GREGOR telescope – start of commissioning

R. Volkmer[*a], O. von der Lühe[a], C. Denker[b], S. Solanki[c], H. Balthasar[b], T. Berkefeld[a], P. Caligari[a], M. Collados[d], C. Halbgewachs[a], F. Heidecke[a], A. Hofmann[b], M. Klvana[e], F. Kneer[f], A. Lagg[c], E. Popow[b], D. Schmidt[a], W. Schmidt[a], M. Sobotka[e], D. Soltau[a], K. Strassmeier[b]

[a]Kiepenheuer-Institut für Sonnenphysik, Schöneckstr. 6, 79104 Freiburg, Germany;
[b]Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany;
[c]Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Str. 2, 37191 Katlenburg-Lindau, Germany; [d]Instituto de Astrofísica de Canarias, Vía Láctea s/n, 38200 - La Laguna (Tenerife), Spain;
[e]Astronomical Institute AV CR - Ondrejov, Fricova 298, 25165 Ondrejov, Czech Republic;
[f]Institut für Astrophysik Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany;

ABSTRACT

With the integration of a 1-meter Cesic primary mirror the GREGOR telescope pre-commissioning started. This is the first time, that the entire light path has seen sunlight.

The pre-commissioning period includes testing of the main optics, adaptive optics, cooling system, and pointing system. This time was also used to install a near-infrared grating spectro-polarimeter and a 2D-spectropolarimeter for the visible range as first-light science instruments. As soon as the final 1.5 meter primary mirror is installed, commissioning will be completed, and an extended phase of science verification will follow. In the near future, GREGOR will be equipped with a multi-conjugate adaptive optics system that is presently under development at KIS.

Keywords: mirror cooling, mirror support, actuators, solar telescope

1. INTRODUCTION

The GREGOR[1] project was initiated in 2002 by the Kiepenheuer-Institut für Sonnenphysik, Freiburg, the Institut für Astrophysik, Göttingen (IAG, former Universitäts-Sternwarte, Göttingen), and the Astrophysikaliche Institut Potsdam (AIP). GREGOR would replace the already 40 years successfully working solar Gregory-Coudé Telescope (GCT). The GCT was widely used by the solar community, but the 45-cm diameter aperture of the evacuated telescope was too small to resolve the theoretically expected small-scale magnetic features on the solar surface.

In 2002 the construction of GREGOR started with dismantling of the old telescope and its dome. In order to adapt the building to the much larger telescope the top floor had to be replaced by a stiffer construction. A Gregory-coudé design was chosen for the 1.5-meter aperture telescope to optimize spatial resolution and throughput. Because of this large free aperture a paradigm change was necessary, away from evacuated telescope towards a telescope with an open structure. The new telescope will be the largest completely open telescope for solar observations in the wavelength range from visible to near infrared.

The GREGOR primary mirror will receive about 2000 W solar radiation. A small portion of about 10 % will be absorbed and increases the primary mirror temperature if this is not suppressed by suitable cooling. The thin face sheet of the mirror allows removal of heat from the backside with cold air blowing into the pockets of the light-weighted mirror blank. The absorbed heat is removed by a water-cooled heat exchanger mounted on the backside of the mirror support system (mirror cell). The water is pre-cooled by the central air condition system of the observatory.

[*] volkmer@kis.uni-freiburg.de; phone: ++49-761-3198316; FAX: ++49-761-3198316; kis.uni-freiburg.de

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Figure 1. GREGOR telescope facing the Sun, with open dome. The dome on the left of the picture is from the ESA optical ground station (OGS). The bright spot inside the telescope structure is the reflection of the incident sunlight off the field stop.

The telescope structure is a stiff and open Serrurier system[2] allowing the frequently blowing winds to pass and remove the remaining warm air from the front side of the mirrors. The completely retractable[3] dome facilitates wind flushing through the telescope to support the cooling of the telescope structure and optics (see Figure 1).

The new dome and the telescope structure without optics were ready in 2004. During the following years the complete optics were integrated with the exception of the primary mirror. In March 2009 a 1-meter primary mirror was integrated to start the preliminary commissioning of the telescope until the final 1.5-meter Zerodur mirror is ready.

