STOKES PROFILE MEASUREMENTS IN EACH SODIUM D-LINE USING SINGLE AND DUAL BAND MAGNETO-OPTICAL FILTERS ON BOARD OF SOLAR ORBITER

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ABSTRACT
The main scientific aims are: 1) to obtain precisely calibrated line profile information with detailed center-to-limb variations of the scattering polarization in the Na D1 and D2 lines, which is made possible by the exact and extensive Doppler scanning by the spacecraft orbital motion in combination with the extremely stable and narrow MOF passband; 2) to obtain a sequence of precisely calibrated magnetograms throughout the line profiles of the Na D1 and D2 lines accessed by the orbital Doppler scanning, thereby covering a wide height range from the photosphere to the chromosphere; 3) to obtain simultaneous Stokes and Intensity images at the same line profile position; 4) to obtain full disk and possibly high resolution Hanle-effect maps for complementary magnetic fields diagnostic. The above measurements from space will be assisted by ground based Doppler and Polarimetric measurements with identical instruments.

INSTRUMENT CONCEPT
The instrument is the Magneto-Optical Filter (MOF). It is based on magneto-optical effects and can transmit dual or single band in and around the core of a resonant spectral line. Currently it is being used at several observatories, mainly for Helioseismology and it is also

![Graph of Na D1 line profile compared with the MOF passband at the times of extreme Sun-spacecraft velocities (±30 Km/s).]
being considered for the NASA space mission STEREO. The most comprehensive description of the MOF working principle is given in a JPL report [Cacciani, A., Rosati, P., Ricci, D., Egidi, A., Apporchaux, T., Marquedant, R.J., Smith, E.J., (1990 and 1994) "Theoretical and Experimental Study of the Magneto-Optical Filter", JPL#11900], and other papers [as for example SPIE, Vol. 2198, p. 219].

For the Solar Orbiter, we plan to use the MOF in a single-band mode and take advantage of the high relative sun-spacecraft motion to scan across the line profile (see Figure 1 through 4). The instrument is equipped with a polarization package in front of it as the one used in the magnetograph of Cacciani et al. (Solar Physics, 1996 Vol. 174, p. 115).

In Figure 2 we reproduce Doppler and magnetic images taken with the MOF of Figure 3. Its best transmission profiles are shown in Figure 4. The main characteristics of the instrument are its simplicity, compactness and absolutely stable spectral behaviour.

The single or dual band MOF versions do indeed deliver magnetograms throughout most of the orbit, although the passband position with respect to the line center varies considerably due to the orbital motion. This means that the relation between the degree of circular polarization and the line-of-sight field strength also varies, but this variation can be calibrated with very high precision, because the orbital motion is known, and the passbands are extremely stable (Figure 5).

In the single band mode we can obtain maps of the full Stokes polarization in the sodium line (through detailed measurements of the shapes of the filter-convolved Stokes profiles across the whole solar disk). We can also provide detailed profile mapping of the linear polarization due to coherent scattering in the Na D1 and D2 line system (see Figure 6 from Stenflo, Gondorfer and Keller, A&A, 2000). This scattering polarization, which involves a combination of quantum interference, optical pumping, hyperfine structure splitting, and Hanle effect in both the atomic ground and excited states, is not yet physically understood, but it may have
a profound effect on our understanding of the fundamental nature of solar magnetism according to the recent theory of E. Landi Degl’Innocenti (Nature 392, 256, 1998, see also the observational paper by Stenflo et al A&A 2000). As a by-product of the orbital Doppler scanning in combination with the sodium MOF the experiment can deliver a unique data set for addressing this kind of novel physics.

Using the MOF technology and a preceding Lyot filter element (calcite + splitter in Figure 7) it is possible to separate the sodium D1 and D2 lines. Figure 7 shows the mechanical arrangements for separated Na D1 and D2 polarimeter that can be used on board of Solar Orbiter. For each line it provides two simultaneous pass bands. Magnetograms can be recorded in each line separately. The full Stokes vector (circular and linear polarization) is modulated by the polarimeter package, which allows diagnostics of the vector magnetic field via both the Zeeman and Hanle effects at each line profile position.

The project can also be assisted by ground based observations, with the same instrumentation, for two kinds of reasons: the first reason is related to the possibility of investigating the interior of the sun having a stereo vision of it; the second reason is related to the difficulty to derive the vector magnetic field from the measured Stokes vector, the main obstacle being that practically all the solar flux elements are spatially unresolved and the longitudinal and transverse Zeeman effects respond in fundamentally different ways to these spatially unresolved fields when averaging over the angular resolution element.

The important novel aspect offered by the Orbiter is that when combining magnetograms obtained with the different viewing angles of the Orbiter and the Earth, then what is transversal Zeeman effect as seen from Earth may become longitudinal Zeeman effect as seen from the spacecraft, and vice versa. This is of great importance for the disentangling of various effects in the diagnostics of the spatially unresolved vector magnetic fields.

Other useful aspects are:

- the capability to obtain simultaneous Stokes and intensity images at the same line profile positions;
- to obtain full disk and possibly also high resolution Hanle-effect maps of the solar disk for complementary magnetic field diagnostics (see Gandorfer, Stenflo and Wenzler, these proceedings);
- to study different kinds of polarization during flare occurrence (Henoux).

HIGH DYNAMIC POLARIMETRIC CAPABILITY

The overall instrument of Figure 7 is made of a small telescope providing a large field of view, and a package of polarization. The Detector is a smart camera based on CMOS technology with logarithmic output, able to integrate many small differential signals coming from the sequence of incoming modulated frames.

Just a comment for the utility of having a logarithmic output from the sensor:
Figure 6
Enigmatic Na I D1 and D2 Polarization profiles (Stenflo)

Figure 7
Na D1-D2 line Profile Stokes Polarimeter
considering that the input degree of polarization is small, the difference between two sequential frames (taken through a Liquid Crystal modulator synchronized with the camera frame rate) can be considered as a differential, that is

\[ \frac{d(\log I)}{I} = \frac{dI}{I} \quad (I=\text{intensity of the corona}) \]

This means that the polarimeter is directly normalized to the local intensity. The advantage is that the same exposure time is useful for bright as well as for faint regions.

Furthermore, in the case of low contrast images, as the solar disk is, we can select only the useful window of the photometric histogram, before digitization, still mantaining the local normalization. This makes the instrument particularly suitable for very low degrees of polarization. Longer the integration time, smaller is the degree of polarization detected. Our experience with the MOF magnetograph confirms the suitability of this technique (see also Figures 2 and 8).

It is useful to mention here that we have made progress on the solution of two weak element of our instrumentation. They are: the Liquid Crystal Modulator and the MOF cell life.

As for the LC we are in collaboration with the University of Cosenza for the fabrication of a robust unit that is being tested in our laboratory. As far as the cell lifetime our new cells have been used for three years now without failure. Other alternatives are also being considered for both problems.

Finally we note that a complete set of instrumentation is already working and available in our laboratory for tests and improvements.

FINAL REMARKS

Two optical systems can be used to feed the same polarimeter modulation package. One system provides full disk, the other high resolution viewing. The different viewing angle of the Sun from the Orbiter is of great importance for better recordings of the high-latitude and polar magnetic fields than is possible from Earth. In addition there is also the above mentioned fundamentally new aspect in the diagnostics of solar magnetic fields. This is of great importance for the disentangling of various effects in the diagnostics of the spatially unresolved vector magnetic fields.