1 Introduction

Ground-based solar observations are currently entering a new era, mainly thanks to two technological advances: (1) solar AO (see Rimmele 2000) to surmount the deleterious effects of Earth’s turbulent atmosphere and (2) an open telescope design as demonstrated in the Dutch Open Telescope (DOT; Rutten et al. 2004), which was essential to overcome the aperture limitation encountered in the traditional design of solar vacuum telescopes. The New Solar Telescope (NST; Denker et al. 2006) and the German GREGOR project (Volkmer et al. 2007) with apertures of about 1.5 m are currently being commissioned, thus, paving the way for the 4-meter class Advanced Technology Solar Telescope (ATST; Wagner et al. 2008, entering the construction phase) and the European Solar Telescope (EST; Collados 2008, in the design and development phase).

Imaging spectropolarimeters belong nowadays to the standard equipment of solar telescopes, since they are photon-efficient and the data can be improved using image restoration techniques without requiring multi-conjugate AO to observe a large field-of-view (FOV). This type of instrument has been in use for almost two decades, e.g., the Göttingen Fabry-Pérot interferometer (Bendlin, Volkmer, & Kneer 1992) and the Telescopic Etalon Solar Spectrometer (TESOS, Kentischer et al. 1998) at the Vacuum Tower Telescope (VTT) on Tenerife, the Interferometric Bidimensional Spectrometer (IBIS, Cavallini 2006) at the Dunn Solar Telescope (DST) in New Mexico, and the visible-light and NIR imaging magnetographs (Denker et al. 2003) at Big Bear Solar Observatory (BBSO) in California. First results of the recently installed CRISP imaging spectropolarimeter at the Swedish Solar Telescope (SST) on La Palma were presented in Scharmer et al. (2008).

Finally, the transition of the Göttingen Fabry-Pérot interferometer (Puschmann et al. 2006) to the GFPI has been described in Puschmann et al. (2007). Early commissioning has already started at GREGOR using a 1-meter aperture CeSiC mirror on loan from the SolarLite project. After installation of the final 1.5-meter Zerodur mirror commissioning and science demonstration time will continue until the end of 2011 before entering routine observations in 2012.

Challenges for instrumentation and data analysis will be described in the following sections focussing on the GFPI. This selection, however, is just a reflection of the author’s bias and familiarity with this instrument. Despite this, many conclusions should be applicable to other imaging spectropolarimeters as well as other types of instruments, which are envisioned for the next generation of solar telescopes.

2 GREGOR Fabry-Pérot Interferometer

GFPI is a dual-etalon Fabry-Pérot interferometer for high-resolution two-dimensional spectropolarimetry. The coatings of the etalons were optimized for the wavelength range from 530–860 nm. The spectral resolution is about $R = 250,000$, which makes it possible to use spectral line inversion codes to derive physical parameters from sequences of narrow-band filtergrams. The image scale is $0.038''$ pixel$^{-1}$, which results in a FOV of $52.2'' \times 39.5''$ taking into account the $1376 \times 1040$ pixel detectors. The diffraction limit of the 1.5-meter GREGOR telescope at 600 nm is $\lambda/D = 0.082''$, which corresponds to about 60 km on the solar surface. Image restoration will always be essential to increase the data quality, since AO correction is only valid for the isopla-
One obvious way to improve the photon efficiency of the system is to improve the duty cycle of the detectors. While the current exposure times are of the order of 10–20 ms, the data acquisition rate is only 15 frames s\(^{-1}\). However, it could be as high as 50–100 frames s\(^{-1}\) considering the relatively short exposure times. Thus, the temporal resolution could be increased 3–6 times with high frame rate detectors.