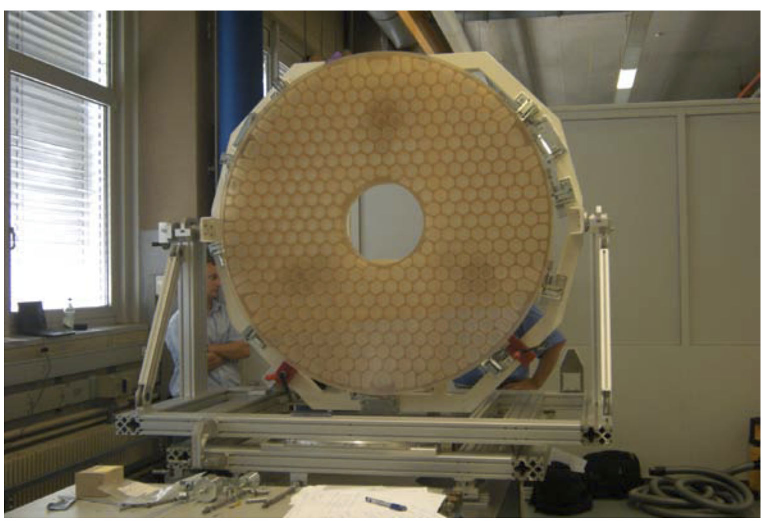


Figure 2. Light-weighted Zerodur primary mirror blank during testing of its surface quality (final mass 205 kg). The cell pattern of the pockets at the backside shines through the 12 mm thin transparent face sheet.

The temporarily mounted 1-meter primary mirror is made from Cesic, a silicon carbide material[4]. Cesic has a high stiffness and a high thermal conductivity compared to glass or Zerodur. The good thermal conductivity allows effective cooling of the mirror from the backside. The high stiffness provides good performance, especially during strong wind conditions. It was originally intended to also build the primary mirror from Cesic, but technology problems prevent the production of such a mirror within a foreseeable time. The new primary mirror is a backside-open, light-weighted Zerodur blank (see Figure 2).

With integration of the 1m mirror engineering first-light was achieved. Thus, testing and validating of optical, cooling, and control systems started. This was followed by the integration of the first post-focus instruments. The final 1.5-meter Zerodur primary mirror has been figured and light-weighted at Schott[5]. Polishing started at Zeiss, Oberkochen in summer 2009. Finishing the production is expected in fall 2010 including a pre-integration of the mirror and its cell. Delivery and integration is planned until end of 2010, followed by the final commissioning including science demonstration time at Observatorio del Teide on Tenerife.

2. MAIN OPTICS TESTS

2.1 Optical design

GREGOR is an alt-azimuth mounted telescope with a modified Gregory-coudé configuration (see Figure 3). The parabolic primary mirror M1 forms a solar image at the field stop at the position of the primary focus F1. The nominal field-of-view (FOV) is limited to 150″. The light outside of this FOV is reflected out of the telescope, thus preventing warming up the subsequent optics and decreasing the stray light. The elliptical secondary mirror M2 provides a focus at F2 which it has in common with the also elliptical tertiary mirror M3. A calibration and polarization unit[6] is mounted at the secondary focus. Until F2 the light path is still symmetric and the intrinsic polarization of the optics is still small. A second calibration unit at the exit window of the telescope assures high precision polarimetric observations. The tertiary mirror forms another solar image at the tertiary focus F3. The transfer optics M4 to M7 feed the light through the elevation and azimuth axes into the adaptive optics (AO) system located in an optical laboratory below the telescope platform. The AO system corrects the wavefront of the incoming light. Following the AO the light is distributed to the different post-focus instruments such as the infrared slit spectrometer GRIS[7] and the two-dimensional spectro-polarimeter GFPI[8].

