Liquid Crystals Lyot Filter for Solar Coronagraphy

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ABSTRACT

The "Association de Satellites Pour l'Imagerie et l'Interférométrie de la Couronne Solaire", ASPIICS, is a solar coronagraph to be flown on the PROBA 3 Technology mission of the European Space Agency. ASPIICS heralds the next generation of coronagraphs for solar research, exploiting formation flying to gain access to the inner corona under eclipse-like conditions in space. The science goal is high spatial resolution imaging and two-dimensional spectrophotometry of the Fe XIV, 530.3 nm, emission line. This work describes a liquid crystal Lyot tunable-filter and polarimeter (LCTP) that can implement this goal. The LCTP is a bandpass filter with a full width at half maximum of 0.15 nm at a wavelength of 530.3 nm. The center wavelength of the bandpass is tunable in 0.01 nm steps from 528.64 nm to 533.38 nm. It is a four stage Lyot filter with all four stages wide-fielded. The free spectral range between neighboring transmission bands of the filter is 2.7 nm. The wavelength tuning is non-mechanical using nematic liquid crystal variable retarders (LCVR's). A separate LCVR of the Senarmont design, in tandem with the filter, is used for the polarimetric measurements. A prototype of the LCTP has been built and its measured performances are presented here.

Keywords: spectro-polarimetry, solar coronagraphy, liquid crystals

1. INTRODUCTION

Spectroscopic and imaging observations of the solar corona in visible-light and infrared emission lines are a valuable tool for the diagnostics of the dynamics of the solar corona. Emission profiles from forbidden transitions of the "Green Line" (Fe XIV, 530.3 nm) and the "Red Line" (Fe X, 637.4 nm) contain information on physical parameters such as temperature, mass motion, and turbulence. For instance, Fabry-Perot (F-P) interferometric observations in the coronal "Green Line" (Fe XIV, 530.3 nm) and "Red Line" Fe X, 637.4 nm) have detected Doppler shifts that provided significant information on the macroscopic mass motions (e.g., waves) in the corona [1]. Doppler widths measurements together with imaging of the "Green" and "Red" lines with the piezo-electrically tunable F-P of LASCO-C1 have allowed the building of radiance and temperature maps of the off-limb solar corona [2]. Alfvén waves were detected in intensity, line-of-sight velocity, and linear polarization images of the solar corona taken using the FeXIII 1074.7 nm coronal emission line using an electro-optically tunable birefringent filter [3]. This is a Lyot four-stage calcite birefringent filter [4] where each of the calcite stages has a corresponding Nematic Liquid Crystal Variable Retarder (LCVR) for spectral tuning.

This type of electro-optically tunable filter presents several advantages for space-based coronagraphy: there are no moving mechanisms, unlike in the piezo or tiltable F-Ps; the Lyot filter has polarimetric and 2D imaging capabilities, unlike the interferometric measurements with the tiltable F-P that is limited to 1D imaging [1]. Electro-optically tunable F-Ps, with no moving mechanisms, have been developed by laminating birefringent, nematic liquid crystals (LC) between the substrates of an etalon [5]. However, these devices do not make use of LCVRs, and cannot be used for both spectroscopic and polarimetric measurements, as the LCVR-based Lyot filters [3]. For these reasons, a Lyot tunable-filter and polarimeter has been proposed as an alternative to the tiltable F-P etalon that represents the baseline configuration for spectro-polarimeter in the coronagraph "Association de Satellites Pour l'Imagerie et l'Interférométrie de la Couronne Solaire" [6]. ASPIICS, is a solar coronagraph to be flown on the PROBA 3 Technology mission of the European Space Agency. ASPIICS heralds the next generation of coronagraphs for solar research, exploiting formation flying to gain access to the inner corona under eclipse-like conditions in space [7]. The science goal is high spatial

