Spectro-polarimetry in the era of large solar telescopes

H. Socas-Navarro*

Instituto de Astrofísica de Canarias, Avda Vía Láctea S/N, La Laguna 38200, Tenerife, Spain

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This paper discusses some of the challenges of spectro-polarimetric observations with a large aperture solar telescope such as the ATST or the EST. The observer needs to reach a compromise among spatial and spectral resolution, time cadence, and signal-to-noise ratio, as only three of those four parameters can be pushed to the limit. Tunable filters and grating spectrographs provide a natural compromise as the former are more suitable for high-spatial resolution observations while the latter are a better choice when one needs to work with many wavelengths at full spectral resolution. Given the requirements for the new science targeted by these facilities, it is important that 1) tunable filters have some multi-wavelength capability; and 2) grating spectrographs have some 2D field of view.

1 Introduction

The Advanced Technology Solar Telescope (ATST), the European Solar Telescope (EST) and the so-called plan B for the space mission Solar-C are all being designed with multi-wavelength spectro-polarimetry as one of the top priorities. This kind of observations will permit novel studies of the processes taking place through the solar atmosphere, from the photosphere to the corona, as they traverse very different physical regimes with conditions that typically vary over several orders of magnitude.

Observing the chromosphere/corona at disparate wavelengths with spectro-polarimetry is still challenging even with the large-aperture telescopes currently under development. The science goals dictate requirements that typically include the following:

– High spatial resolution. We are interested in observing processes that take place at very small spatial scales. Thus, the telescope needs to be able to observe near the diffraction limit.

– High cadence. The demand for high spatial resolution imposes also requirements on the time cadence. If a particular feature is moving with a projected velocity \( v \), integrating over time scales comparable or longer than \( t = \Delta x/v \) (where \( \Delta x \) is the spatial resolution) will result in image degradation. The sound speed (which is often taken as a first estimate for \( v \)) in the photosphere is typically around 6 km s\(^{-1}\). However, in the chromosphere it is significantly larger and one often finds supersonic flows.

– High spectral resolution. Many science goals require not only imaging but also the observation of detailed line profiles to be able to track shock waves in the shape of chromospheric lines, as well as other interesting phenomena that produce emission features or other imprints on the intensity or polarization spectral profiles. Ideally one would want to resolve the Doppler width of the lines. Many interesting chromospheric lines are from H and He ions and have large Doppler widths, but others (particularly Ca) impose requirements for a better resolution.

– High signal-to-noise ratio. Polarimetric signals are often weak, especially those coming from the chromosphere. Typically, a continuum signal-to-noise ratio of 1000 is required for diagnostics based on the Zeeman effect (some times an order of magnitude better is required for Hanle-effect studies).

Unfortunately, it is not possible to meet all four of these requirements simultaneously, regardless of the telescope size. Observers will have to make compromises and optimize the instrument configuration for the problem at hand. Compromising will then be a key notion in observational solar physics for the next decade.

2 Tunable filters vs grating spectrographs

The nature of instrumentation itself provides us with a first natural set of choices. In recent years, technological advances have brought the development of tunable filters (TFs) to a point where the narrow passbands and tuning capabilities permit the observation of spectrally-resolved profiles, providing similar functionalities to those of conventional grating spectrographs (GSs). However, TFs and GSs exhibit significant differences that one should keep in mind when designing an observing campaign. Generally speaking, TFs

* Corresponding author: e-mail: hsocas@iac.es
make it easier to reach the highest possible spatial resolution and are susceptible to the application of more or less standard image reconstruction techniques (such as speckle, phase diversity or multi-object multi-frame blind deconvolution). In practice, one is limited to one or two spectral lines and the interpretation of the observed profiles may be complicated because the Sun evolves in time during the measuring process. On the other hand, GSs should be utilized for an optimal measurement of the spectral properties of lines and continua, especially if this is required at many wavelengths.

Scanning a field of view with GSs is becoming increasingly painful as the spatial resolution improves (and also the field to observe grows with newer large-format detectors). Just to give an idea, scanning a 50′′ field of view with diffraction-limited resolution requires the observation of about 3000 slit positions, or some 4 hours of observation. This is simply unacceptable. Clearly, a further step in the evolution of GSs is necessary to at least alleviate this issue. Several alternatives already exist with varying degrees of maturity, namely:

- **Multi-slit:** The growing size of (typically square) detectors often results in pixel rows that are too large for the observation of the desired spectral range. As an example, with a 4k × 4k camera one could acquire a range of around 60 Å, much larger than the free spectral range that one normally has. This wasteful situation may be avoided by using multiple slits separated just enough to avoid overlapping between their respective spectra (Martin et al. 1974; Jaeggli et al. 2008). Ideally, one would like to have pre-filters with a square shape to facilitate multi-slit observations. In this manner, it should be possible to dramatically reduce the time required to scan a given field of view by an order of magnitude or even more.

- **Image slicing:** This technique introduces optics in the focal plane to slice the field of view in the horizontal direction and reimage the pieces together forming a column in the slit direction (see, e.g., Weitzel et al. 1996). Thus, a long slit may accommodate different parts of a 2D field of view.

- **Fiber optics:** Here, a densely packed fiber optics bundle is used to again reimage a 2D portion of the focal plane onto the 1D spectrograph slit. Losses at the junctions of individual fibers may be minimized by introducing a properly designed array of micro-lenses (Allington-Smith & Content 1998).

