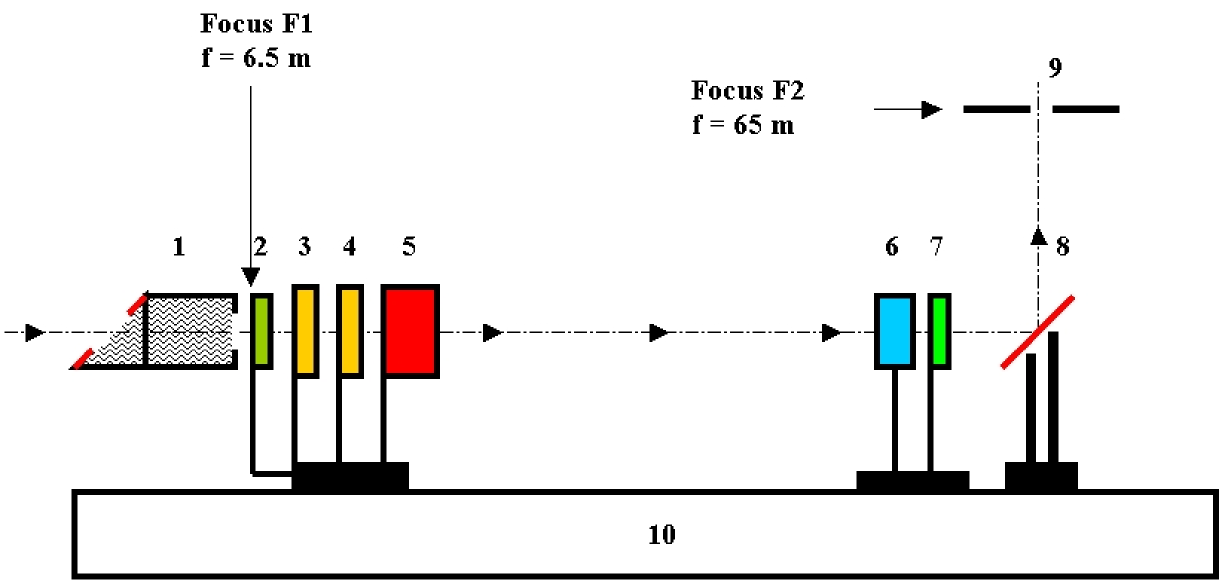
First observations of the second solar spectrum with spatial resolution at the Lunette Jean Rösch

Malherbe, J.-M., Moity, J., Arnaud, J., Roudier, Th., July 2006

The experiment setup in spectroscopic mode

The Pic du Midi LJR is a 50 cm aperture refractor (focal length of 6.45 m for λ = 550 nm at the primary focus F1) supported by an equatorial mount. The beam has an axial symmetry along the optical axis. Polarization analysis is achieved before transmission to the spectrograph by a flat mirror at 45° (Fig. 1). Therefore instrumental polarization is minimized. The spatial resolving power (including the refractor and the spectrograph) is 0.3" in the yellow part of the spectrum. The primary image is magnified 10 times at the secondary focus F2 where the slit of the spectrograph is located, according to the magnification lens, providing an equivalent focal length of 65 m so that the spectrograph operates at f/130. We used a new prototype of liquid crystal polarimeter between focus F1 and F2. It was used for the first time in April 2004 in a simplified version and upgraded to the full Stokes version in September 2004.



1: water cooling device (field stop)
2: UV/IR filter 380-700 nm
3: variable retarder 1
4: variable retarder 2
5: magnification lens (f=60 mm)
6: interference filter
7: precision dichroïc linear polarizer
8: flat mirror
9: spectrograph entrance slit
10: optical rail

Fig. 1*: The optical setup between the primary focus F1 and the secondary focus F2 in spectroscopic mode (the 50 cm refractor is located on the optical axis at left)*

The polarimeter receives white light and has the following elements (Fig 1):

