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Polarimetry with GREGOR – An Ongoing Project

A. Hofmann

Astrophysical Institute Potsdam, Sonnenobservatorium Einsteinturm,
An der Sternwarte 16, 14482, Potsdam, Germany

e-mail: ahofmann@aip.de

GREGOR is the project of a high-resolution solar telescope with an aperture of 1.5 *m* and an effective focal length of about 55 *m*. It is designed to support accurate, high sensitive spectro-polarimetry of the solar photosphere and chromosphere for studying the dynamics of the solar atmosphere and the underlying physical processes. The Astrophysical Institute Potsdam is currently developing the polarimetric unit (GPU) of GREGOR. The GPU is an integral part of the telescope and allows to calibrate polarimeters in any post-focal device, like the Tenerife Infrared Polarimeter (TIP) or the POlarimetric LIttrow Spectrometer (POLIS). The new telescope and its polarimetric equipment will allow high-precision measurements of magnetic fields and plasma motions in the solar atmosphere down to scales of 70 *km* on the Sun.

The GREGOR Project

In the autumn of 2006 we expect "first light" for GREGOR at the Observatorio del Teide on Tenerife, and at that time the most effective solar telescope worldwide will be available for solar research and night astronomy. GREGOR is developed as a common Project of the Kiepenheuer Institut Freiburg (KIS), the Institut für Astrophysik Gőttingen (USG), and the Astrophysikalisches Institut Potsdam (AIP) in cooperation with the Astronomical Institute Ondrejov (Czech Republic).

GREGOR belongs to a new generation of large, high technology telescopes. It is designed for spectro-polarimetric observations of the Sun with high angular, high temporal and high spectral resolution. GREGOR is an open telescope on an alt-azimuthal mount with an aperture of 1.5 *m* (Fig. 1).

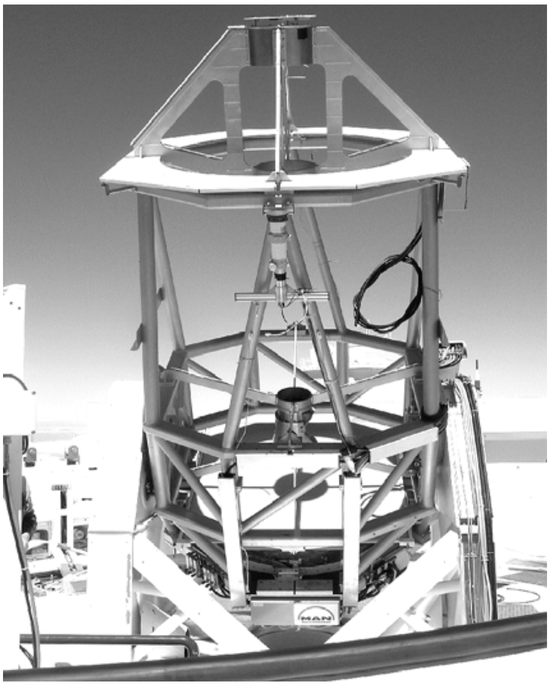

Fig.1.Telescope structure after mounting in the dome. Courtesy of E.Popow (AIP).

It will be equipped with an adaptive optics system (AO) in order to compensate for the deformation of the wavefront of the incoming light caused by air turbulence. This will provide observations at visible and infrared wavelengths with a resolution down to 70 *km* on the Sun and is the only way to reconcile the conflicting requirements of high spatial, spectral, and temporal resolutions and of spectro-polarimetric precision. GREGOR replaces the previous Gregory-Coudé telescope and will be located at the top of its building. A new protecting dome has been completed; it can be folded down during operation, allowing the air to flow freely through the telescope (Fig. 2).

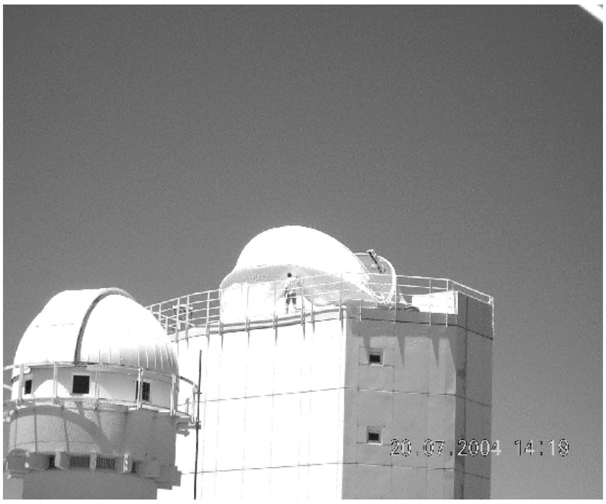

Fig.2. New dome for housing GREGOR. Courtesy of GREGOR-Consortium.

