GREGOR
Telescope, AO, BBI

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CASSDA School, April 20\textsuperscript{th}, 2015
The demand for high spatial resolution
Show the simulations the truth?

Courtesy Oskar Steiner, KIS
Show the simulations the truth?

Solar Tornado

Credits: Wedemeyer-Böhm (2012). Image produced with VAPOR
High Resolution
Diffraction Limited Resolution

\[ \theta = 1.22 \frac{\lambda}{D} \] [\text{rad}]

Example:
\[ \lambda = 550 \text{ nm} \]
\[ D = 1 \text{ m} \]

\[ \theta = 0.67 \ \mu\text{rad} = 0.14 \text{ arcsec} \]

http://www.olympusmicro.com/primer/anatomy/numaperture.html
By the way: There is no free lunch

- Number of photons per arcsec\(^2\) \(\propto T \times D^2\)
- Size of the resolution element in arcsec\(^2\) \(\propto 1/ D^2\)

The number of photons per resolution element [arcsec\(^2\)] is a function of throughput not of diameter
Strehl

Strehl > 0.6  „good“
Strehl > 0.8  „diffraction limited“

[Diagram showing light intensity and Strehl factor comparison]
GREGOR Modulation Transfer Function (MTF)
Aperture, f-ratio, field of view

- Desired resolution at 550 nm: 0.1 arcsec
  - $\rightarrow$ $D = 1.4$ m
- Pixel size = 10 µm
  - $\rightarrow$ image scale = 0.1 arcsec/20 µm = 5 arcsec/mm
  - $\rightarrow$ $f = 41.2$m
  - $\rightarrow$ f-ratio = $f/30$
- Number of pixels = 4096
  - $\rightarrow$ FOV = 200 arcsec

**Image scale [arcsec/mm]** = $\frac{1\text{ mm}}{5 \text{ arcsec}}$ = $\frac{206270}{f\text{[mm]}}$
Three types of mirror telescopes

Newton

Cassegrain

Gregory
Optical Design 1
The Simple Solution
McMath-Pierce, f/54

McMath-Pierce Solar Telescope Facility

f=86 m
McMath-Pierce (Lazy Seven, f/54)
Vacuum Tower Telescope (VTT)

D = 0.7 m
f = 45 m
f/64
VTT optical layout

3D Layout

VTT fov = 600 arcsec
19.03.2015

D. Soltan
KIS

VTTonly.png
Configuration:
SOLIS: A solar Cassegrain telescope
The Gregory Coudé telescope

\[ D = 0.45 \text{ m} \]
\[ f = 25 \text{ m} \]
\[ f/55 \]
From Gregory to GREGOR

- Has to be shorter than 4 m to fit into dome
- Diameter: 1.5 m
  - $f/#$ of primary appr. 2
  - Diffraction limited resolution = 0.08 arcsec
- Central obscuration < 0.3 $\iff f/# M2 > 1$
- Secondary focus F2
Heat load in a solar telescope focus

- Solar power density (max) 0.1 W/cm²

In any solar telescope focus:

\[
power \text{ density magnification} \approx 10000 \left( \frac{D}{f} \right)^2
\]

Table 4.1 Heat intensity and maximum temperature related with different welding processes

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Welding process</th>
<th>Heat density (W/cm²)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gas welding</td>
<td>$10^2 - 10^3$</td>
<td>2500-3500</td>
</tr>
<tr>
<td>2</td>
<td>Shielded meta arc welding</td>
<td>$10^4$</td>
<td>&gt;6000</td>
</tr>
<tr>
<td></td>
<td>Gas metal arc welding</td>
<td>$10^5$</td>
<td>&gt;8000-10000</td>
</tr>
<tr>
<td>3</td>
<td>Plasma arc welding</td>
<td>$10^6$</td>
<td>15000-30000</td>
</tr>
<tr>
<td>4</td>
<td>Electron beam welding</td>
<td>$10^7 - 10^8$</td>
<td>20,000-30000</td>
</tr>
<tr>
<td>5</td>
<td>Laser beam welding</td>
<td>$&gt;10^9$</td>
<td>&gt;30,000</td>
</tr>
</tbody>
</table>

Power density in GREGOR F1 ≈ 300 W/cm² !!
Optical Design

D = 1.5 m
f/40
## Power mirrors

<table>
<thead>
<tr>
<th></th>
<th>Radius of curv.</th>
<th>Conic const</th>
<th>f/#</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>-5013 mm</td>
<td>-1</td>
<td>f/1.8</td>
</tr>
<tr>
<td>M2</td>
<td>-1039 mm</td>
<td>-0.306</td>
<td>f/1.2</td>
</tr>
<tr>
<td>M3</td>
<td>-2797 mm</td>
<td>-0.538</td>
<td>f/4</td>
</tr>
</tbody>
</table>

