Astron. Nachr. / AN **331**, No. 6, 624 – 627 (2010) / **DOI** 10.1002/asna.201011388

GREGOR solar telescope: Design and status

R. Volkmer[1,⋆], **O. von der Lühe**[1], **C. Denker**[2], **S.K. Solanki**[3], **H. Balthasar**[2], **T. Berkefeld**[1], **P. Caligari**[1], **M. Collados**[4], **A. Fischer**[1], **C. Halbgewachs**[1], **F. Heidecke**[1], **A. Hofmann**[2], **M. Klvaňa**[5], **F. Kneer**[6], **A. Lagg**[3], **E. Popow**[2], **D. Schmidt**[1], **W. Schmidt**[1], **M. Sobotka**[5], **D. Soltau**[1], and **K.G. Strassmeier**[2]

[1] Kiepenheuer-Institut für Sonnenphysik, Schöneckstr. 6, 79104 Freiburg, Germany
[2] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
[3] Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Str. 2, 37191 Katlenburg-Lindau, Germany
[4] Instituto de Astrofísica de Canarias, Via Lactea, 38200 La Laguna, Spain
[5] Astronomical Institute, Academy of Sciences of the Czech Republic, Fričova 298, 25165 Ondřejov, Czech Republic
[6] Institut für Astrophysik, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany

Received 2010 Jan 19, accepted 2010 Mar 29

Key words instrumentation: adaptive optics – instrumentation: high angular resolution – instrumentation: interferometers – instrumentation: polarimeters – instrumentation: spectrographs – telescopes

The integration and verification phase of the GREGOR telescope reached an important milestone with the installation of the interim 1 m SolarLite primary mirror. This was the first time that the entire light path had seen sunlight. Since then extensive testing of the telescope and its subsystems has been carried out. The integration and verification phase will culminate with the delivery and installation of the final 1.5 m Zerodur primary mirror in the summer of 2010. Observatory level tests and science verification will commence in the second half of 2010 and in 2011. This phase includes testing of the main optics, adaptive optics, cooling and pointing systems. In addition, assuming the viewpoint of a typical user, various observational modes of the GREGOR Fabry-Pérot Interferometer (GFPI), the Grating Infrared Spectrograph (GRIS), and high-speed camera systems will be tested to evaluate if they match the expectations and science requirements. This ensures that GREGOR will provide high-quality observations with its combination of (multi-conjugate) adaptive optics and advanced post-focus instruments. Routine observations are expected for 2012.

1 Introduction

The GREGOR solar telescope (see Fig. 1) was built to study the dynamics and magnetic fields of the photosphere and chromosphere as an integrated system (Volkmer et al. 2007; von der Lühe et al. 2001). Scrutinizing small-scale magnetic structures with high spectral and spatial resolution including accurate vector magnetic field measurements is the prime objective of GREGOR. During night-time the telescope will observe solar-like stars (Strassmeier et al. 2007). GREGOR facilitates technological studies paving the way for larger solar telescopes such as the Advanced Technology Solar Telescope (ATST, Wagner et al. 2008) and the European Solar Telescope (EST, Collados 2008).

In 2001 a consortium was founded by the Kiepenheuer-Institut für Sonnenphysik (KIS, Freiburg), the Astrophysikalisches Institut Potsdam (AIP), and the Institut für Astrophysik Göttingen (IAG) to build the telescope. In 2009 the Max-Planck-Gesellschaft (MPG, Munich) took over the contingent of IAG. The consortium maintains international partnerships with the Instituto de Astrofísica de Canarias (IAC, Spain) and the Astronomical Institute of the Academy of Sciences of the Czech Republic (AsU, Ondřejov).

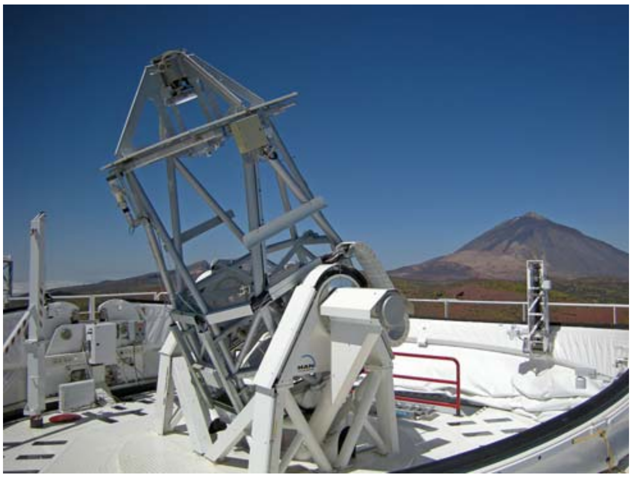

Fig. 1 (online colour at: www.an-journal.org) The 1.5 m GREGOR solar telescope at Observatorio del Teide, Tenerife, Spain.