1) Two variable retarders (retardance continuously adjustable between 0 and 700 nm) made by Meadowlark (USA) which combine a single Nematic Liquid Crystal cell with a static birefringent element (Fig. 2). A 2 KHz square wave signal with zero mean value is applied

to the crystal; the amplitude of the signal (0 to 10 V) determines the retardance. The maximum birefringence (so the maximum retardance) is obtained for an amplitude of 0 V and decreases continuously with increasing voltage (no retardance at about 6 V). Consequently, a variable retarder can be exactly quarter or half wave for any wavelength according to the voltage applied to the electrodes. The calibration was performed in laboratory using a white light source, various interference filters of 10 nm bandwidth, with a 10 bits CMOS camera used as a detector and mounted on an optical rail (Fig. 3). It takes about 25 ms for the retarder to switch between zero to half wave using fast transient nematic effect: in order to speed up the response of the crystal, a high to low voltage transition is preceded by a short (5 ms) 0 V pulse, while a low to high voltage transition is preceded by a 10 V pulse. The NLC is protected by a pass band filter in order to avoid damage of the crystal by the UV radiation (below 380 nm), and heating by IR radiation (above 700 nm). The temperature of the two liquid crystals is controlled permanently (active heating by resistive elements and passive cooling) and is ordinary set to 20° C.

2) A precision dichroïc linear polarizer from Meadowlark (USA) is located at the exit of the system, on the optical axis, before the reflecting mirror to the spectrograph. The acceptance axis is orthogonal to the long direction of the entrance slit in order to be orthogonal to the rules of the Echelle grating of the spectrograph (maximum luminosity). The precision of the polarizer is of the order of 10^{-5} (this value represents light transmission through two identical crossed polarizers). The fast axis of the first retarder is parallel to the acceptance axis of the polarizer, while the fast axis of the second retarder makes an angle of 45°.

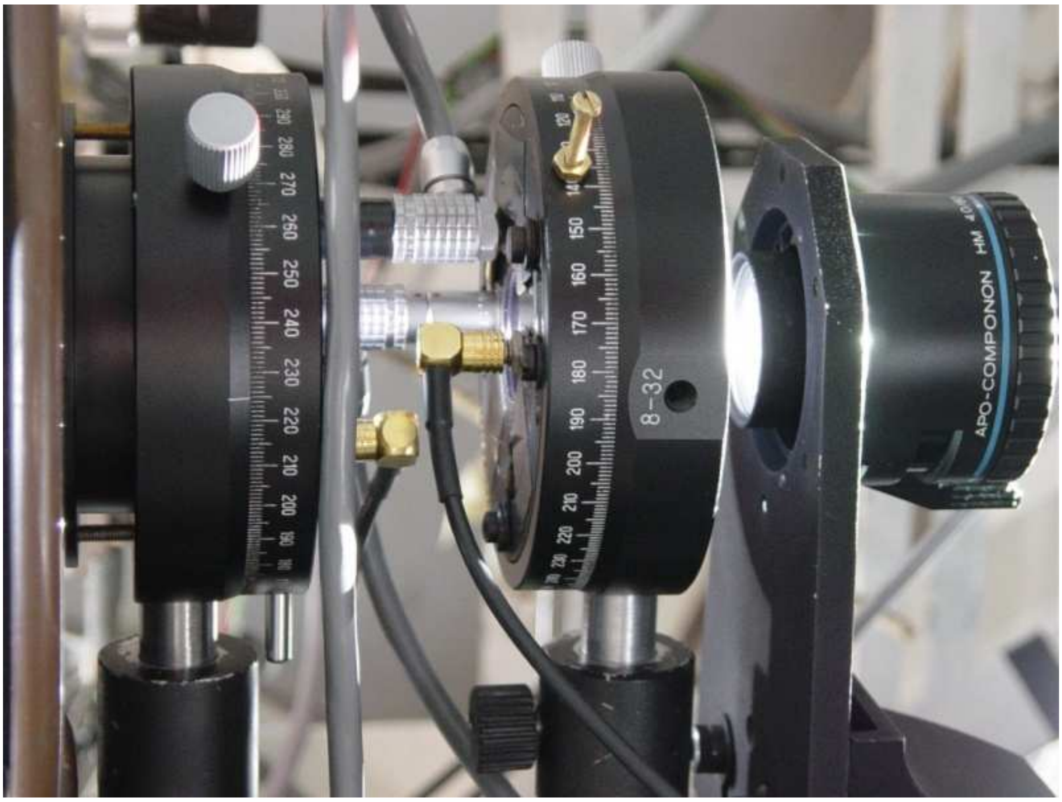


Fig. 2*: the two variable retarders (at left) and the magnifying lens (at right) in the beam near focus F1 with wires for temperature control and modulation*

Version of the polarimeter with two retarders:

The signal S provided by the polarimeter with two NLC is given by :

$$S = (1/2) (I + Q \cos\delta 2 + \sin\delta 2 (U \sin\delta 1 - V \cos\delta 1))$$

where I, Q, U and V are the Stokes parameters defined by the relations:

$I = AA^* + BB^*$
$Q = AA^* - BB^*$
$U = A^*B + AB^*$
$V = i\,(A^*B - AB^*)$

A and B are the complex amplitudes of the electric field (the conjugate quantity is denoted by the star) $E = (A\,e^{i\varpi t}, B\,e^{i\varpi t}, 0)$, $\varpi = 2\,\pi / \nu$, ν frequency of the light, in a reference frame where the x axis is the geographic East West direction, the y axis is the geographic North South direction of the equatorial mount of the refractor, and the z direction is the optic axis. $\delta 1$, $\delta 2$ are the retardance of the two NLC. When the first retarder is set to 0 wave ($\delta 1 = 0$), and when the second retarder modulates between quarter ($\delta 2 = \pi/2$) and three quarter wave ($\delta 2 = 3\pi/2$), we get sequentially I +/- V; when it modulates between 0 ($\delta 2 = 0$) and half wave ($\delta 2 = \pi$), we obtain I +/- Q. In order to measure I +/- U, the first retarder must be set to quarter wave ($\delta 1 = \pi/2$), while the second retarder has to modulate between quarter ($\delta 2 = \pi/2$) and three quarter waves ($\delta 2 = 3\pi/2$). In our reference frame, the angle α of the polarization direction with x axis is given by $\alpha = (1/2)$ arc tan (U / Q) so that Q characterizes schematically the linear polarization parallel or orthogonal to x axis (A = 0 or B = 0 gives U = 0), while U is related to the linear polarization at +/- 45° of x axis (A = +/- B implies Q = 0). V as usual characterizes the circular polarization.