Before describing new detector technology in detail, let us briefly discuss the impact of higher frame rates for image restoration and imaging spectropolarimetry. Short exposure times (\(\Delta t_{\text{exp}} < \tau_0 \approx 40 \text{ ms}\)) are needed for post-facto image restoration to “freeze” the seeing in individual exposures. Here, \(\tau_0\) is the typical coherence time of daytime seeing. Typical exposure times are in the range from 5–20 ms. Assuming \(\Delta t_{\text{exp}} = 20 \text{ ms}\), which is a good choice considering that the narrow-band filtergrams are photon-starved, we would arrive at a maximum data acquisition rate of 50 Hz. The other important time scale results from the photospheric sound speed \(c_s \approx 8 \text{ km s}^{-1}\). The size of a pixel on the solar surface would be about 28 km, i.e., a feature moving at a velocity \(c_s\) would traverse that distance in about 3.5 s. In principle, only \(3.5 \times 50 = 175\) images could be obtained during this relatively short time period. If four images are used for full Stokes polarimetry (see Balthasar et al. 2009; Bello González & Kneer 2008) and 25 wavelength points are used to cover a line, about two complete scans could be carried out. However, using speckle polarimetry about eight images are needed per wavelength point, increasing the observation time four times to about 15 s. In this case, features traveling faster than 2 km s\(^{-1}\) would violate Nyquist’s sampling theorem. The fact that two images are taken within \(\tau_0\) is of minor concern, since they are obtained in different polarization states and reconstructed independently.

3 Impact of large-format detectors with high data acquisition rates

Commercial, of-the-shelf (COTS), large-format detectors with high signal-to-noise (S/N) and high data acquisition rates are currently entering the market. At the moment the GFPI is using two Imager QE CCD cameras with Sony ICX285AL detectors. The cameras are part of a turn-key
Scientific CMOS (sCMOS, www.scmos.com) is one candidate for future upgrades of the GFPI, since it will be supported by LaVision’s DaVis software. The format of the sCMOS sensors is $2560 \times 2160$ pixel with a pitch of $6.5 \mu m \times 6.5 \mu m$. A microlens array is used to improve the photon-collecting efficiency. The wavelength coverage and quantum efficiency ($QE_{\text{max}} = 60\%$) is comparable to that of the Imager QE system. In the global shutter mode using a split frame architecture, the maximum frame rate is 50 Hz, which is exactly as needed for imaging spectropolarimetry. Considering that the exposure time is 20 ms and that the charge transfer after an exposure is complete in less than a 1 $\mu s$, no image smear is expected using the electronic shutter, i.e., no mechanical shutters are needed.

Anti-blooming ensures that, e.g., bright features such as flares will not affect neighboring pixels. The rms read noise of the sCMOS detector will be 2–3 electrons for the 50 Hz frame rate. Thus, a dynamic range of 84 dB (16,000:1) can be reached so that a digitization depth of 14-bit is required to record the signal without any loss. The intrinsic non-linearity of the sCMOS device is about 1% but can be corrected to better than 0.2%. Dual analog-to-digital converters (ADCs) with high and low gain settings provide simultaneously a high S/N and broad dynamic range. This is important for solar observations considering the low contrast of solar granulation and the high dynamic range required to observe sunspots. Much of the information contents of a spectral line is contained close to the core, where the rest intensity is low. Here, the largest gain of the dual ADCs is to be expected. Finally, the sCMOS device offers standard features such as binning and region-of-interest (ROI) read-outs so that read-out speed and/or S/N can be improved.

Carrying out the same computations as in Section 3, we arrive at a data volume of 8.8 GB for the 800 images in a spectral line scan. Note, however, that even though the data volume is 15 times larger, it only takes a third of the time to acquire the data. As a benefit, taking the calibration data will only take a third of time as well, thus reducing the observational overhead by a factor of three. In summary, making the leap to the next generation of COTS detector technology will increase the data volume by a factor of 50. In the following, we will discuss some of the implications and show that this requires a paradigm shift for ground-based solar instrumentation.

If we assume again a two hours observing day and 30 min worth of calibration data, the daily data volume will be about 5 TB even with lossless compression. These data rates and volumes can be handled by today’s technology using, e.g., dual Camera Link interfaces, RAID controllers and SATA-600 harddisks, dual 64-bit/100 MHz PCI buses, and 100 Gigabit Ethernet. These hardware devices belong to the high-end sector and require knowledgeable technical support to build a working system. Obviously, the resources to deal with such data volume go well beyond what PIs of an observing run will find at their disposal in their office.

