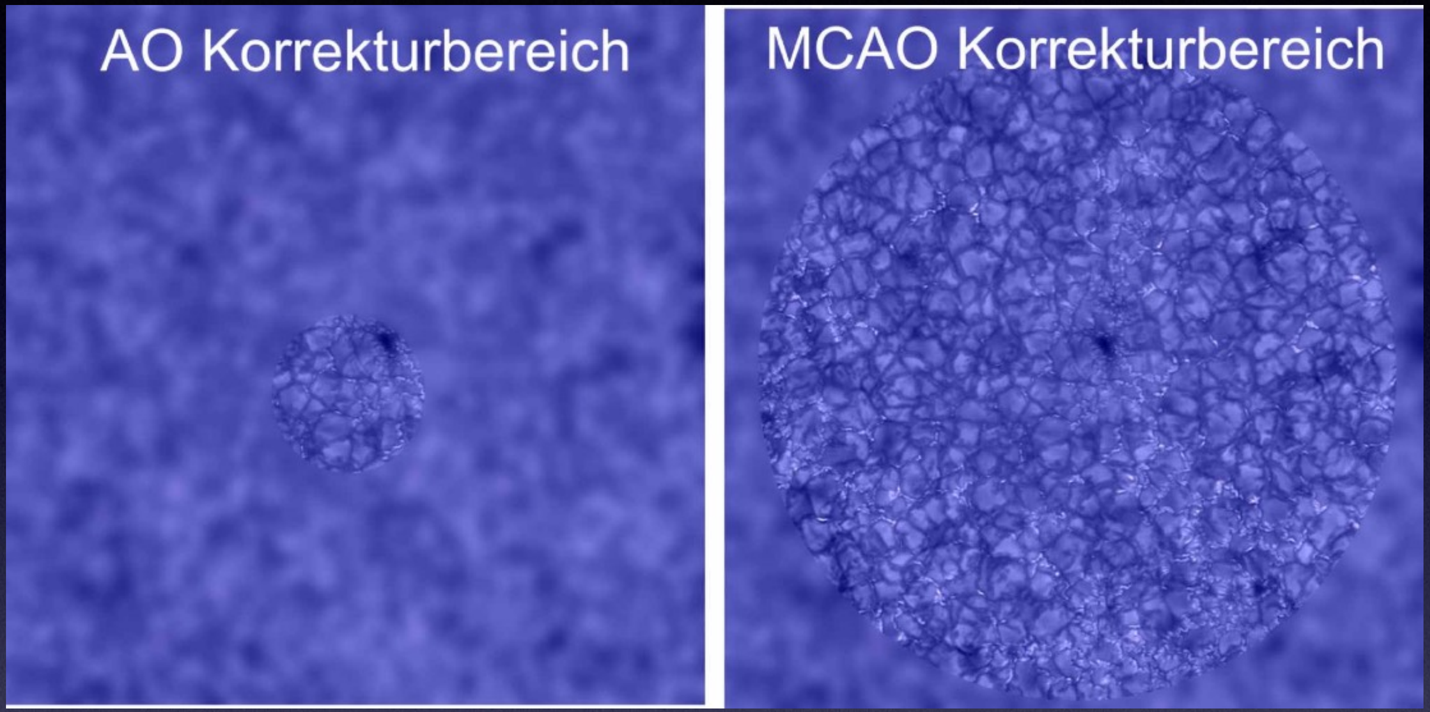
„Bimorph deformable mirror with 35 actuators (LaPlacian Optics)