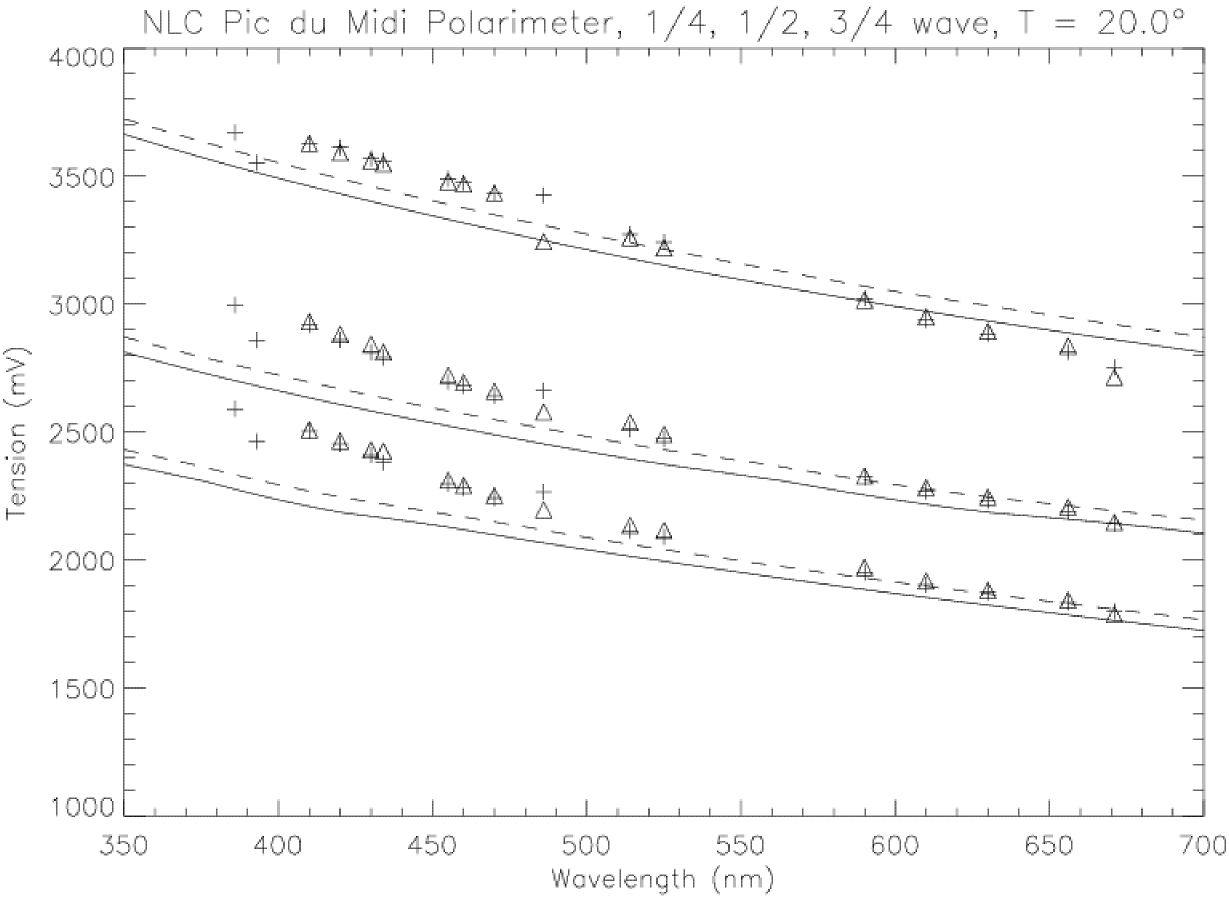


Fig. 3*: the voltage applied to the two NLC as a function of wavelength for quarter (top), half (middle), or three quarter (bottom) wave retardance. Crosses and triangles indicate our calibration points obtained with various interference filters (10 nm bandwidth) for the two retarders at 386, 393, 410, 420, 430, 434, 455, 460, 470, 486, 514, 523, 590, 610, 630, 656 and 670 nm. For comparison, the two curves were extrapolated from data provided by the manufacturer.*

Version of the polarimeter with one retarder:

We use for observations which do not require the full Stokes configuration a simplified version of the polarimeter, running only with one retarder (no possible U determination). In such a configuration ($\delta 1$ is permanently set to zero), the polarimeter allows in practice modulation from zero to three quarter waves, providing analysis either of the circular or linear polarization of light. Hence, Stokes parameters I +/- V are obtained sequentially from the output signal :

$S = (1/2)\,(I + Q\cos\delta - V\sin\delta)$

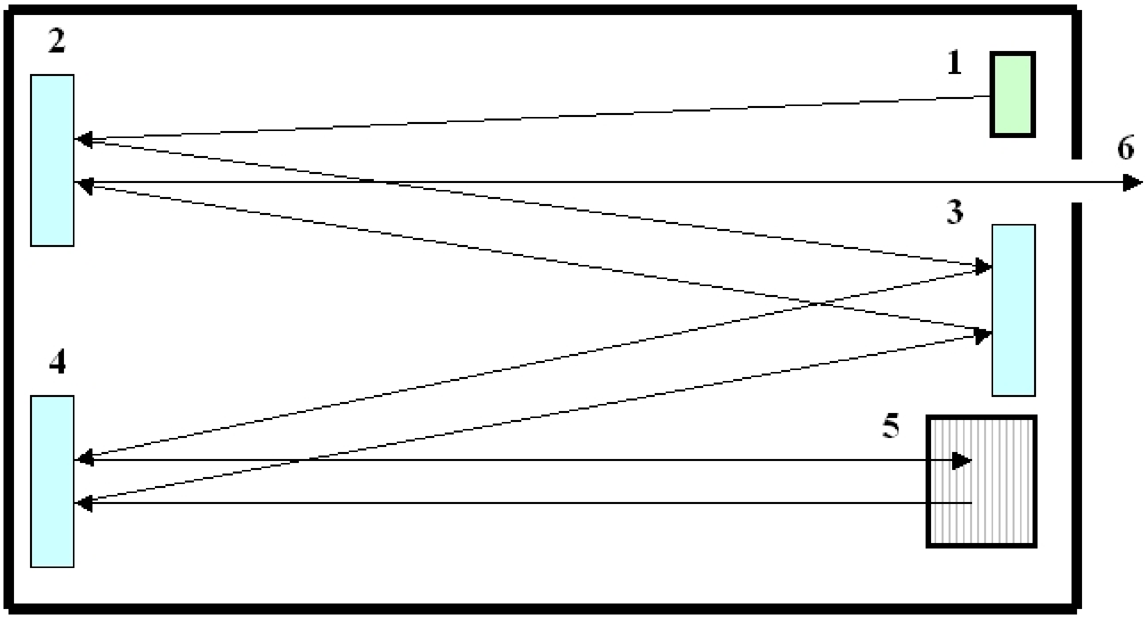
where $\delta = (\pi/2, 3\pi/2)$ is the retardance of the NLC. This property was used by Roudier et al. (A & A, 2006, in press) for high resolution Zeeman magnetometry on the disk. In the present paper, we are interested only by I +/- Q which were derived from this formula with $\delta = (0, \pi)$.