GREGOR replaces the venerable 45 cm Gregory-Coudé Telescope (GCT), which has been operated on Tenerife since 1985. To host the new telescope on top of the same building, the uppermost floor and the dome were refurbished (2002–2004). Telescope structure, cooling systems, control systems, and the complete optics with a 1 m Cesic

---

[⋆] Corresponding author: volkmer@kis.uni-freiburg.de primary (Krödel, Luichtel & Volkmer 2006) for testing purposes were integrated (2004–2009). Engineering first-light was achieved with the interim 1 m SolarLite mirror in March 2009. Thus, testing and validating of optical, cooling and control systems started. This was followed by the integration of the first post-focus instruments (GFPI and GRIS). The final 1.5 m Zerodur primary mirror has been figured and light-weighted at Schott. Polishing started at Zeiss Oberkochen in August 2009 and delivery and integration is expected in the summer of 2010. At this point final commissioning including science demonstration time will start.

2 Telescope design

The telescope is designed with an open Serrurier structure with full performance at wind speeds of up to 15 m s^{-1} (Emde et al. 2003). The completely retractable dome allows wind flushing through the telescope to support the cooling of the telescope structure and optics (Bettonvil et al. 2008; Jägers et al. 2008). The optical design is an alt-azimuth mounted Gregory-Coudé type telescope (Fig. 2). The mirror blank of 1.5 m free aperture is light-weighted (final mass ≈205 kg with a pocket size of 68 mm and a face-sheet of only 12 mm) to allow a better removal of the absorbed heat load by air-cooling from the backside. About 9% of the primary mirror area is obstructed by the secondary mirror (M2) mounted on a hexapod. The water-cooled field stop at the primary focus (F1) reflects most of the unused light out of the telescope. Only the nominal field-of-view (FOV) of about 150$''$ diameter will be transmitted. In special cases, a field stop of 300$''$ diameter replaces the nominal one. The GREGOR Polarimetric Unit (GPU, Hofmann, Rendtel & Arlt 2009) at the secondary focus (F2) and an additional calibration unit after the exit window of the telescope (see Fig. 2) assure high-precision polarimetric observations.

The light is transmitted via the mirrors M2, M3, M4 through the evacuated coudé path into the optical laboratory to feed the adaptive optics (AO). We plan to compensate the image rotation introduced by the alt-azimuth mount with a removable image derotator between the exit window of the coudé path and the AO (see Fig. 2). The deformable mirror (DM) of the first-light AO has 80 actuators (Berkefeld, Soltau & von der Lühe 2004; Soltau, Berkefeld & Volkmer 2006). It will be upgraded after the first year of observation to a high-order AO system using a DM with about 250 actuators. Each post-focus instrument will have a separate Shack-Hartmann wave front sensor (WFS).

An extension of standard AO to multi-conjugate adaptive optics (MCAO, Berkefeld, Soltau & von der Lühe 2006; Schmidt et al. 2009) for diffraction-limited observations across a larger FOV with about 60$''$ diameter is already running in an optical laboratory at KIS. It will be integrated into the telescope in the future. In addition to correcting wave front aberrations in the entrance pupil of the telescope, MCAO will operate with two additional DMs (see Fig. 3), which are conjugate to two atmospheric layers at heights of 8 km and 25 km above ground.