Optical Design

The optical design (see the optical scheme in Fig. 3) includes at first an axial-symmetric 3-mirror configuration where the first two mirrors form a classical Gregory telescope. The first three mirrors (M1, M2 and M3) are curved to provide imaging. The effective focal length is about 55 *m*, the entrance pupil diameter 150 *cm*, therefore the effective focal ratio is F/36.5 and the image scale becomes 3.75 *arcsec/mm*.

The current concept includes lightweighted Cesic (silicon carbide with carbon fibers) as the material of choice for the first three mirror blanks. The main motivation for using this material is the thermal control of all three mirrors. Cesic has a thermal conductivity which is 100 times higher than that of conventional glass ceramics. This allows an active cooling operating on the mirror back side (cf. Fig. 4), where pre-cooled air removes the excess heat from the blank. This procedure results in excellent thermodynamic stability and a very homogeneous mirror temperature. We consider this property crucial for a precise control of the air temperature fluctuations in front of the mirror surface, which should be the main cause of internal seeing of an open telescope. The successful completion of the Cesic mirrors was a great breakthrough.

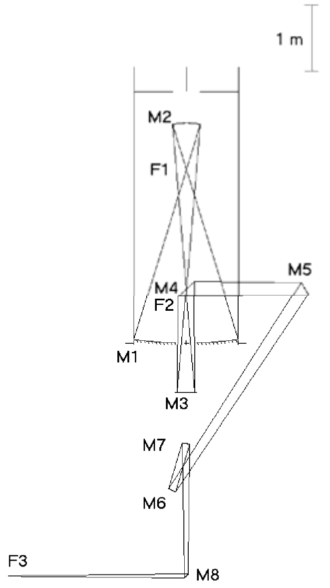

Fig.3. Basic optical scheme of GREGOR. Abbreviations M or F indicate mirrors or foci, respectively. Courtesy of GREGOR-consortium.

The primary mirror M1 is a f/1.67 paraboloid with a focal length of 2500 *mm*. A cooled field stop at the prime focus (F1) reflects most of the sunlight outwards and transmits a field of view of 300 *arcsec*. The elliptical secondary mirror M2 has a diameter of 400 *mm* and a focal length of about 500 *mm*. There is a secondary focus (F2) near the center of the telescope tube. An elliptical tertiary mirror M3 (cf. Fig. 5) with a focal length of 1400 *mm* reimages the secondary focus into the laboratory area. On this way M4 and several other flat mirrors reflect the light through the altitude and azimuth axes to the image derotator and the AO.

The science focus (F3) can be fed into either of the two topmost floors of the building. Here different high performance focal instruments will be added. These are, e.g., a high-resolution Fabry-Perot filter spectrometer, different polarimeters, a Czerny-Turner spectrograph, and instrumentation for infra-red spectroscopy and polarimetry.

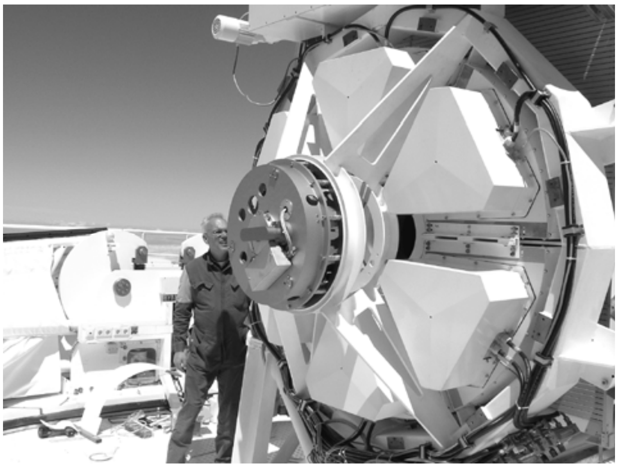

Fig.4. View on the back of the Telescope showing the cooling system for M1 and the mounting for mirror M3 (dark-gray). Courtesy of E.Popow (AIP).

Polarimetric Objectives

Magnetic fields and their interaction with the turbulent electrically highly conductive gas of the atmospheric layers are responsible for most of the dynamic, active processes at the Sun and other stars. Such basic astrophysical processes are often concentrated on spatial scales of 100 *km* and less and on the involved very short time scales. The magnetic field is the key parameter which determines all processes of solar activity and of their influence on the Earth. Moreover, the magnetic field provides the interconnection of the structures between the different layers from the sub- photosphere up to the corona.

To get information on magnetic fields and its relation to other thermodynamic parameters in the solar atmosphere we have to analyze the polarization in magnetic sensitive spectral lines as a function of wavelength. Below we give a brief list of the main requirements for high precision spectro-polarimetry we want to achieve with GREGOR.