Since measurements of I +/- P (where P is any Stokes parameter) are not simultaneous, our polarimeter can operate with a good efficiency in two particular domains:

1) observations of the line of sight magnetic fields on the disk, with the 2D imaging spectroscopy device provided by the Multichannel Subtractive Double Pass (MSDP), as described by Malherbe et al. (A & A, 2004, 427, 745) and Mein (A & A, 2002, 381, 271); with a 2D field of view, we use cross correlation and destretching methods to superimpose properly solar structures observed sequentially in two states of circular polarization (I +/- V);
2) observations of the second solar spectrum near the limb; since the polarization degrees are small (less than 1%), the signal has to be derived from the statistical analysis of hundreds or thousands of spectra obtained sequentially, in order to improve the signal to noise ratio. Consequently, non simultaneous measurements of I +/- Q have a moderate impact on the final polarization rates. Since the spectrograph has a good transmission in the blue part of the spectrum, and the CCD detector has the maximum quantum efficiency (65%) around 400 - 500 nm, our observations are mainly focused in this range of the second solar spectrum. We started observations with two scientific goals:
   - measurements of weak polarizations (0.01%) at moderate spatial resolution: when the seeing conditions are not excellent, we use a 0.6” x 140” slit and accumulate a large amount of spectra to achieve the best polarimetric sensitivity as possible; data can be averaged partially or totally along the slit to reduce the noise.
   - measurements of stronger polarizations (0.1% to 1%) at higher spatial resolution, as in the SrI 460.7 nm line: when the seeing conditions are fairly good, we use a thin slit of 0.3” x 140” in order to select structures along the slit, in terms of bright and dark regions. Such a diagnostic is theoretically able to bring new information about turbulent unresolved magnetic fields in the structures of the quiet sun.

The spectrograph

We used the 8 meter Littrow Echelle spectrograph (Fig. 4) built by Paris Observatory at the LJR twenty years ago and modified later for 2D spectro imagery (MSDP). The dispersive element is a grating (316 rules/mm, blaze angle 63° 26’) and provides a typical dispersion of 50 mm per nm at the focus of the spectrograph. The interference order is isolated by filters of typically 10 nm bandwidth. The spectrum obtained at the focus of the spectrograph is reduced to form on a CCD camera from LaVision (Germany) with temperature control (Peltier cooling at –10° C). This is a shutterless interline scan camera using a detector with microlenses manufactured by Sony (1376 x 1040, 6.45 μ square pixels). The spatial pixel size on the CCD is 0.2” along the slit direction and the spectral pixel size around 1.1 pm (in the blue part of the spectrum) in our setup. Each pixel can accumulate up to 20 000 electrons corresponding to a dynamic of 12 bits (readout noise of 4-5 electrons, gain of 4 electrons per analog digital unit). In general, we work in the continuum at 0.8 times the saturation level giving approximately a signal to noise ratio of 120, corresponding to a photometric accuracy of 0.8 10^{-2}. In the core of the lines (smaller number of photons), this precision can drop to about 1.6 10^{-2}. The exposure time is typically 50 ms during our runs around 450 nm at μ = 0.15 (limb distance of 10”) with the 0.6” slit.



1 : flat mirror (45°) 2,3: flat mirrors 4: collimator f = 8 m
5: grating (316 groves/mm, blaze angle 63°26’)
6: spectrum, transfer optics to the detector

Fig. 4*: the 8 m Littrow Echelle spectrograph.*

Signal to noise ratio

Our polarimetric observations consist of shooting sequentially as fast as possible couples of images I +/- Q (typically 700 pixels in the solar direction x 300 pixels in the spectral direction). The polarimeter is able to run at the frequency of 40 Hz, but in practice we are limited by exposure times and by the readout speed of our CCD camera and data acquisition system, so that the maximum speed is at best 10 Hz around 450 nm, including polarimetric modulation.

Since a couple of images I +/- Q has a photometric precision of about 10^{-2}, one hour of observation at the limb at 450 nm allows to reach roughly 10^{-4} with the average throughput of 5 images/s. It is even possible to attain weaker polarization signals by integrating partially or totally in the solar direction along the slit (700 pixels). In the case of total integration, a single couple of images I +/- Q will deliver a precision better than 10^{-3}, and after one hour of observations, a ratio better than 10^{-5} can be achieved.