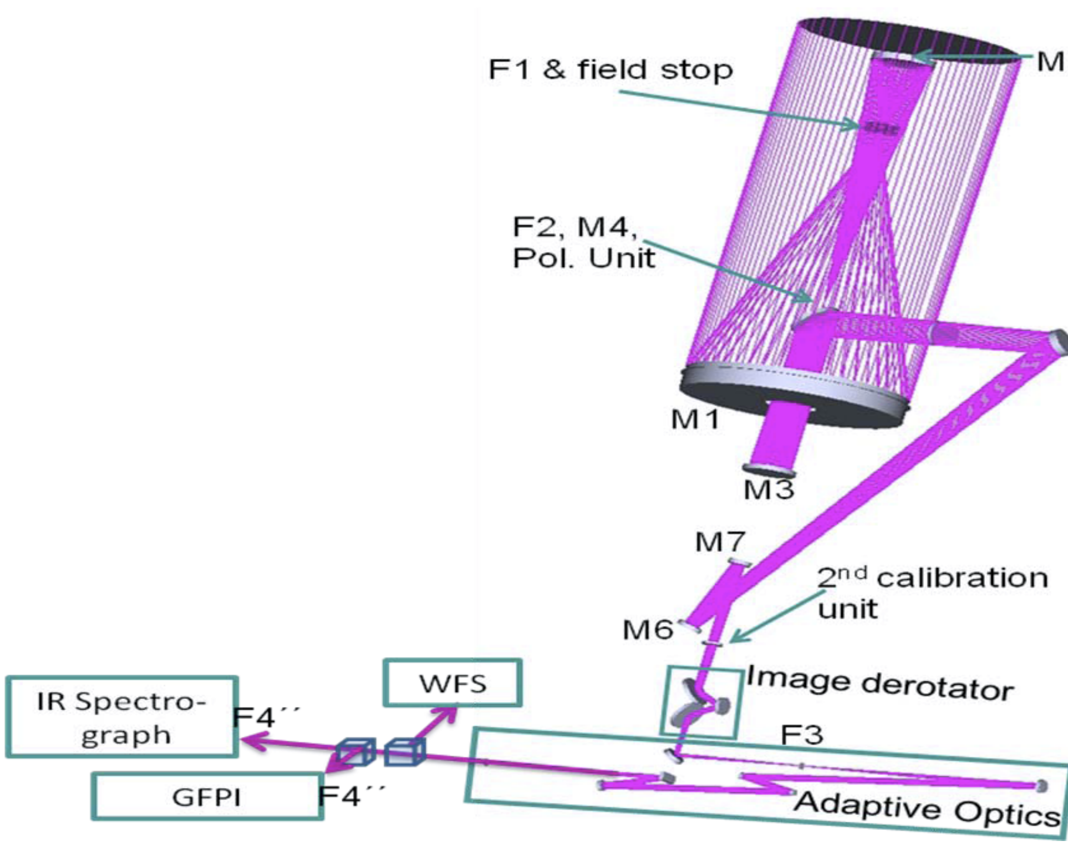


Figure 3. Optical light path of the GREGOR telescope including image deratorator, adaptive optics system, and dichroic beamsplitters, which distributes the light to the wavefront sensor and post-focus instruments.

2.2 Integration of the 1m SolarLite mirror

The 1-meter SolarLite mirror was manufactured to demonstrate that large mirrors can be built utilizing Cesic technology. Originally, it was planned to use the mirror on Sunrise[9], a balloon-based solar telescope launched in 2009. Finally, for that experiment a Zerodur-mirror blank was chosen and the SolarLite mirror was made available for use with the GREGOR telescope. From the beginning the Sunrise and GREGOR mirrors were designed to have the same radius of curvature to benefit from manufacturing synergies. Therefore it was possible to integrate this mirror without changing the other optical components of the GREGOR telescope. Only an adapter was needed to mount the smaller mirror onto the original GREGOR mirror cell.

Polishing of the mirror was carried out by Zeiss on a best effort basis to have the mirror ready in March 2009. The optical quality of the mirror at that time was sufficient to perform the planned tests. No scientific observations were intended with this mirror.

After delivery of the mirror to the Canary Islands it was coated with aluminum at the facilities of the Instituto de Astrofisica de Canarias (IAC), our partner institute on Tenerife. The coating chamber admits mirrors with diameters up to 2 m (see Figure 4).