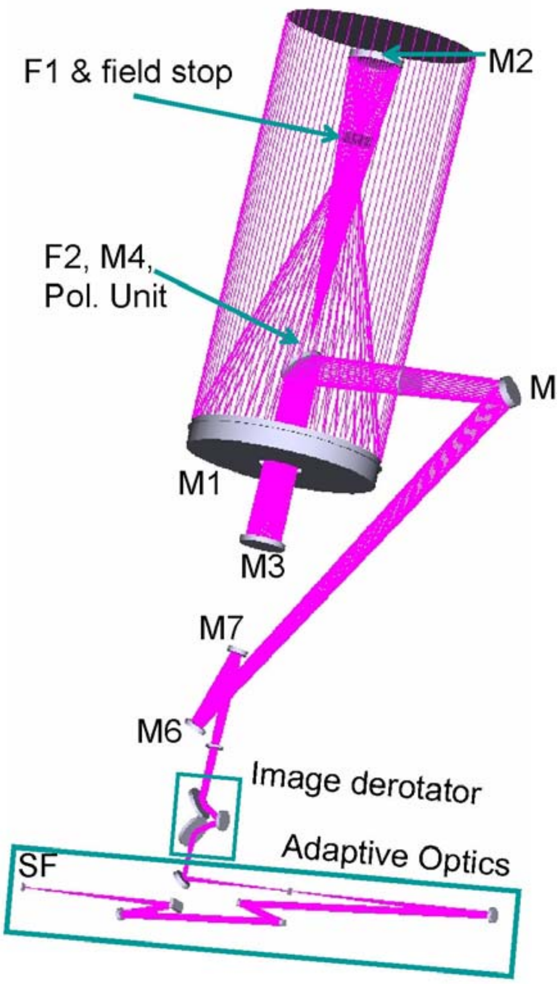

Fig. 2 (online colour at: www.an-journal.org) Optical light path of the GREGOR telescope including image derotator and adaptive optics.

3 Post-focus instruments

At the science focus (F4) the telescope provides an effective focal ratio of $F/38$. The diffraction-limited 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 2 000 nm. Longer wavelengths can be accessed after removing the entrance and exit windows of the evacuated coudé path. GREGOR will have three fully working first-light instruments: (1) GFPI, (2) GRIS, and (3) dedicated large-format, high-cadence detectors for high-spatial resolution imaging including post-facto image restoration. Multi-instrument observations will be possible from the beginning. AO, GFPI, and the GRIS slit-jaw unit are located in an optical laboratory (see Fig. 4), whereas the GRIS optics, grating and camera reside one floor below in a separate thermally stable room.

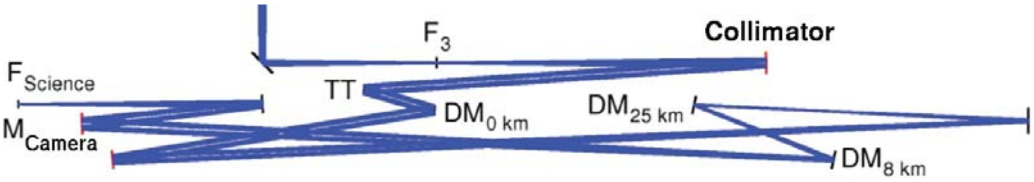

Fig. 3 (online colour at: www.an-journal.org) Configuration of the multi-conjugated adaptive optics with three deformable mirrors correcting seeing at the level of the entrance aperture and two heights of 8 km and 25 km above ground.

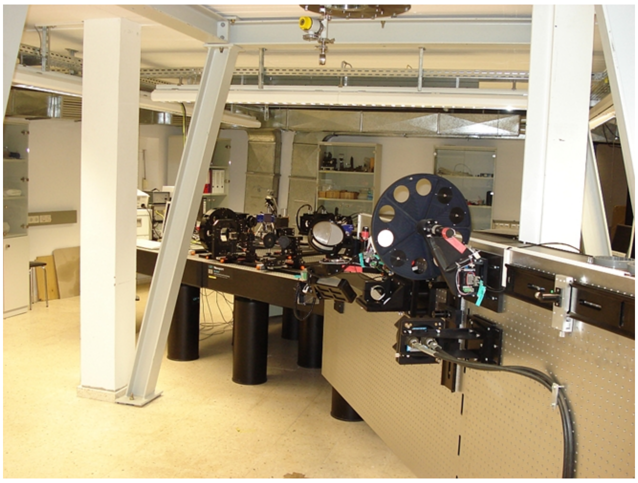

Fig. 4 (online colour at: www.an-journal.org) Adaptive optics (right) and the GREGOR Fabry-Pérot Interferometer (back) in the laboratory below the telescope platform.

3.1 GREGOR Fabry-Pérot Interferometer

GFPI is an imaging spectropolarimeter for high spatial, temporal and spectral resolution observations of the solar photosphere and chromosphere (Puschmann et al. 2007). Its roots can be traced back to the first instance of the Göttingen Fabry-Pérot Interferometer (Bendlin, Volkmer & Kneer 1992), which has evolved considerably since then (Puschmann et al. 2006). The two GFPI etalons are mounted in the collimated beam. Their coatings have been optimized for the wavelength range of 530–870 nm. Using narrow-band interference prefilters, up to six wavelength settings can be selected to scan spectral lines with a spectral resolution of $\mathcal{R} \approx 250\,000$. 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 (Balthasar et al. 2009; Bello González & Kneer 2008). The $52'' \times 40''$ FOV is sufficient to cover a substantial part of a sunspot.