Flat Field and data processing

Flat field observations are made around disk center in the quiet sun where linear polarization signals should vanish. But good flat fielding is a difficult challenge at the LJR because the spectrograph is attached to the refractor (in equatorial mount) and moves with time, producing very small but permanent mechanical shifts. For that reason, the spectral line has to be precisely tracked by the software at sub pixel precision in the direction of dispersion. For observations on the disk, the transversalium is followed in the direction of the slit, while for observations with the slit perpendicular to the limb, the position of the limb itself is detected by the software with about 1" accuracy, depending on seeing. The flat field is consequently never done exactly in the same conditions than the observing run. In particular, polarization fringes cannot not be properly corrected by the flat field procedure. They are not important for polarizations in the range 10^{-3} to 10^{-2} but have to be considered carefully for polarizations of 10^{-4} or smaller. We have two kinds of fringes: filter fringes (mainly due to the interference filter) which have a level of about 1% to 2% of the continuum and vanish in the difference between two consecutive states of polarization; and polarization fringes (due to the variable retarders), which are more than 100 times fainter (0.01% of the continuum) and which appear only after a long time of integration in the difference between alternate polarizations. Such fringes are hard to handle, because the residual pattern generally shifts slowly during the observing run and is comparable to weak solar polarizations signals (10^{-4}). Flat fielding is very useful to determine precisely the transmission of the instrument for the two states of polarization (a difference of about 0.2% is typical, depending on the line, because the transmission of the NLC varies slightly with retardance). We make the assumption that the polarization rate is null at disk center in the quiet sun, and determine the zero level of the polarization signal from the flat field as a function of wavelength (the retardance in the observed spectral range varies faintly with wavelength and consequently induces a Q/I slope of about 5 10^{-4} per nm which is easily corrected by linear adjustment).

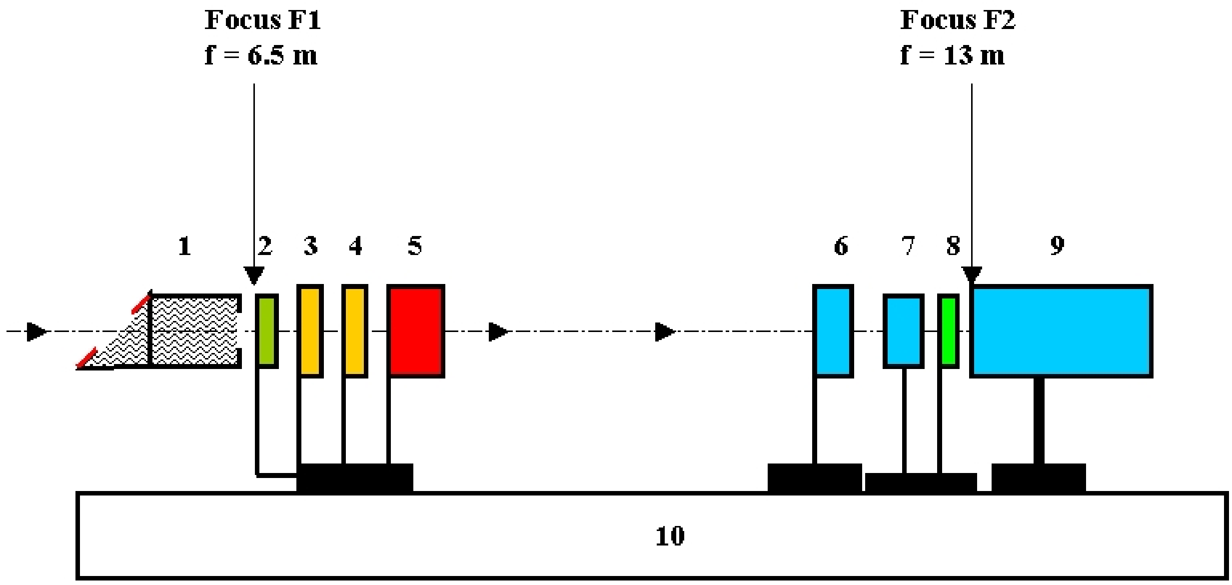
Stability of polarization measurements

The stability of polarization measurements may be affected by several effects, as solar, but also seeing and instrumental variations. It was noticed in the past that the image quality deteriorates when the main objective holder is heated by the sun. For that reason, P. Mehltretter suggested to protect the holder by a reflective ring with clear aperture corresponding exactly to the diameter of the lens (Fig. 5). We discovered that instrumental depolarization (up to –25 %) occurs without the ring two hours before and after the meridian. With the ring, we measured only small fluctuations which are mainly due to variations of the limb distance which can move within a few arc sec between each test, as we do not have a precise guiding system. In conclusion, if it remains some instrumental depolarization, it is not easily detectable.