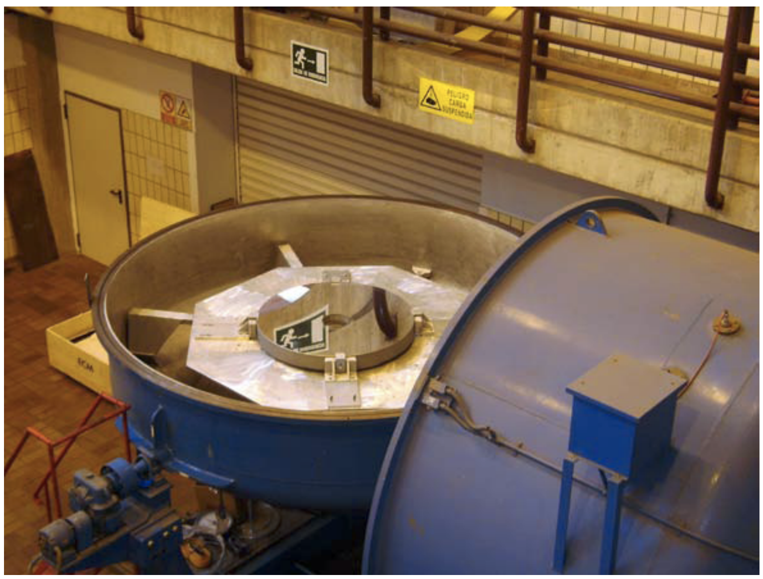


Figure 4. SolarLite mirror after Al-coating mounted in the IAC coating chamber.

The GREGOR telescope cooling system had to be adapted to the different cell pattern of the 1-meter mirror. After coating the mirror was mounted on an adapter that fits into the existing mirror cell. With the integration of the Cesic primary mirror in March 2009 the entire optical light path had seen Sun light for the first time.

2.3 Mirror alignment

One major issue during commissioning of a telescope is the optical alignment of its mirrors. Provisions were taken to mount all mirrors mechanically along the optical axis and to align the optical axis with the elevation and azimuth axes.

To assure that the telescope points correctly to the Sun, the offset of the telescope pointing was determined at first. With the next step the optical and mechanical azimuth axes were aligned. Then, the mirrors of the transfer (M11 – M4) and telescope (M3 – M2) optics were aligned in a reverse order up to the primary focus. The primary mirror was mounted such that its focus is at the defined position in the field stop. Different iterations of alignment procedures were necessary to decrease image wobbling at the tertiary focus in front of the AO system.

An point-like source, the end of an illuminated fiber, was used at the primary and secondary foci to facilitate the alignment. It was also used to determine and correct image wobble. Turning the telescope about one axis produces image motion on a circle around a constant center point position. Turning the telescope about the other axis the image circles around a different center point. The radii of the circles depend on the alignment of the mirrors but could not be compensated independently for each axis. It was possible to minimize the radius of one axis, but this increased the radius for the other axis. However, the distance of both center points remained constant. As a compromise the radii of both circles were optimized. The known small misalignment of elevation and azimuth axes could not explain the large distance of both center points at the focal plane F3.

2.4 Foucault test

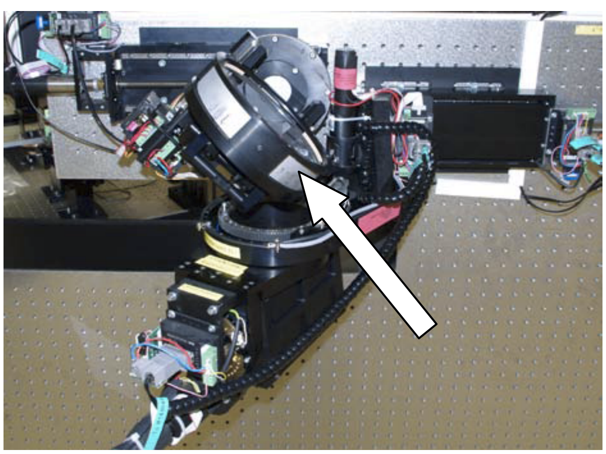
A Foucault test[10] was applied to evaluate the optical quality of the telescope. The solar limb was used as a known source and a narrow slit acted as a knife edge. Using two orthogonal slit directions with the north/south and east/west limb of the Sun produces two pupil maps of the wavefront error gradients in orthogonal directions. It was possible to reproduce the (already known) mechanical deformations of the 1-meter primary mirror. This modified Foucault test is a simple and useful tool for in-situ testing of large optics.