Shack-Hartmann WFS with 36 subapertures, 12 arcsec field of view each

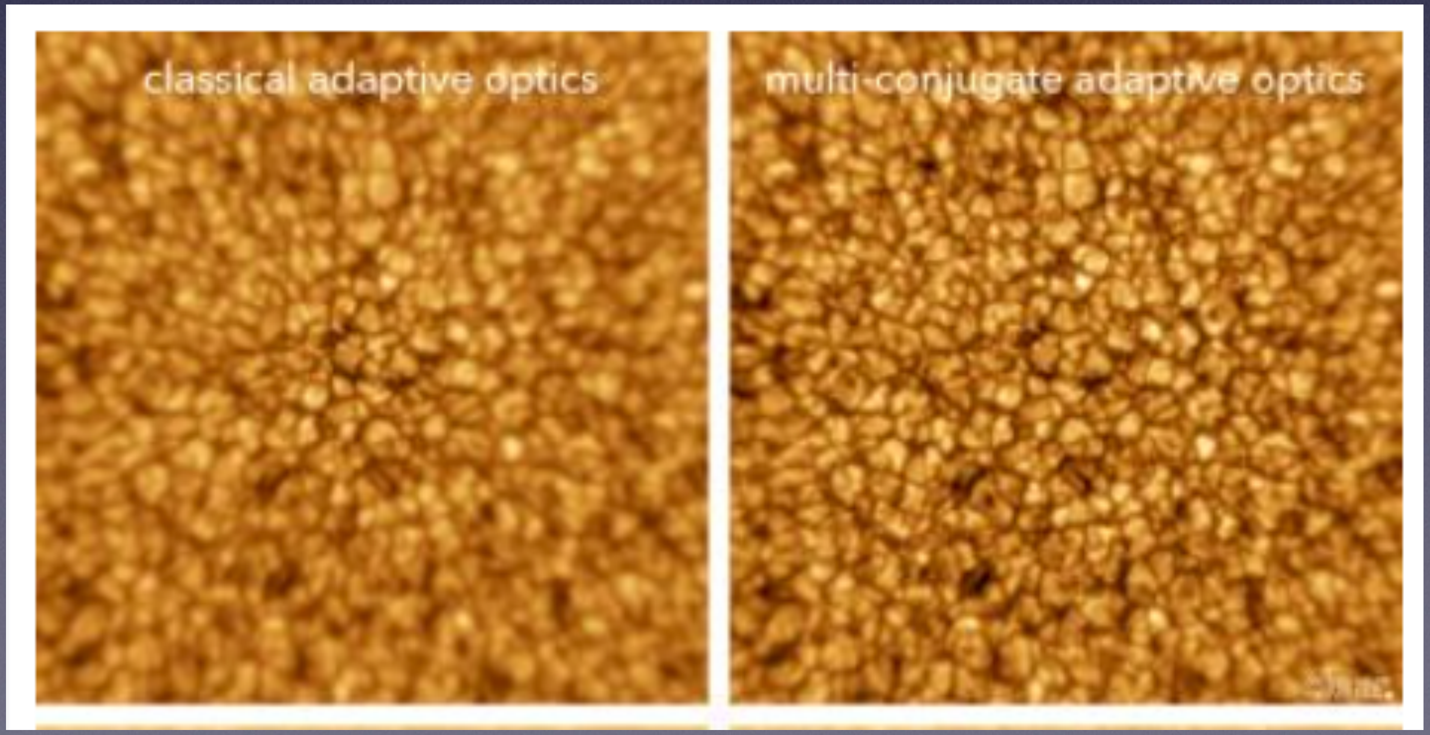
Corrects static und dynamical instrumental aberrations und seeing

Stabilizes image motion (correlation tracker)