Similarly, we can arrive at an estimate of the computational efforts required to analyze such data. Image restoration of a data cube of 800 subimages with $128 \times 128$ pixel takes about 40 s on a single CPU. Speckle deconvolution and data calibration of narrow-band images raise the computation time for the stack of 800 subimages to about 80 s. The size of the subimages corresponds approximately to the diameter of the isoplanatic patch ($\approx 5''$ or 3600 km on the solar surface). Allowing for some overlap of neighboring isoplanatic patches, we arrive at $40 \times 34 = 1360$ isoplanatic patches, which need to be individually restored before being reassembled to yield the restored spectral line scan. The computation time for one spectral line scan would be about 30 hours. The total computation time for the 450 spectral line scans during the two hour observing period would be about 600 days on a single CPU. Thus, data analysis presents an even more stringent challenge than handling the data volume. However, using a cluster with 500 quad core CPUs would reduce the computation time to less than one day as needed to keep up with the stream of observational data. On a positive note, once the data is reduced, the volume is reduced by a factor of 10 to about 500 GB per day. While still not small, this data volume can be handled in the archives of today’s virtual observatories.

4 Discussion

While the previous sections were concerned with the particulars of the GFPI and possible upgrades to large-format, high frame rate and high S/N detectors, the discussion will focus on the broader picture. Imaging spectropolarimeters are photon-efficient instruments and with the advent of new detector technology, the last remaining inefficiency can be removed. Thus, each precious photon can be detected. Further gains in photon-efficiency would require multi-instrument, multi-wavelength observations. This has been implemented in the GREGOR concept for post-focus instruments. Dichroic beamsplitters (pentaprism) are used for simultaneous observations with the GFPI, the scanning near infrared spectrograph and broad-band imagers.

The Blue Imaging Solar Spectropolarimeter (BLISS) is a second generation instrument for GREGOR, which will add observing capabilities in the blue part of the spectrum (below 530 nm) in 20130. This is also cost-effective considering that the cost of building a telescope scales with the area of the primary mirror. In terms of spatial resolution, observing at 400 nm instead of 600 nm corresponds to using 2.25-meter instead of a 1.5-meter telescope! On the downside, multi-instrument observations raise the complexity of instruments, data calibration/analysis, and operations. Even
today data calibration will take as much (or even more) time than science observations. Therefore, a major effort has to be spent on the development of a reliable and well documented production code for data calibration and analysis.

Exponential growth rates are encountered in a variety of areas relevant to imaging spectropolarimetry: processing speed, harddisk and memory capacity, network bandwidth (which is today’s bottleneck), number of pixel in digital cameras, but also in the power consumption of computer nodes. The growth rates are related to what is nowadays called Moore’s law, i.e., the statement that the number of transistors that can be placed at minimum cost on an integrated circuit has doubled approximately every 18 months (see Moore 1965). The results of the digital revolution have been of enormous benefit for astronomical instrumentation.

However, the quest for photon-efficiency has driven the instruments to a level of complexity, where the data handling, storage and analysis requires high-end computer technology, i.e., data rates of modern solar instruments reach the limits of today’s technology. Since the next generation of solar telescopes (ATST and EST) will use even larger detectors, Moore’s law only ensures that the requisite technology will be available. However, we should not expect that the demand for computer resources will diminish, i.e., photon-efficient instruments will be in step with innovation cycles. Current predictions project the validity of Moore’s law to hold until 2020, when ATST and EST would be operational.

Another word of caution might be appropriate at this stage. Moore’s law does not apply to institute budgets or funding schemes! Since data rates and volume exceed the resources of individual users, the data has to be analyzed in data centers, which could be located at the host institutions of the post-focus instruments. This in turn means that significant resources have to be reallocated or new funding has to be acquired. For new instruments the total cost of ownership (TCO) has to be considered, which consists of (1) the cost of acquisition and (2) the cost of operation, which can be full of hidden costs, e.g., the personnel and computer resources at the data center. While COTS parts might help to reduce the cost of an instrument, it has a minor impact on the cost of operations. The GFPI might be the last of a type of solar interferometers, which were developed over the last two decades under the leadership of Dr. F. Kneer. The 1.5-meter solar telescope GREGOR is built and operated by the German consortium of the Kiepenheuer-Institut für Sonnenphysik in Freiburg, the Astrophysikalisches Institut Potsdam, and the Max Planck Institut für Sonnensystemforschung in Katlenburg-Lindau with contributions by the Institut für Astrophysik Göttingen and other partners.

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