2.5 Test of AO system

At first-light GREGOR will use an 80 actuator deformable mirror (DM). The performance of the first-light AO system was successfully tested with an illuminated pinhole at the primary focus as light source. During final commissioning this DM will be replaced by a 200 actuator DM, which will give a much higher performance of wavefront correction extending observing times to include moderately good seeing conditions[11]. An upgrade from the AO system to a multi-conjugated adaptive optics (MCAO) system is planned for the near future. An experimental setup of the MCAO was already successful tested in the optical laboratory at the Kiepenheuer-Institut in Freiburg[12].

2.6 Pupil image motion

The misalignment of the telescope optics creates displacements of the pupil image on the deformable mirror (DM) with changing elevation and azimuth angles. This pupil image motion diminishes the AO performance. GREGOR uses an active controlled mirror (M11 shown in Figure 5) near the focus F3 to compensate these displacements. The displacements are measured by determining intensity differences between opposite, outside pupil images at the WFS. Measurements using a pinhole as a light source at the primary focus demonstrated the capability of such a compensation system.



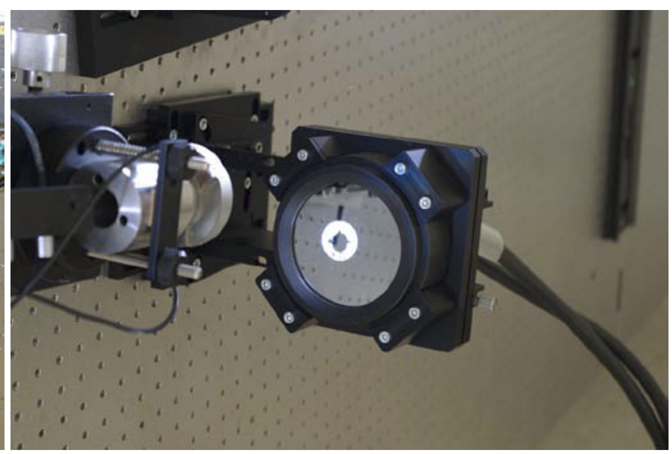


Figure 5. Slowly movable mirror M11 (arrow, left picture) to compensate pupil motion on the deformable mirror (right picture)

3. COOLING SYSTEM

3.1 Thermal control system: Field stop

The GREGOR field stop at the primary focus rejects most of the light coming from M1, but about 200 W of the incoming solar radiation remains in the device. In the near future a protected silver coating with high reflectivity will be applied to the field stop to reduce the absorbed heat. The diameter of the solar image (see Figure 6) at the primary focus is about 24 mm[13.] The energy density at the primary focus is about 22 000 W/m^2 with the 1-meter and 56 000 W/m^2 with the 1.5-meter primary mirror. A dual-circuit cooling circulation system[13] holds the temperature of the field stop close to ambient temperature (see Figure 7). If the cooling system fails, the field stop and surrounding parts will probably melt. In case of a detected malfunction, e.g. of high temperature at the field stop or low flow of the cooling fluid, the cover of the primary mirror will be closed immediately to interrupt the illumination. Intensive tests of the field stop cooling system have been performed, including fail safe tests. During all tests the field stop and cooling system worked properly.

Figure 6. The GREGOR field stop illuminated by the 1-meter SolarLite mirror. The solar image is still slightly off-center because the primary mirror was not precisely aligned during the first-light observations. The reflective part of the field stop is still an experimental setup. It allows mounting a pinhole or an artificial light source (fiber) on top of the reflective surface. The final field stop will have a smaller hole to limit the FOV to a diameter of 150″.