1. **High polarimetric sensitivity**: Observations of inter-network fields in the photosphere and weak fields in the chromosphere will require to detect states of polarization at a level of 10exp(-4).
2. **Multi-line spectroscopy with high spectral resolution**: Stokes line profiles depend not only from the magnetic field but also from other thermodynamic parameters like velocity, density, temperature and their gradients. This requires measurements of several sets of lines with different sensitivities to the local physical conditions. The polarimetry is required over a broad range of wavelengths and for many objectives with a spectral resolution $\Delta\lambda / \lambda$ of at least 3·10exp(-5).
3. **High spatial resolution**: The largest part of photospheric magnetic fields outside sunspots is concentrated in very small flux tubes of *kG* field strength. The scale of these structures is believed to

be determined by the pressure scale height of about 100 *km*. Inside sunspots elementary structures with scales of the same order like umbral dots and penumbral filaments and grains are observed.

4. **Temporal resolution**: The exposure time Δt has to be shorter than the time *t* during which the resolution element Δx can change. *t* is related to the sound speed and for the photosphere we can estimate: $\Delta t \leq t \approx \Delta x$ / 10 *km/sec*.

All these requirements cannot be achieved simultaneously and independently, on the contrary, they are mutually exclusive. Only a telescope with large filled aperture and using new technologies like GREGOR can collect enough photons within a short time to investigate the solar processes on scales of high resolution with sufficient precision.

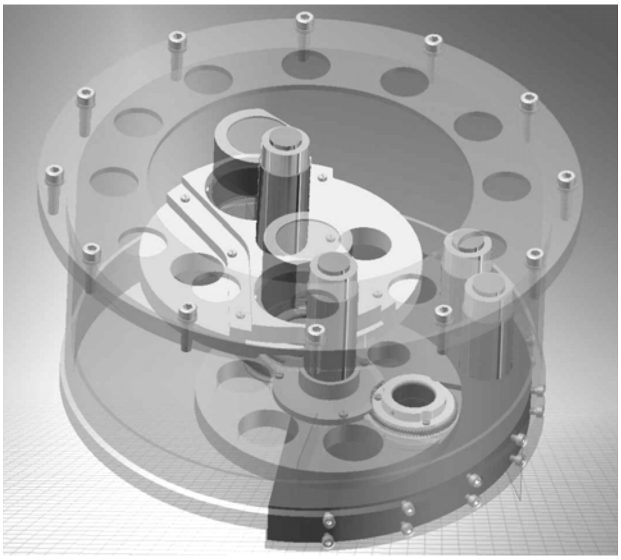

Fig.5. Sketch of the polarimetric unit. There are two wheels to insert and rotate different pieces of the calibration optics into the beam. Courtesy of S.M.Bauer (AIP).

Basic Concept of Polarimetry with GREGOR

Polarimetric measurements strongly depend on the spatial, spectral, and temporal resolution and the photometric/ polarimetric accuracy. The task at hand is to make trade-offs between these parameters for the specific objectives of the observations. At GREGOR this is realized by an optimum relationship between the intensity of light and the sampling. With an aperture of 1.5 *m*, a focal ratio of about 40 in the science focus and a resolution of about 0.1 *arcsec* we have an intensity of light exceeding this of a diffraction limited telescope by about 50%. Additionally the most mirrors after M4 will be coated with silver having 5% more reflexivity as compared to aluminum. This will result in a transmission being 30% higher than with aluminum coatings when five mirrors are considered. This high throughput achieves a high *S/N* ratio for polarimetric purposes.

Taking benefit from these facts, polarimetric measurements will be performed by several instrumentations which are optimized to specific spectral ranges or scientific objectives, respectively. There will be three main instruments on which the polarimetry at GREGOR is based:

- **TIP**: The **T**enerife **I**nfrared **P**olarimeter of the Institutio de Astrofisico de Canarias (Spain) was designed for the wavelength range between 1 *μm* and 2.3 *μm* (see [1]). The modulation is based on ferroelectric liquid crystals and a rate of 8 *Hz*. The Zeeman splitting, relative to the Doppler width, increases proportional to wavelength λ. Therefore the infrared is a regime of high magnetic sensitivity and ideal for measuring field strengths much lower than 1 *kG*. TIP was used extensively and with great success at the German Vacuum Tower Telescope (VTT) (see [2]). The optics of GREGOR is designed on pure mirror optics without any window or lens. Thus it will have full transmission to the limit of about 20 *μm* predetermined only by the atmosphere of the Earth, and will provide a high scientific potential in the infra-red spectral range. The spatial resolution at 1.5 *μm* amounts to about 0.2 *arcsec*. This opens for TIP the opportunity to study the magnetism from the deepest photospheric layers up to the highest chromosphere with high spatial resolution as well as magnetic sensitivity using i.e. the FeI lines at 1.56 *μm* and the HeI line at 1.083 *μm*.