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resolution imaging and two-dimensional spectrophotometry of the Fe XIV, 530.3 nm, emission-line. This work shows how the proposed liquid crystal Lyot tunable-filter and polarimeter can implement this goal. The performances of this high-resolution ($\lambda/\Delta\lambda$ = 3.5E+3), Liquid Crystal Tunable – filter and Polarimeter (LCTP) were compared with the those of a classical very high-resolution ($\lambda/\Delta\lambda$ = 2.5E+4) Fabry – Perot (F-P) etalon that is mechanically tilted for spectral tuning. The results of the tests show that even if the F-P etalon has a higher instrumental resolution, the LCTP has the same effective spectral resolution thanks to its electro-optical fine-tuning capability in wavelength. In addition, the LCTP has the advantage over the F-P etalon of using no mechanisms, and of having polarimetric and imaging capabilities.

2. FILTER DESIGN

This liquid crystal Lyot tunable-filter and polarimeter is a customized version of a standard product line of Meadowlark Optics [8]. It is a bandpass filter with a full width at half maximum of 0.15 nm at a wavelength of 530.3 nm. The center wavelength of the bandpass is tunable in 0.01 nm steps from 528.64 nm to 533.38 nm. It is a four stage Lyot filter with all four stages wide -fielded in the manner described by Evans using split elements with intervening half wave retarders [4]. The free spectral range between neighboring transmission bands of the filter is more than 2.7 nm.

The wavelength tuning is non-mechanical using nematic liquid crystal variable retarders (LCVR's). The filter is passively thermally-compensated so that the wavelength change with temperature is less than 0.003 nm/°C over the temperature range of 21° to 26°C. The bandpass center wavelength is computer controlled using Meadowlark Optics' standard filter controller with software modified to permit the fine-tuning steps required for this application.

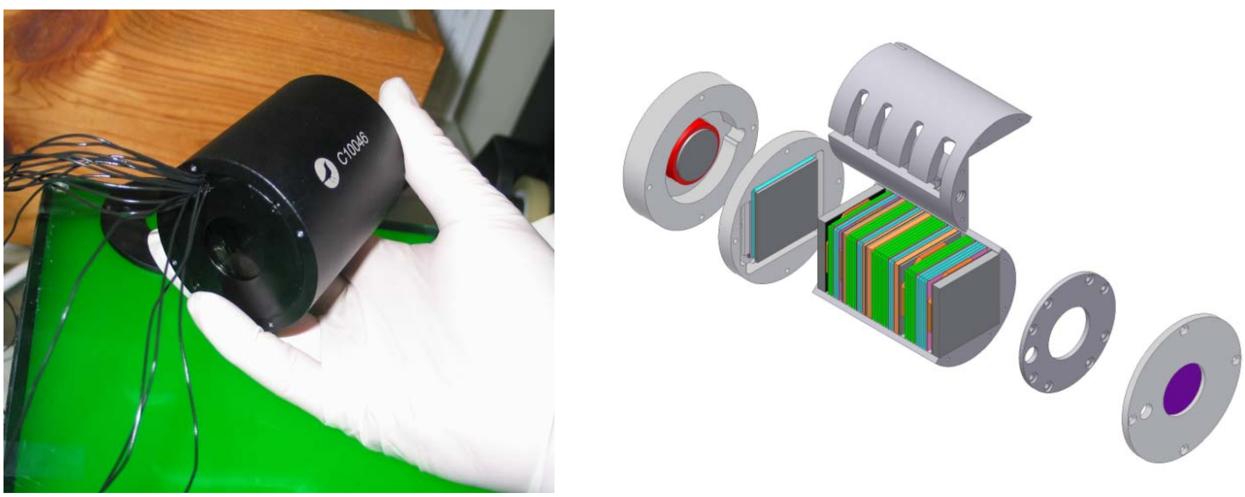

Figure 1 Left: *The filter prior to adding the electrical connector for LCVR control.* ***Right:*** *Filter mechanical assembly. The prefilter and the LC Polarization Rotator (LPR) are shown to the left of the main filter*