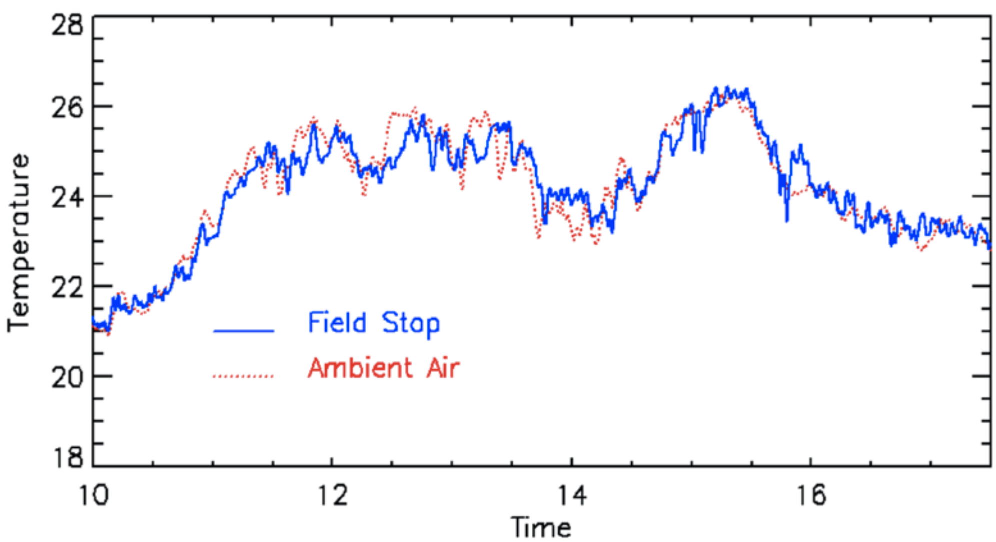


Figure 7. Surface temperaturse of the field stop as compared to the ambient air temperature

3.2 Backside primary mirror cooling

The 1-meter mirror is equipped with 25 temperature sensors mainly at the backside but also a few at the front side. This allows an intensive study of the temperature distribution on top and behind the reflective surface. Additional sensors are placed on the backside of the light-weighted secondary mirror. The secondary and tertiary mirrors are also made from Cesic to achieve fast heat exchange between the ambient air and the mirrors. Both M2 and M3 mirrors are prepared for active cooling if this is needed in the future.

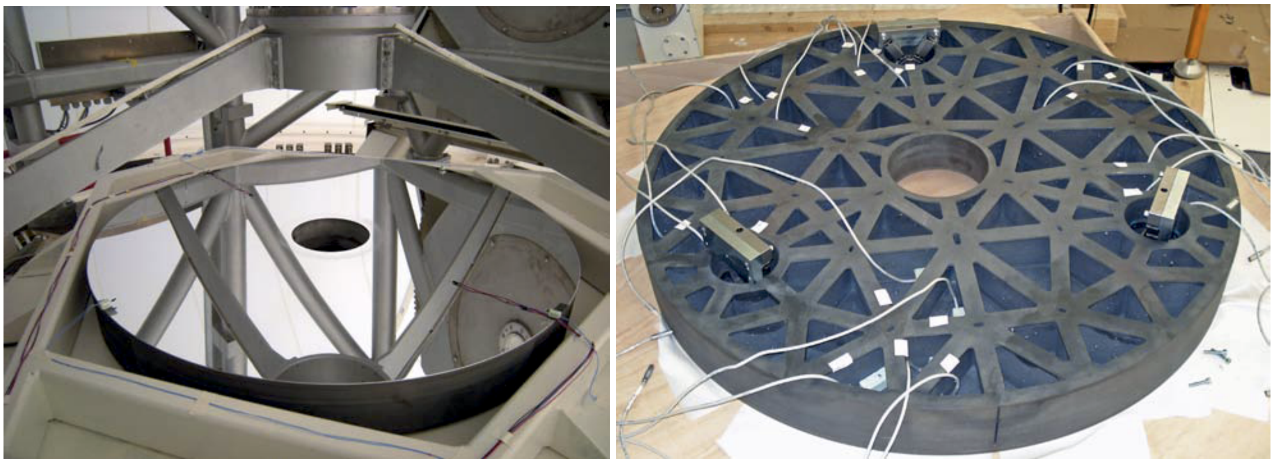


Figure 8. 1-meter SolarLite mirror with temperature sensors on the front and on the backside. The sensors on the front side are placed in the shadow of the spiders to avoid direct illumination with sunlight. The ambient temperature just in front of the mirror is measured with 4 sensors in a distance of about 10 mm off the mirror surface.