### Foci (FOV = 150 arcsec)

<table>
<thead>
<tr>
<th></th>
<th>f/#</th>
<th>Image scale</th>
<th>Magn.</th>
<th>FOV</th>
<th>Power</th>
<th>Power dens.</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>1.8</td>
<td>82 arsec/mm</td>
<td>1.8 mm</td>
<td>1.8 mm</td>
<td>1600 W</td>
<td>300 W/cm²</td>
</tr>
<tr>
<td>F2</td>
<td>6</td>
<td>23.6 arcsec/mm</td>
<td>3.5</td>
<td>6.3 mm</td>
<td>10 W</td>
<td>30 W/cm²</td>
</tr>
<tr>
<td>F3</td>
<td>40</td>
<td>3.6 arcsec/mm</td>
<td>6.6</td>
<td>41.6 mm</td>
<td>4 W</td>
<td>0.3 W/cm²</td>
</tr>
</tbody>
</table>
Optical quality in F1 (FOV = 200")

Scatter diameter: 150 µm = 12 arcsec
Optical quality in F2 (FOV = 200")

Scatter diameter: 40 µm = 1 arcsec

30 W/cm²
Optical quality in F3 (FOV = 200")

Scatter diameter:
20 µm = 0.07 arcsec

0.7 W/cm²
Overview of telescope structure and optical path

Dr. Reiner Volkmer, Kiepenheuer Institut für Sonnenphysik, Freiburg
Telescope structure

- Sun heats structure and mirrors $\rightarrow$ open telescope and completely foldable dome (telescope in free air flow). *Telescopes with 1.5 m free aperture and evacuated light path are very difficult to build*.

- Full performance at wind speeds up to 20 m/s with relative pointing error (rms): 0.5” (open loop)

- Temperature difference to ambient : $\Delta T < -0.5$ K
Structure
Why Silicon Carbide main mirrors?

- solar radiation on surface of 1.5 m main mirror: **2000 W**
- $\Delta T$ mirror – ambient temperature should be < 1K (internal seeing)
- heating of mirrors is critical !!!
- silicon carbide has high thermal conductivity:
  
  $$K(\text{silicon carbide}) \sim 100 \times K(\text{Zerodur})$$

- silicon carbide mirrors can be "thinned" and structured (high stiffness)
  - ► light weight mirror (M1 ~ 90 kg) ➔ faster reaction on temperature changes
  - ► removal of heat on back side

- GREGOR: Primary, secondary and tertiary are silicon carbide mirrors
Mirror seeing - Mirror Cooling

• Heat transfer by thermal conductivity:

\[ \dot{Q} = \frac{\lambda}{d} A \cdot \Delta T \]

\(d\) = thickness
\(A\) = area

<table>
<thead>
<tr>
<th>Material</th>
<th>(\lambda) [W/(mK)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.03</td>
</tr>
<tr>
<td>Glass</td>
<td>0.76</td>
</tr>
<tr>
<td>Cesic</td>
<td>121</td>
</tr>
<tr>
<td>Zerodur</td>
<td>1.46</td>
</tr>
<tr>
<td>Copper</td>
<td>403</td>
</tr>
</tbody>
</table>

Example M1: Zerodur
\(D = 30\) mm
\(A = 1.7\) sqm
\(\Delta T = 3\) K
\(\Rightarrow\) \(\frac{dQ}{dt} = 250\) W

Example F1 heat stop: Copper
\(D = 10\) mm
\(A = 0.0005\) sqm
\(\Delta T = 10\) K
\(\Rightarrow\) \(\frac{dQ}{dt} = 200\) W
Primary mirror and field stop cooling
Thermal control system
The enemy
Some atmospheric optics
(index of refraction for air)

\[ n(\lambda) = 1 + \left(272.6 + \frac{1.22}{\lambda^2}\right)10^{-6} \]

Wave length dependence of \( n \)

\[ n(r) - 1 = \frac{77.6P}{T}10^{-6} \]

T and P –dependence of \( n \)

Example : \( P=1000 \text{ mbar}, \ T=293 \text{ K} \rightarrow \Delta n=10^{-6} \text{ per degree} \)
Some atmospheric optics (turbulence)

\[ R_e = \frac{\rho \cdot v \cdot d}{\eta} \]

\( \rho \) : density
\( v \) : velocity
\( d \) : spatial scale
\( \eta \) : viscosity

\[ E(k) \propto k^{-11/3} \]