New development: MCAO

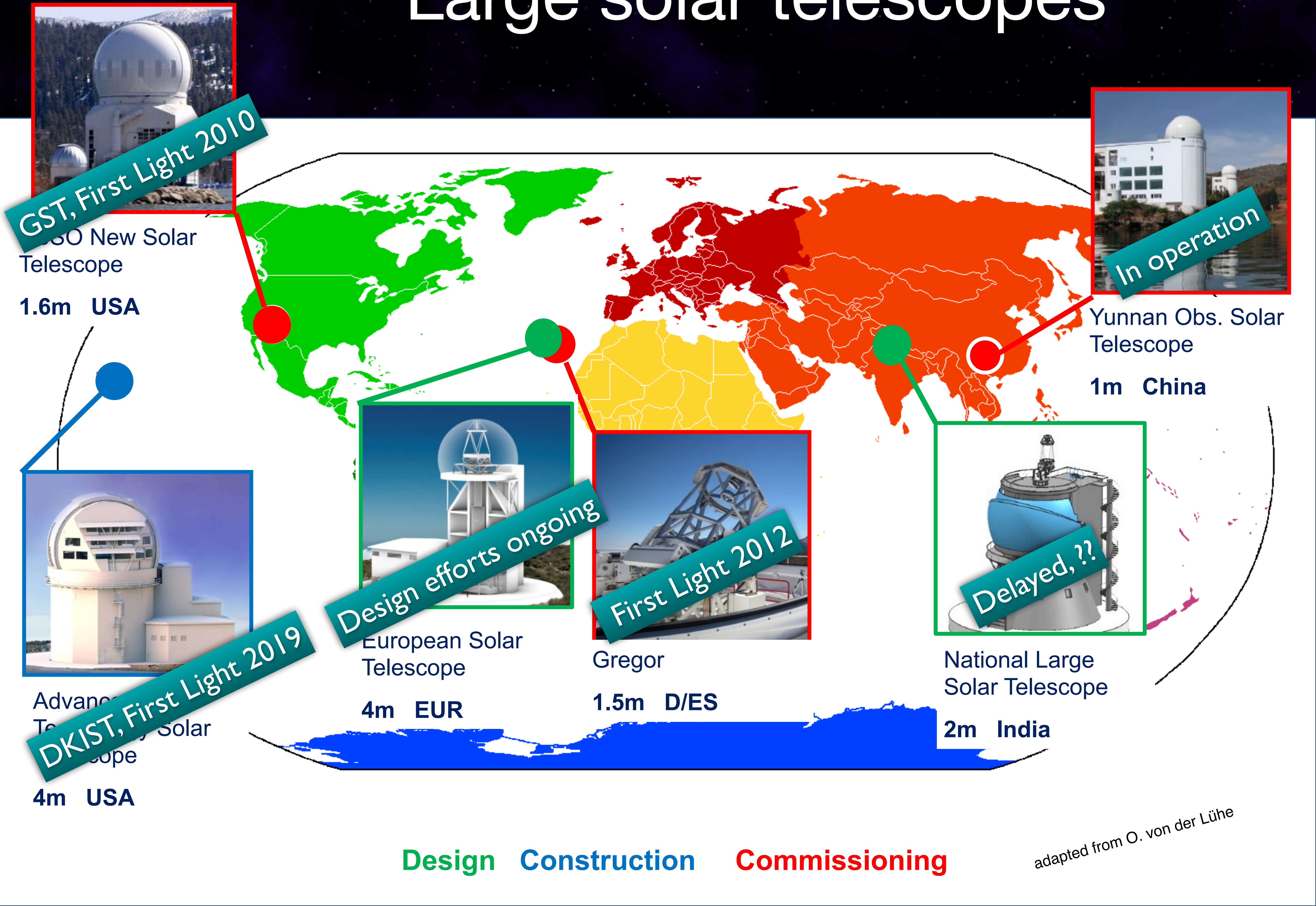


Schematic



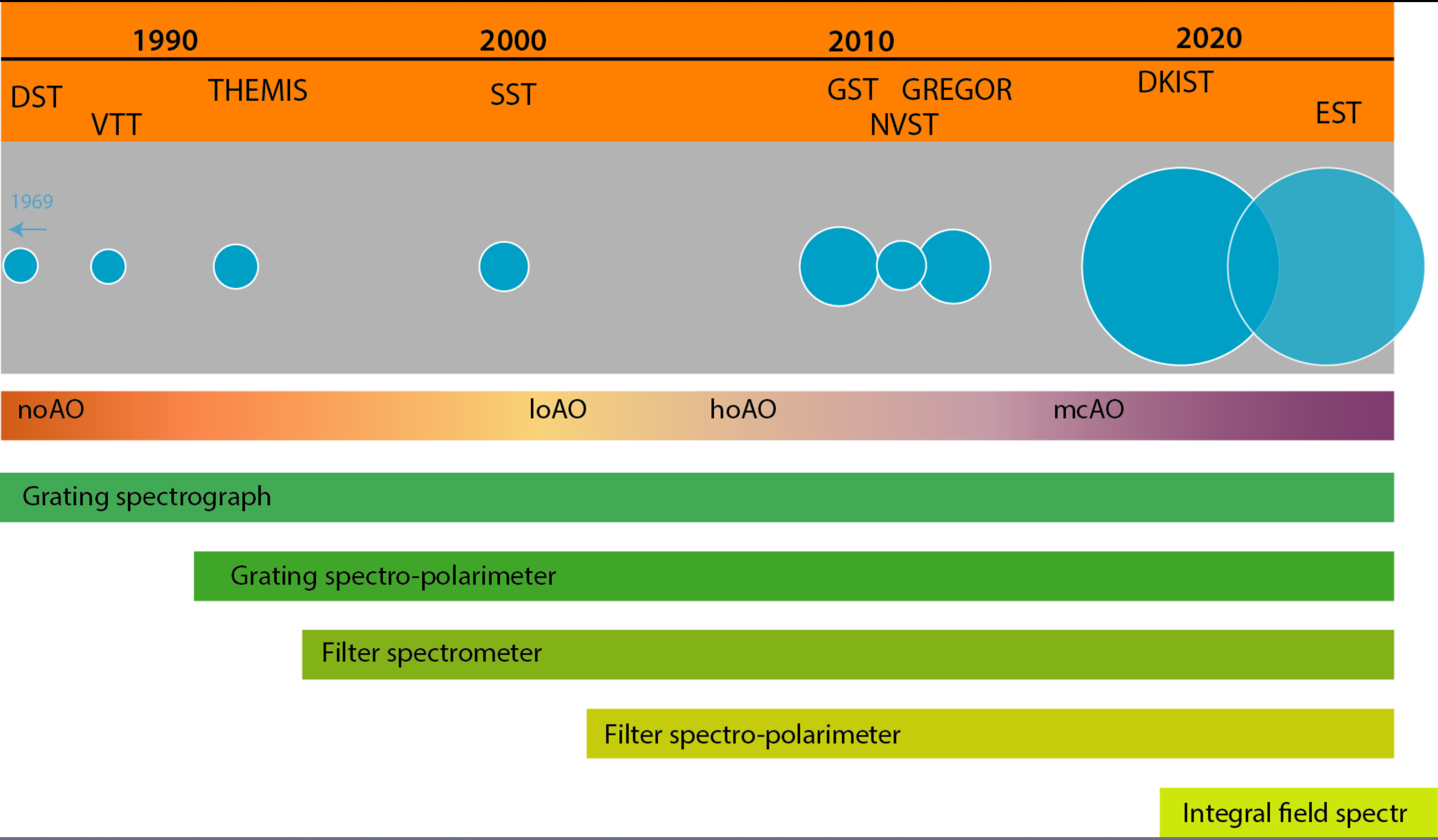
Real: GST, 2017

Large solar telescopes

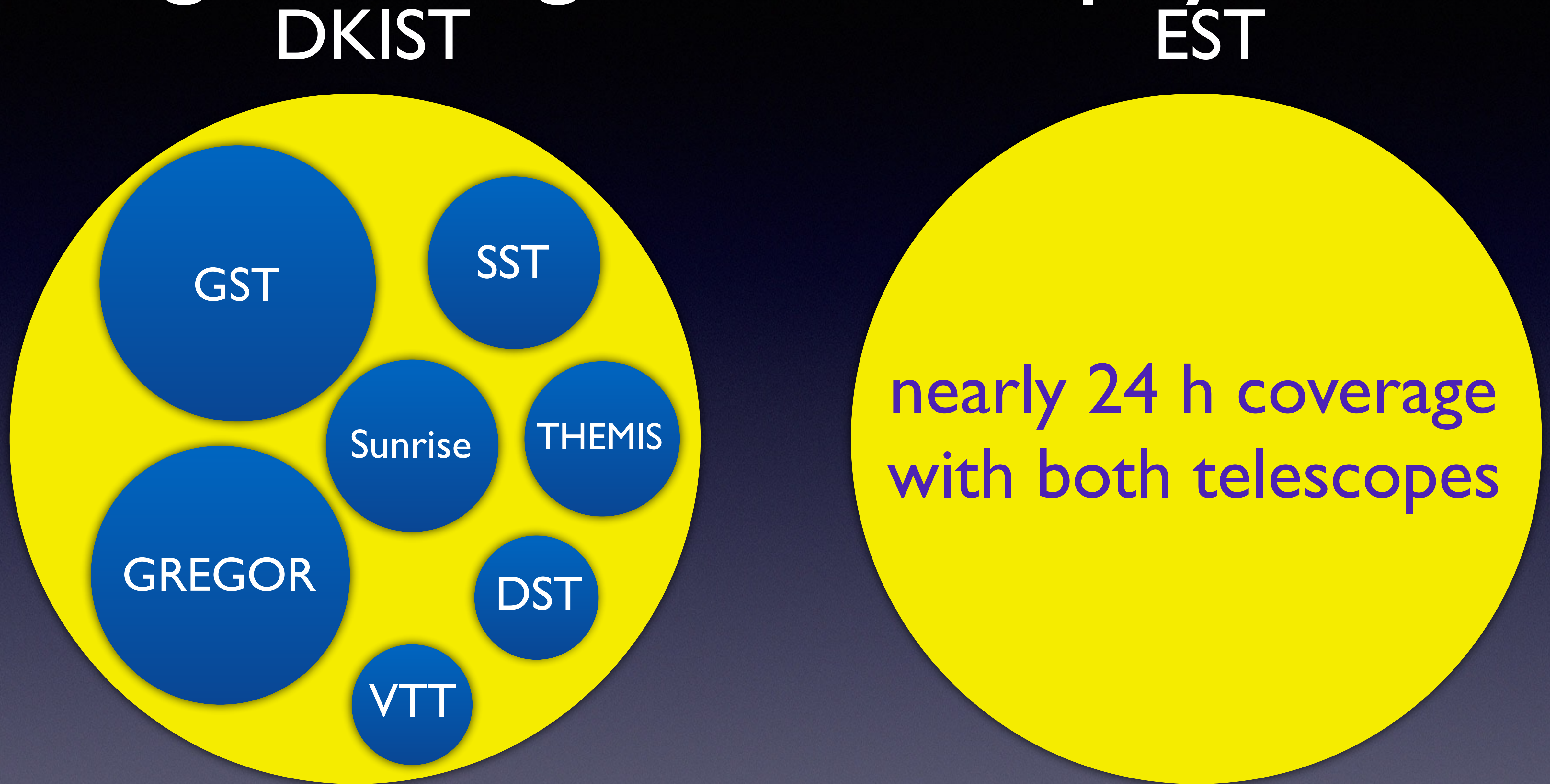


Large Solar telescopes

stagnation & progress



A golden age for solar physics



The DKIST and the EST each have (or will have) twice the photon-collecting power of all major solar telescopes (>70 cm) together