Cooling system tests with the 1-meter SolarLite mirror showed that the temperature difference between ambient air temperature and the average surface temperature of the Cesic mirror stayed small during the day (see Figure 9). The primary mirror was slightly overcooled to avoid positive temperature differentials, which could lead to mirror seeing. The mirror temperatures are not equally distributed and differ up to a few degree across the mirror surface. Detailed analysis is pending, but it was already found that the power of the cooling system is not sufficient under some circumstances. As a result the capacity of the cooling system will be increased to match the demands of the 1.5-meter Zerodur mirror. The results will be compared with later measurements scheduled for the final 1.5-meter Zerodur mirror.

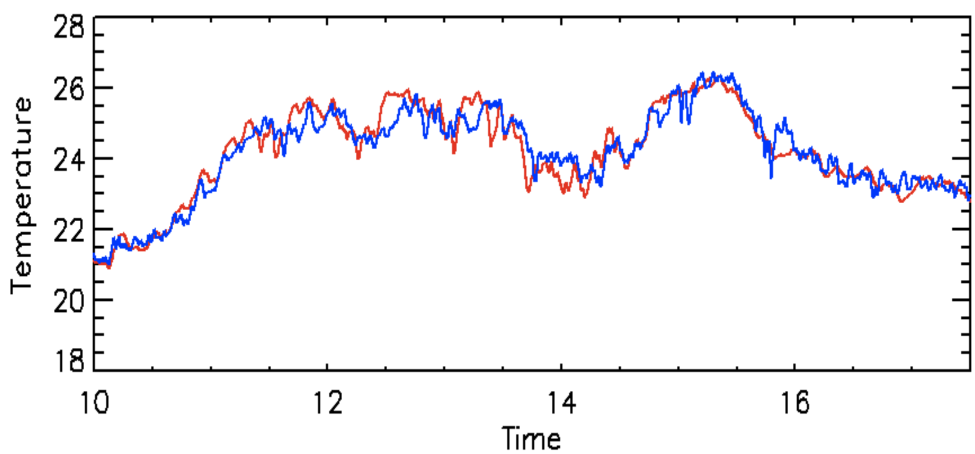


Figure 9. Averaged surface temperature of the primary mirror (blue) as compared to the ambient air temperature (red).

4. POST-FOCUS INSTRUMENTS

At the science focus F4 the telescope provides an effective focal ratio of F/38. The spatial resolution is about 0.06″ at 500 nm, corresponding to 50 km on the solar surface. The usable wavelength range is between 360 nm and about 2000 nm. Longer wavelengths can be accessed after removing the entrance and exit windows of the coudé path. GREGOR will have three fully working first-light instruments: GFPI, GRIS, and dedicated large-format, high-cadence detectors for high-spatial resolution imaging including post-factum image restoration. From the outset dichroic beamsplitters provide the means of multi-instrument observations with GFPI and GRIS.