Kolmogorov spectrum

Reynolds number \( R_e \): \( 10^5 \), i.e. . Atmosphere is always turbulent and never laminar

Kolmogorov’s theory of turbulence

van Gogh, „Starry Night“
Some atmospheric optics: structure function

\[ D_n = \left\langle \left[ n_r(\vec{r}_1 + \vec{r}) - n_r(\vec{r}_1) \right]^2 \right\rangle = C_n^2 r^{-2/3} \]

Dn = Structure function \hspace{1cm} C_n^2 = structure constant (unit m^{-2/3} )

\[ C_n^2 \text{ is a function of height} \]

\[ C_n^2 = 10^{-17} \text{ m}^{-2/3} \]

\[ C_n^2 = 10^{-14} \text{ m}^{-2/3} \]
$C_n^2$ profile (Example Hufnagel model)

$$C_n^2(h) = \begin{cases} \left(2.210^{-53}\right)h^{10}\left(\frac{W}{27}\right)^2 e^{-h/1000} + 10^{-16} e^{-h/1500}\end{cases} e^{r(h,t)}$$

$$W = \left[\frac{1}{15\text{km}} \int_{5\text{km}}^{20\text{km}} v^2(h) dh\right]^{1/2}$$
Fried’s Parameter $r_0$

$$r_0 = \left[ 0.423 k^2 \sec(\beta) \int_0^L C_n^2(h) dh \right]^{-3/5}$$

$r_0$ is a kind of atmospheric “aperture”

$$k = \frac{2\pi}{\lambda}$$

$$r_0 \propto \lambda^{6/5}$$

$$\sigma_{\text{tilt}}^2 = 0.364 \left( \frac{D}{r_0} \right)^{5/3} \left( \frac{\lambda}{D} \right)^2 \left[ \text{rad}^2 \right]$$

Übrigens: Allein die Korrektur für tip/tilt halbiert die durch die Turbulenz verursachte Varianz
Measuring $r_0$ (example)

$$\sigma_{\text{tilt}}^2 = 0.364 \left( \frac{D}{r_0} \right)^{5/3} \left( \frac{\lambda}{D} \right)^2 \text{[rad}^2\text{]}$$
DIMM = „Differential image motion monitor“
Adaptive Optics: The Idea

• Babcock (1953): *The possibility of compensating astronomical seeing*

Horace Welcome Babcock, 1912 - 2003
Adaptive Optics: An Additional Requirement for a Telescope Design

We need a pupil image

→ Relay Optics

http://lyot.org/background/adaptive_optics.html
GREGOR AO System: GAOS
GAOS: How many actuators do we need?

Subaperture: 10 cm x 10 cm
How large is the corrected FOV?

\[
\theta = 0.314 \frac{r_0}{H}
\]

Example: \( r_0 = 10 \text{ cm} \)
\( H = 2 \text{ km} \)

\( \theta = 1.6 \times 10^{-5} \text{ rad} = 3 \text{ arcsec} \)
Deformable mirror

DM Characteristics
• stacked-Piezo, made by CILAS
• 256 actuators, 196 illuminated
• 48mm illuminated diameter
• 5μm stroke
• 3.2mm actuator pitch
• new glueing technology
• first resonance frequency > 10 kHz
CILAS DM: 256 actuators

Figure 1: Waffle mode as tested in Orléans
Shack Hartmann WFS
Solar AO

- Target: Granulation
  - Intrinsic contrast: 14%
  - in telescope 2% bis 5%
  - structure size typical 2"

Observations mostly done in the visible and near infrared
Minimum size of subaperture?

![Graph](image)

19.04.2015
Data for 0.5500 to 0.5500 μm.
Surface: Image
Bottle neck: The WFS camera

1600 fps
Night time AO performance
Night time performance with AO

FWHM = 0.2 arcsec
Multi Conjugate AO for GREGOR
Back end instruments

- GRIS
- GFPI
- BBI (Broad Band Imager)
Broad Band Imager

- From telescope
- BS
- F4
- Collim. f = 400 mm
- BS
- Pupil
- Filter (wheel)
- Camera f = 486 mm
- Detector 1: PCO Sensicam
- Detector 2: (PCO 4000)
Broadband Imager
First Results - BBI

- June 2013, parallel with Sunrise flight
- Courtesy A. Lagg, R. Schlichenmaier, M. Franz
Summary

• GREGOR provides world class observing capabilities. It is:
  – A large telescope
  – at an excellent site
  – fully equipped with AO and back
  – beside an excellent VTT

...waiting for your exciting ideas