The filter has an attached linear polarization rotator (LPR) that permits non-mechanical user control of an input linear polarization direction over a 180° range using LCVR's. The LPR is also controlled with the filter controller. There is also an attached pre-filter from Andover Corporation with a full width at half maximum of 1.89 nm and a center wavelength of 530.69 nm. There is a small heater attached to the cell of this pre-filter to control its temperature to 23°C since it has a temperature wavelength shift of 0.017 nm/°C, much higher than the tunable filter. The filter is 60 mm in diameter and 90 mm long with a clear aperture of 20 mm and is shown in Figure 1, together with a mechanical drawing of the filter assembly. The tunable filter is a four stage Lyot filter. Each stage is a Type 1 wide field combination of two fixed multi-wave retarders as described by Evans [4]. An LCVR is added to permit each stage to be independently tuned in wavelength as shown in Figure 2. A shim retarder is added to the multi-wave retarders to center the transmission wavelength of each stage at 530.3 nm when no voltage is applied to the LCVR.

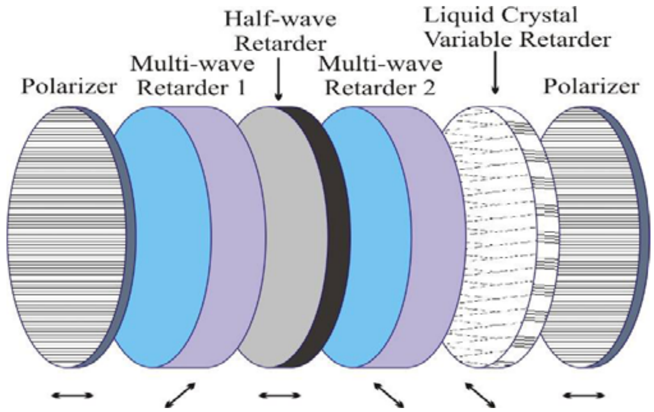

Figure 2 *Shows the optical configuration of a stage in the tunable filter.*

3. FILTER CALIBRATION AND PERFORMANCES

The filter was calibrated at Meadowlark Optics on a 0.85 meter f/7.8 double Czerny Turner spectrometer. The entrance and exit slits were set to 20 μm for most tests, which corresponds to about 0.005 nm spectral width since the plate scale is approximately 0.25 nm/mm. The intermediate slit width between the first and second gratings is 1mm, which is a spectral bandwidth of 0.25 nm. The filter was tested in a collimated beam from a quartz tungsten halogen light source preceding the entrance slit of the spectrometer. The full aperture of the filter was illuminated for the test results in this report except for the study of variation of the spectral bandpass with angle of incidence. The wavelength calibration of the spectrometer is checked using a neon line source with an emission line at 533.078 nm. Calibration is stable to ±0.005 nm over a period of several weeks. The detector at the spectrometer exit slit is a Hamamatsu H5784-04 photomultiplier tube. Spectral measurements were made at a wavelength step interval of 0.004 nm for the test results shown in the following sections.