- **Double-pass spectrograph:** A technique originally called Stenflo (1968), later developed by Mein (1977) in MSDP, and more recently in TUNIS (López Ariste et al., in preparation). With this technique, the light hits the grating before the field of view is blocked by the slit. The subsequent passage through the slit selects then a specific wavelength (which varies in the direction perpendicular to the slit) and the light is then reflected back to the grating. This second incidence reverses the wavelength dispersion and collapses the beam to form again the original 2D image, with the peculiarity that each column is now observed at a specific wavelength or combination of wavelengths. By moving the slit, the wavelengths observed at each column change, providing a simple tuning mechanism. In addition to this, it is possible to have multiple slits and also to reconfigure them dynamically, in order to scan the (r,λ)-space in an optimal manner to minimize the number of measurements required (Asensio Ramos & López Ariste 2010). Fig. 1 shows an example of simulated data with such a clever combination of slits. An interesting alternative application of this kind of instrument would be as a replacement for a Fabry-Perot filter for large-aperture telescopes, where the fabrication of a sufficiently large etalon could represent a technical problem.

A more complete discussion of methods for 2D spectroscopy can be found e.g. in Bershady (2009).

### 3 Multi-wavelength observations

The need for observing at multiple wavelengths has become increasing obvious in recent years for the reasons stated below. Unfortunately, this enterprise is still very challenging. When the instrumentation employed is not designed for this purpose, one has to coordinate the operation of different instruments and often different telescopes as well. Various operational and logistic issues complicate such coordinated campaigns, including the pointing procedure to ensure that all of the instruments are observing the same field.

Even when the entire campaign is carried out with one telescope and instrument, one has to deal with chromaticity issues (in the telescope, transfer optics and instrumentation) and balancing beams with intrinsically different photon flux (i.e., making sure that all the detectors receive enough photons to build the necessary signal-to-noise ratio while at the same time avoiding saturation). This latter problem is more critical if one is also doing polarimetry, as the modulation rate must be adequate for all of the detectors (or, alternatively, have a separate modulator for each beam). In that case, it is also important to ensure that the modulation efficiency is high at all the observed wavelengths. In general, this is not straightforward to accomplish unless one has a monochromatic polarimeter. Finally, on top of all these difficulties ground-based facilities are affected by differential atmospheric refraction. This effect, which is more pronounced in the blue side of the spectrum, produces a shift of the image on the focal plane in the direction connecting the horizon with the zenith. For imaging instrumentation, such as TFs, this issue is not critical since it is possible to correct the shift a posteriori by properly realigning the data cubes. The same is not true for GS, however, as the process of scanning over the field of view introduces a time lag in the images of an object at different wavelengths. One way to overcome this difficulty is to observe with the slit perpendicular to the line connecting the horizon and the zenith, so that
Fig. 1  Simulation of a TUNIS dataset using Hinode observations of a sunspot. Top-left: Combination of 31 slits (mask) employed to create the observation in the right panel. Top-right: Observed field of view. Each column is observed at a different combination of wavelengths, dictated by the mask configuration. Bottom-left: Another measurement with a different mask configuration. Bottom-right: Reconstructed spectra as if observed through a slit. The horizontal axis is the wavelength dispersion direction and the vertical is the spatial direction. The aspect ratio of the two (x, y) images shown corresponds to that of the original observation and is distorted because the slit stepping is different from the pixel sampling along the slit. Figure courtesy of A. Asensio Ramos and A. López Ariste

the differential refraction shift is along the slit and then it is easier to again make the correction a posteriori (Filippenko 1982). In any case, atmospheric differential refraction is another argument to push for GSs that have at least some limited 2D capability, as discussed in Sect 2 above.

The main driver for observing simultaneously at disparate wavelengths is of course to have information of the atmosphere at different heights and be able to reconstruct a 3D view of the processes taking place in it. However, there may be other motivations to do this. One example is to have differential measurements, very useful when one tries to do (relatively) model-independent inferences or when the underlying physics is not entirely well established. An example is the work of Socas-Navarro & Elmore (2005), who found that the polarization plane was different in the CaII and HeI infrared triplet lines observed in spicules. The difference can only be understood in terms of Hanle depolarization, thus providing conclusive model-independent evidence for magnetic fields in spicules. Another reason could be to obtain information on the statistical properties of magnetic structures too small to be resolved and that are expected to exist even with the resolving power of a 4-m aperture. An example of this approach is the work of Socas-Navarro & Sánchez Almeida (2003) who considered 1″ resolution observations of the quiet Sun and showed how the probability distribution function could be investigated by combining observations of the 6302 Å and 1.56 μm pairs of FeI lines.

Observations of the magnetic field at different heights already exist but are difficult to make and even more to interpret. Sunspots are a preferred target (e.g., Centeno et al. 2006; Socas-Navarro 2005 see Fig 2) with current technology because the signal-to-noise ratio still represents a challenge in the quiet chromosphere. However, there have been also breakthroughs in observations of filament loops (Solanki et al. 2003) and network elements (Pietarila et al. 2007).
4 Conclusions

The tremendous leap in spatial resolution that will be provided by the ATST and the EST will require careful rethinking of most conventional observing modes, particularly long slit spectroscopy. Without at least some limited 2D capability, it is not clear how to make these observations work in practice, particularly with the requirement of seamless multi-wavelength operation that is so vital to the science goals of these facilities. It should be noted, though, that a large aperture is still useful for moderate- or even low-resolution observations in which one needs to reach very high polarimetric sensitivities (e.g., for some Hanle effect observations).

Efficient exploitation of the new large solar telescopes with minimum downtimes will be of paramount importance, especially since it now appears that they will concentrate most of the resources devoted by the solar community to observations. This condition implies shifting the telescope operations to a new model more similar to what is currently employed in the large night-time facilities or the space-borne instrumentation such as Hinode. However, there is the risk that the community will be left without a facility where new experimental ideas can be tested. It is extremely important that the new operational model for the ATST/EST considers a provision of at least a small fraction of the observing time to test new ideas or generally speaking, high risk/high return potential campaigns.

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