Fig. 5*: Mehltretter's ring to avoid heating of the lens holder.*

The experiment setup in imagery mode

The instrumental setup is presented in Fig. 6. The polarimetry system is identical to the one used in spectroscopy, but the magnification is smaller (x 2), so that we work at f/30 instead of f/130 in spectro polarimetry. The field of view is 100” x 120” with a pixel size of 0.1”. The detector is installed on the optical rail, at the location of the injection mirror to the spectrograph which is removed for the circumstance.



1: water cooling device (field stop)
2: UV/IR filter 380-700 nm
3: variable retarder 1
4: variable retarder 2
5: magnification lens (f=95 mm)
6: neutral density
7: interference filter
8: precision dichroïc linear polarizer
9: detector
10: optical rail

Fig. 6*: The optical setup between the primary focus F1 and the secondary focus F2 in imagery mode (the 50 cm refractor is located on the optical axis at left)*

Ongoing developments for the spectroscopic mode

From a technical point of view, we know that the present version of our polarimeter has still some limitations which will be removed in the future. In particular, polarization signals I +/- P (P = Q, U, V) are observed sequentially because the analyser is a simple (high quality) dichroïc linear polarizer. A new device is under development to replace it (Fig. 7), consisting of a birefringent linear polarizing beam splitter shifter which will allow to observe simultaneously both signals, so that I +/- P will be focused at the same time on the CCD detector. As a consequence, the field of view will be reduced by a factor two, from 140” to 70” along the sun. The beam splitter shifter will be tested by the end of 2006 and will be located at focus F2 (Fig. 8) just after the entrance slit of the spectrograph. This improvement is of special importance for the polarimetry of specific solar structures observed on the disk (active regions, flux tubes) or at the limb (spicules, prominences) which require perfect coalignment of both signals, in order to eliminate seeing induced polarimetric cross talks. But observations of the second solar spectrum does not suffer from this default, because of statistical effects due to the large amount (thousands) of spectra required to achieve a convenient signal to noise ratio. Beam exchange will be available with the new beam splitter especially for the measure of weak polarization signals.