3.2 Grating Infrared Spectrograph

GRIS is a slit-spectrograph with the capability of full Stokes vector polarimetry in the infrared (IR) wavelength range (Collados et al. 2008) building on the experience with the Tenerife Infrared Polarimeter (TIP, Collados et al. 2007). 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^{-1}. The slit length corresponds to $138''$ ($69''$ for polarimetric observations). At 1083 nm (1565 nm) the spectral sampling is 2.1 pm pixel^{-1} (4.5 pm pixel^{-1}) and the spectral coverage is 2.1 nm (4.6 nm). Dichroic pentaprism beamsplitters provide the means for simultaneous GFPI/GRIS observations.

3.3 Image restoration

High-cadence, large-format cameras provide context images in different wavelengths (Ca II H or K, G-band, Hα, etc.). Post-facto image restoration can be applied to these data, the slit-jaw images and the GFPI data. Depending on seeing conditions, observing mode and access to computational resources, one can choose from a variety of techniques such as speckle imaging, phase diversity, or (multi-object) multi-frame blind deconvolution (e.g., Löfdahl, van Noort & Denker 2007). A cluster of commodity computers on-site allows to restore a significant fraction (or even all) of the data during the observing run. Thus, almost diffraction-limited data will be on hand to immediately evaluate the success of the observing campaign.

3.4 Second generation instruments

A variety of instruments are currently in the design and development phase to enhance the science capabilities of GREGOR. The Blue Imaging Solar Spectropolarimeter (BLISS, Denker 2010) is an extension of the GFPI for observations in the range of 380–530 nm. An extension of GRIS to cover the visible is also envisioned. Using dedicated IR detectors night-time observations with GRIS could become feasible. Another option would be a dedicated night-time spectrograph as proposed by Strassmeier et al. (2007). Such instruments are aimed at investigating photospheric and chromospheric stellar activity and will work robotically. Finally, an instrument similar to the Polarimeteric Littrow Spectrograph (POLIS, Beck et al. 2005) would enable high-precision polarimetry at high spatial resolution at two different atmospheric layers in the visible and UV.

4 Cooling system tests

Thermal control of the primary mirror and field stop F1 has an immediate impact on the optical performance of the telescope (Emde et al. 2004). Cooling system tests with the 1 m

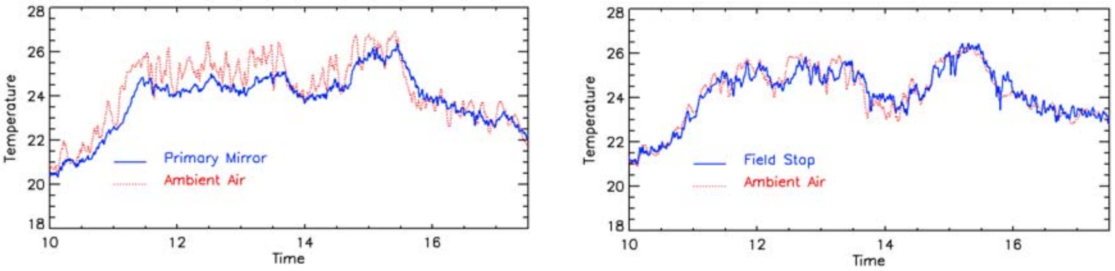

Fig. 5 (online colour at: www.an-journal.org) Surface temperatures of the primary mirror (*left*) and field stop (*right*) as compared to the ambient air temperature.

SolarLite mirror showed that the temperature difference between ambient air and the surfaces of the Cesic mirror and field stop stayed small during the day (Fig. 5). The primary mirror was slightly overcooled to avoid positive temperature differentials, which could lead to mirror seeing.

5 Summary

The GREGOR solar telescope completed several important milestones of the integration and verification phase. In particular, the interim 1 m primary mirror made it possible to perform observatory level tests. Thus, commissioning GREGOR with the final 1.5 m Zerodur mirror can build on this experience and significant time savings are expected. After almost a decade the GREGOR project has progressed to a point, where closing the AO-loop and obtaining the first data with diffraction-limited quality is only a small step away.

Acknowledgements. The 1.5-meter GREGOR solar telescope is built and operated by the German consortium of the Kiepenheuer-Institut für Sonnenphysik in Freiburg, the Astrophysikalisches Institut Potsdam, and the Max-Planck-Gesellschaft in Munich with contributions by the Institut für Astrophysik Göttingen, the Instituto de Astrofísica de Canarias and other partners. The project was partially supported by the Czech Ministry of Education (LA-124).