- **POLIS**: This is a **PO**larimetric **LI**ttrow **S**pectrometer which is designed in cooperation between the KIS and the HAO for full Stokes measurement simultaneously in the visible and UV ranges (see [3]). It is an ideal spectro-polarimeter to study the relation between the photosphere and the chromosphere of the Sun, using a pair of neutral iron lines at 630.15 *nm* and 630.25 *nm*, together with the ionized Ca line at 396.6 *nm*. The evolution and dynamics of small-scale magnetic flux elements, the variation of the magnetic field and of other thermodynamic parameters with height, and the temperature structure and heating of the chromosphere will belong to the most interesting scientific objectives of POLIS. The instrument has its own scanning device with a step width down to 0.1 *arcsec* and a scan range of ±100 *arcsec*. This will enable the observations of small areas with high resolution and fast cadences as well as to scan larger areas. The modulation is done by a retarder rotating continuously with a rate of 15 Hz. The spectral resolution will be 2.2·10exp(-5) at 400 *nm* and it will reach a polarimetric accuracy of 10exp(-4).

- **GPU**: The **G**REGOR **P**olarimetric **U**nit is designed and built in the AIP (Fig. 5). It consists of calibration optics and will be placed near the telescope's secondary focus F2, before the symmetry of the optical train has been broken by any oblique reflection. GPU will be an integral part of GREGOR to support accurate polarimetry with TIP, POLIS or other post-focus instrumentation like the spectral high resolution $\Delta\lambda / \lambda > 5 \cdot 10$exp(-5) Czerny-Turner spectrograph or the imaging Fabry-Perot spectrometer (see [4]).

The GREGOR Polarimetric Unit

The accuracy of polarimetric measurements is significantly limited by instrumental polarization produced by the telescopes due to reflections on mirrors in front of the analyzing system. The effect depends strongly on the angle of reflection. It is virtually zero at vertical incidence but reaches substantial values as it deviates from the perpendicular incidence. This suggests to perform the polarization calibration early in the rotationally symmetric part of the telescope before any oblique reflection occurs. Here the telescope can be regarded as polarization free at a 10exp(-4) level [5].

The polarimetric unit shall be placed in the shadow of the Nasmyth mirrow M4 (cf. Fig. 3) and generates defined states of polarization by rotating a linear polarizer and/or a quarter wave retarder. The rotation angles of the polarizer and waveplates can be chosen user-defined so that the system is open for different procedures (e.g. [6] or [7]) to estimate the Mueller matrix of the following optical system.

Fig.6. Polarimetric unit from the backside. There can be seen the drives for the wheels and some of the mountings for the different pieces calibration optics. Courtesy of E.Popow (AIP).

The unit (Fig. 5 and Fig. 6) has to fulfill two tasks: (i) it calibrates the performance of the polarimeter; (ii) it takes care of the instrumental polarization induced by optics between the calibration optics and the polarimeter. The calibration optics consists of a field stop, a linear polarizer (rotatable), and two achromatic quarter wave plates (rotatable) which are in use alternatively for visual range or infrared observations. However the large aperture angle of about ±6° and the power density of about 25 *W/cm²* at F2 are extreme conditions which necessitate new ways for the calibration optics. A specific air-spaced double Glan-prism was designed by the Halle Nachfl. Comp. (Berlin) as linear polarizer to withstand these conditions and to realize the high distinction ratio of 10exp(-5) needed. Zero-order waveplates of polymethyl-metacrylat were designed by Astropribor (Kiev) as super-achromatic retarders for the high angular acceptance we need. The extinction ratio of 10exp(-6) of the prism, the retardation accuracy of $\lambda/100$ of the waveplates and an accuracy of 0.1° for the position angles will allow to measure the Mueller-matrix at a 10exp(-4) level.

The polarimetric unit (Fig. 6) is currently tested in the laboratory of the Einstein Tower Observatory and will be integrated into the GREGOR-telescope in autumn 2006.

Summary

The concept of polarimetric measurements with GREGOR is a combination of post-focus instrumentation (such as TIP or POLIS) and pre-focus equipment (GPU) where the latter avoids problems occurring at oblique reflections in the telescope. Therefore polarimetric observations with GREGOR allow to choose between exceptional spatial resolution, spectral resolution, or polarimetric sensitivity. A polarimetric sensitivity below 10exp(-3) at 500 *nm* and 0.1 *arcsec* spatial resolution is close to the theoretical limit based on photon statistics and assuming a spectral resolution of 300000 [8]. The new telescope and its polarimetric equipment will allow high-precision measurements of magnetic fields and plasma motions in the solar photosphere and chromosphere down to scales of 70 *km* on the Sun. Hence GREGOR becomes a unique instrument for studying basic physical processes of the dynamic solar atmosphere.

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