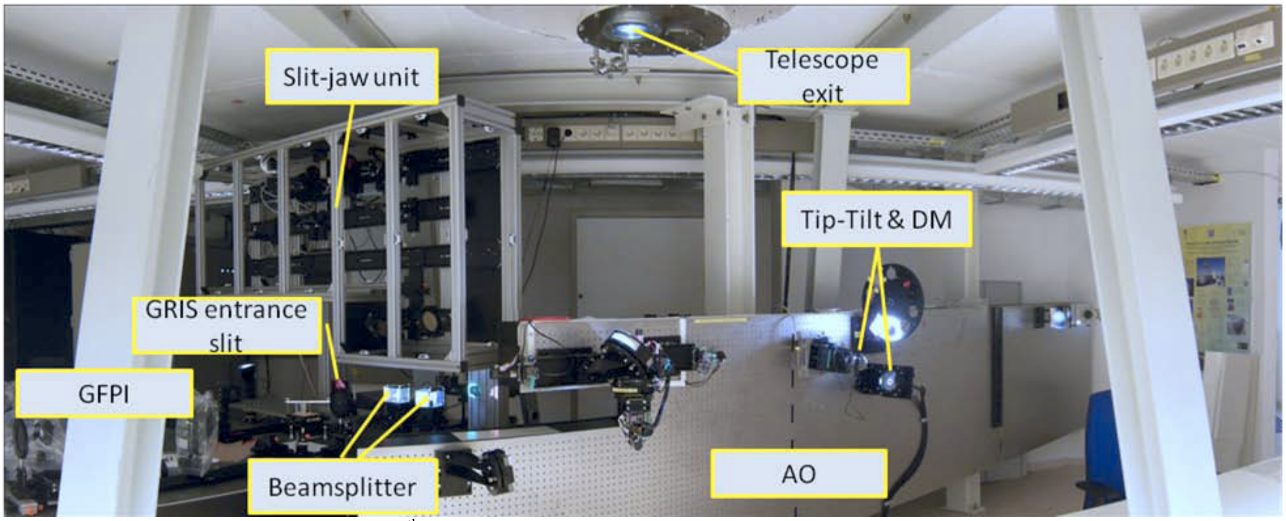


Figure 10. Optical laboratory at the 5th floor of the telescope building. The picture shows on top the telescope exit window and in the middle and right the optical bench with the AO system. The beamsplitters distribute the light between GFPI, GRIS and wavefront sensor (not visible). The slit-jaw unit is shown in the background. The image derotator and the secondary calibration unit between exit window and AO are not yet installed.

4.1 Spectro-polarimeter GFPI

GFPI is an imaging spectro-polarimeter for high spatial, temporal and spectral resolution observations of the solar photosphere and chromosphere. The two GFPI etalons are mounted in the collimated beam which causes a wavelength shift across the FOV, which is corrected during data processing. Their coatings have been optimized for the wavelength range of 530 – 870 nm. Using narrow-band interference prefilters different wavelength settings can be selected to scan spectral lines with a spectral resolution up to 250 000. Vector polarimetry is possible in the range of 580–660 nm using a polarimeter consisting of a modified Savart plate (polarimetric beamsplitter) and two fast-switching ferroelectric liquid crystals[15]. The 52″ × 40″ FOV is sufficient to cover a substantial part of a sunspot. The complete instrument is integrated at the GREGOR optical laboratory and has been tested with sunlight.

4.2 Infrared spectrograph GRIS and slit jaw unit

GRIS is a slit-spectrograph with full Stokes vector polarimetric capability in the infrared (IR) wavelength range. A slit-jaw device with high-speed cameras (Hα, IR, continuum) complements the instrument. The spatial sampling of the infrared spectrograph is 0.135″/pixel. The slit length corresponds to 138″ (69″ for polarimetric observations).
GRIS is fully aligned, both internally and with the optical axis of the telescope. Only illumination with the Sun is still pending, because the IR cameras have to be shared with observers at the Vacuum Tower Telescope (VTT) on Tenerife.

5. FINAL COMMISSIONING AND SCIENCE VERIFCATION

After integration of the final primary mirror final commissioning will start. For safety reasons the fail safe tests of the field stop cooling system must be completed first. Then the alignment of all mirrors up to the science focus (including AO system) will be performed. Control system tests involving pointing and tracking verification will follow. The next step in improving the telescope's performance is the start of the science verification phase. During this period the post-focus instruments will be tested separately and later in combination. This will lead to the first scientific data and at the end of this phase the telescope will be commence regular observations.

6. SUMMARY

The GREGOR solar telescope completed several important milestones of the integration and verification phases. In particular, the interim 1-meter primary mirror made it possible to perform observatory level tests. Thus, commissioning GREGOR with the final 1.5-meter Zerodur mirror can build on this experience and significant time savings are expected.

After delivery of the final primary mirror followed by commissioning and science verification, telescope and post-focus instruments will enter routine operations. GREGOR will be one of the most powerful solar telescopes and is expected to deliver spectacular scientific information of the Sun.

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