References

Balthasar, H., Bello González, N., Collados, M., et al.: 2009, in: K.G. Strassmeier, A.G. Kosovichev, J.E. Beckmann (eds.), *Cosmic Magnetic Fields: From Planets, to Stars and Galaxies*, IAU Symp. 259, p. 665

Beck, C., Schmidt, W., Kentischer, T., Elmore, D.: 2005, A&A 437, 1159

Bello González, N., Kneer, F.: 2008, A&A 480, 265

Bendlin, C., Volkmer, R., Kneer, F.: 1992, A&A 257, 817

Berkefeld, T., Soltau, D., von der Lühe, O.: 2004, in: D. Bonaccini Calia, B.L. Ellerbroek, R. Ragazzoni (eds.), *Advancements in Adaptive Optics*, SPIE 5490, p. 260

Berkefeld, T., Soltau, D., von der Lühe, O.: 2006, in: B.L. Ellerbroek, D. Bonaccini Calia (eds.), *Advances in Adaptive Optics II*, SPIE 6272, p. 627205

Bettonvil, F.C.M., Hammerschlag, R.H., Jägers, A.P.L., Sliepen, G.: 2008, in: E. Atad-Ettedgui, D. Lemke (eds.), *Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation*, SPIE 7018, p. 70181N

Collados, M.: 2008, in: L.M. Stepp, R. Gilmozzi (eds.), *Ground-Based and Airborne Telescopes II*, SPIE 7012, p. 70120J

Collados, M., Lagg, A., Díaz García, J.J., et al.: 2007, in: P. Heinzel, I. Dorotovič, R.J. Rutten (eds.), *The Physics of Chromospheric Plasmas*, ASPC 368, p. 611

Collados, M., Calcines, A., Díaz, J.J., et al.: 2008, in: I.S. McLean, M.M. Casali (eds.), *Ground-Based and Airborne Instrumentation for Astronomy II*, SPIE 7014, p. 70145Z

Denker, C.: 2010, AN 331, 648

Emde, P., Suss, M., Eisenträger, P., et al.: 2003, in: W.A. Goodman (ed.), *Optical Materials and Structures Technologies*, SPIE 5179, p. 282

Emde, P., Kühn, J., Weis, U., Bornkessel, T.: 2004, in: J. Antebi, D. Lemke (eds.), *Astronomical Structures and Mechanisms Technology*, SPIE 5495, p. 238

Hofmann, A., Rendtel, J., Arlt, K.: 2009, Centr. Eur. Astrophys. Bull. 33, 317

Jägers, A.P.L., Sliepen, G., Bettonvil, F.C.M., Hammerschlag, R.H.: 2008, in: E. Atad-Ettedgui, D. Lemke (eds.), *Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation*, SPIE 7018, p. 70181R

Krödel, M.R., Luichtel, G., Volkmer, R.: 2006, in: E. Atad-Ettedgui,D. Lemke (eds.), *Optomechanical Technologies for Astronomy*, SPIE 6273, p. 62730Q

Löfdahl, M.G., van Noort, M.J., Denker, C.: 2007, in: F. Kneer, K.G. Puschmann, A.D. Wittmann (eds.), *Modern Solar Facilities – Advanced Solar Science*, p. 119

Puschmann, K.G., Kneer, F., Seelemann, T., Wittmann, A.D.: 2006, A&A 451, 1151

Puschmann, K.G., Kneer, F., Nicklas, H., Wittmann, A.D.: 2007, in: F. Kneer, K.G. Puschmann, A.D. Wittmann (eds.), *Modern Solar Facilities – Advanced Solar Science*, p. 45

Schmidt, D., Berkefeld, T., Heidecke, F., et al.: 2009, in: P.G. Warren et al. (eds.), *Astronomical and Space Optical Systems*, SPIE 7439, p. 74390X

Soltau, D., Berkefeld, T., Volkmer, R.: 2006, in: L.M. Stepp (ed.), *Ground-Based and Airborne Telescopes*, SPIE 6267, p. 626711

Strassmeier, K.G., Woche, M., Granzer, T., et al.: 2007, in: F. Kneer, K.G. Puschmann, A.D. Wittmann (eds.), *Modern Solar Facilities – Advanced Solar Science*, p. 51

Volkmer, R., von der Lühe, O., Kneer, F., et al.: 2007, in: F. Kneer, K.G. Puschmann, A.D. Wittmann (eds.), *Modern Solar Facilities – Advanced Solar Science*, p. 39

von der Lühe, O., Schmidt, W., Soltau, D., et al.: 2001, AN 322, 353

Wagner, J., Rimmele, T.R., Keil, S., et al.: 2008, in: L.M. Stepp, R. Gilmozzi (eds.), *Ground-Based and Airborne Telescopes II*, SPIE 7012, p. 70120I