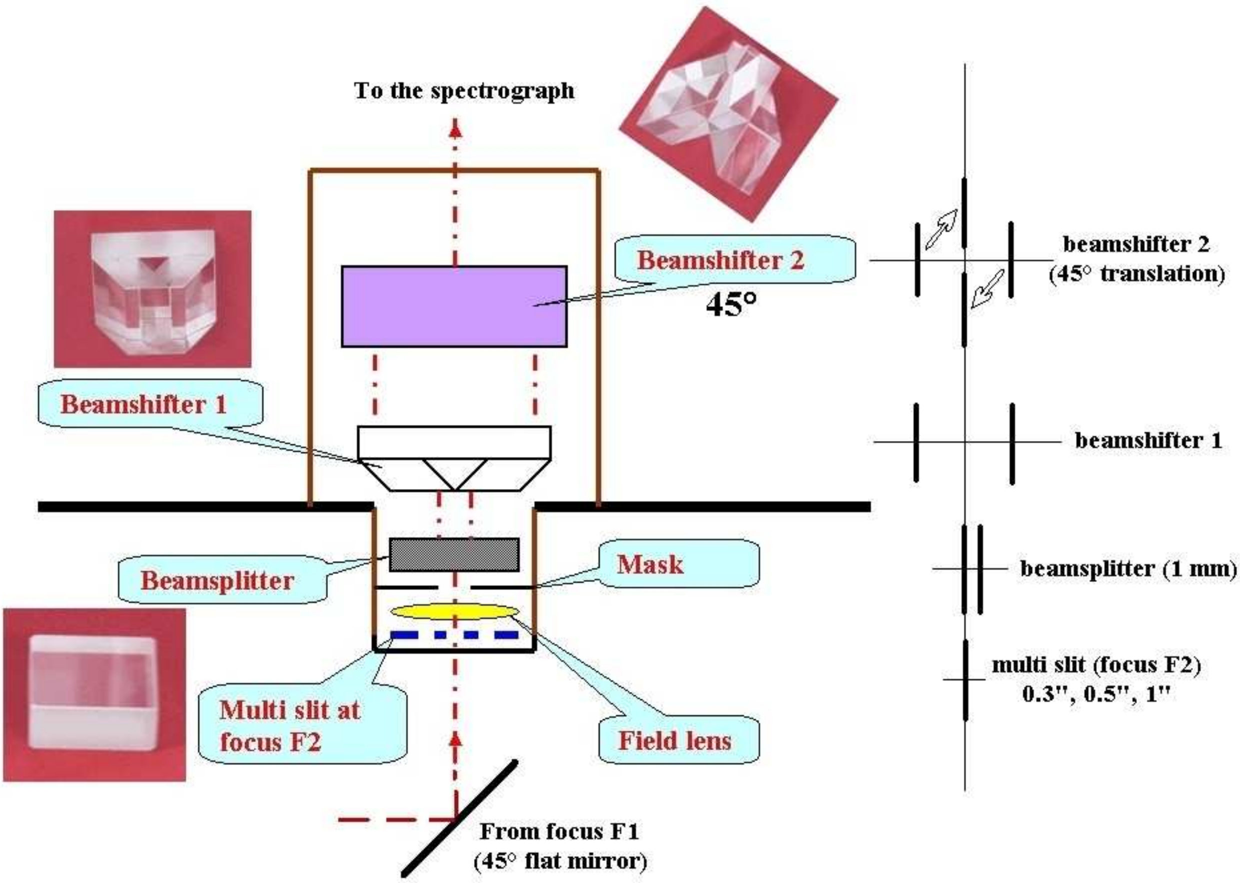
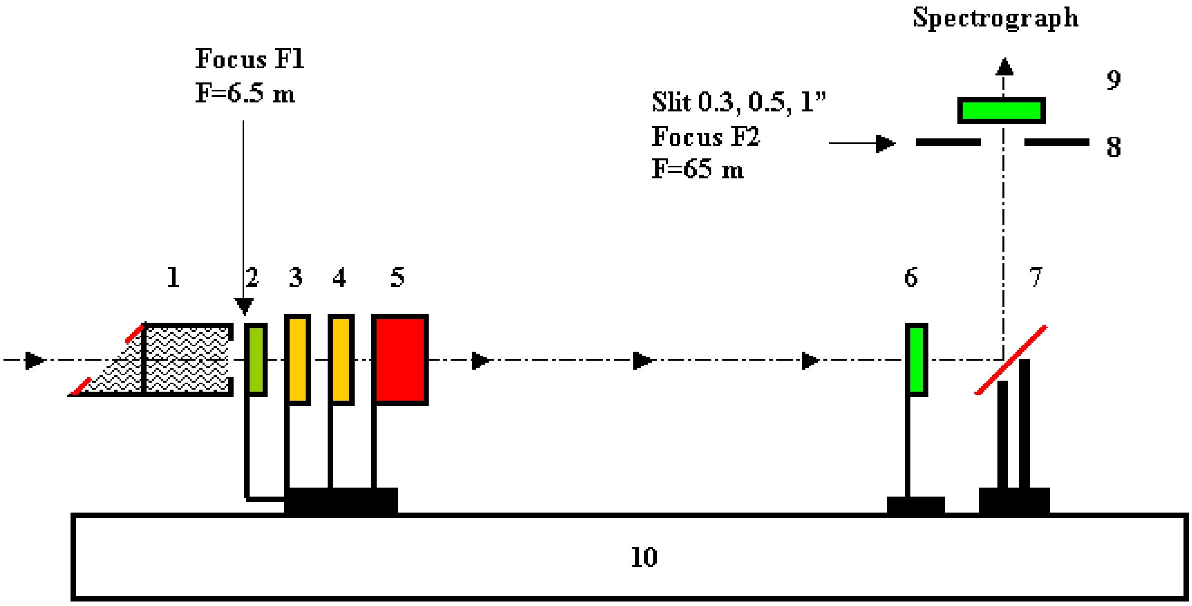


Fig. 7: *Details of the polarizing beam splitter shifter (end 2006)*



1: water cooling device (field stop)
2: UV/IR filter 390-700 nm
3: variable retarder 1
4: variable retarder 2
5: magnification lens (f=60 mm)
6: interference filter
7: 45° flat mirror
8: slit (focus F2)
9: polarizing beamsplitter/shifter
10: optical rail

Fig. 8: *the experiment setup with the polarizing beam splitter shifter (end 2006)*