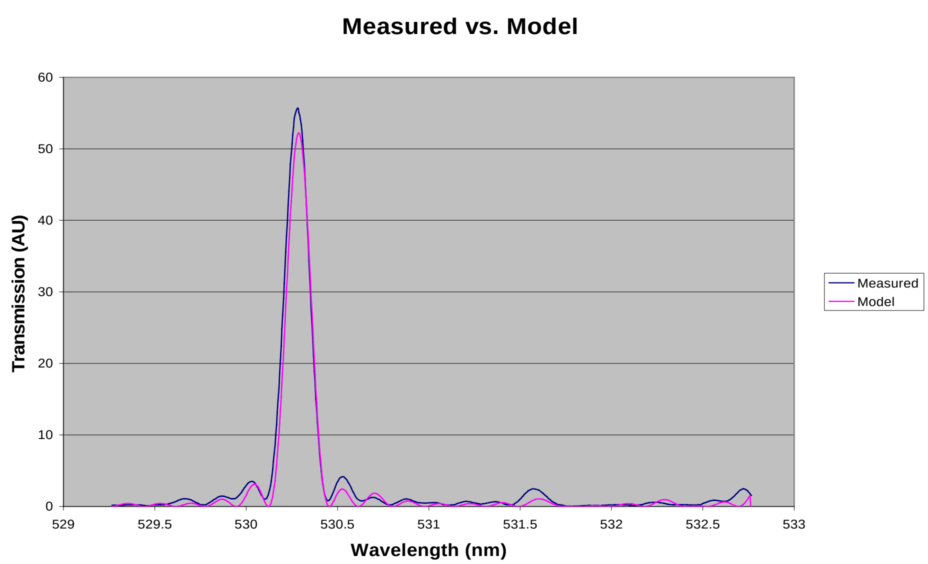

Figure 3 *Comparison between the modeled and measured filter profile at a wavelength of 530.0 nm. The transmission scale is linear but is in arbitrary units.*

3.1 Filter Spectral Profile

There is good agreement between the calibration measurements and the modeled results as shown in Figure 3. The measured full width at half maximum of the filter profile is 0.15 nm. The measured peak transmission of the filter is 29% for polarized light. The error on the peak transmission measurement is ±3% because of the difficulty of avoiding walk-off of the beam on the spectrometer entrance slit when the filter is inserted in the collimated test beam.

The filter center wavelength is tunable in steps as small as 0.01 nm from 528.64 nm to 533.38 nm. The tuning is non-mechanical using LCVR's. Additionally the filter has a fail state, zero voltage transmission profile centered at 530.34 nm. The tests show that the filter is quite stable over time and for a range of temperatures as shown in Figure 4

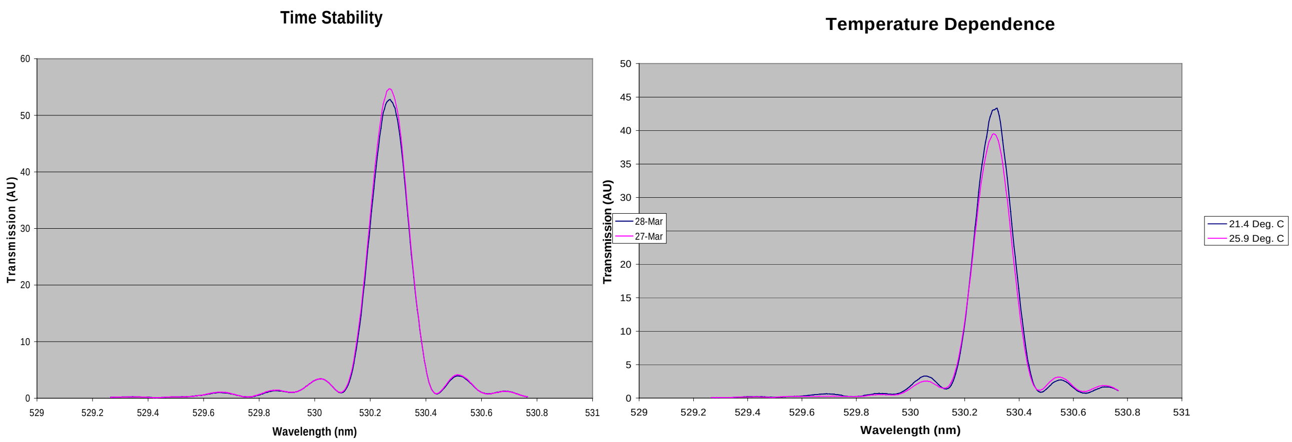

Figure 4 Left: *Filter profile on two successive days when electrically driven to 530.3 nm. The peak transmission is in arbitrary units and differs between the two days probably because of changes in the lamp intensity.* ***Right:*** *Thermal stability of the filter with a passive thermal compensation scheme. The electrical drive voltage to the tuning LCVR's is unchanged between the two scans.*

Figure 5 shows the fine-tuning capability of the filter. Although the tuning steps here are 0.02 nm, they can be as small as 0.01 nm.

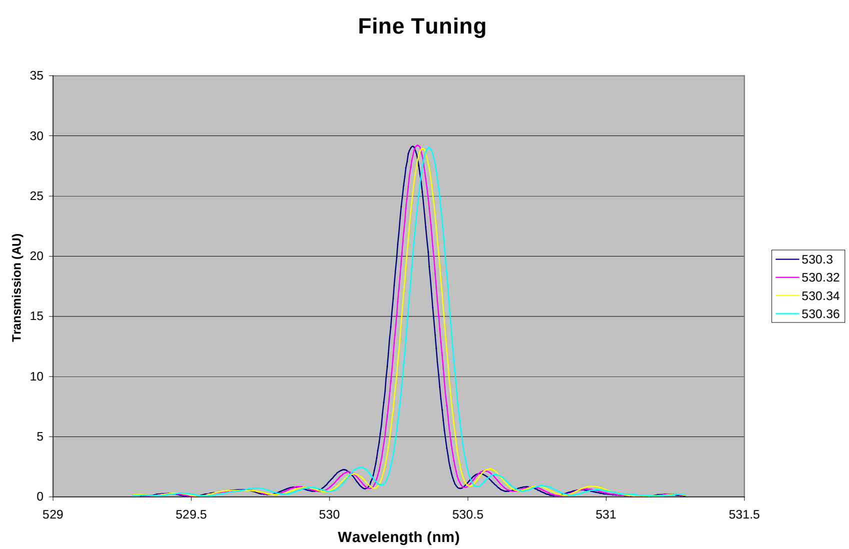

Figure 5 *Fine tuning capability of the filter.*

There is only a small change in the filter wavelength over angle of incidence. The spectral scans of Figure 6 show almost no change for angles smaller than 6°. At 6° the shift is approximately 0.03 nm. The transmission change with angle of incidence is due to a test system efficiency change with angle of incidence and does not represent a real change in filter performance. The transmission efficiency changes with angle of incidence because of beam walk on the spectrometer entrance slit.

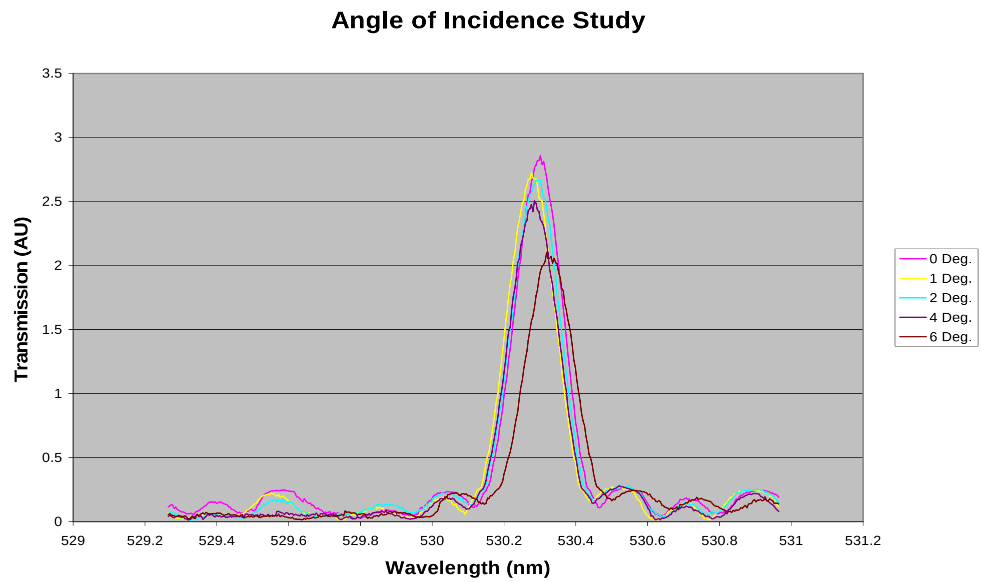

Figure 6 *There is a very small dependence of the filter center transmission wavelength on angle of incidence. The change in peak transmission is an artifact of the measurement and does not represent a real transmission change.*

3.2 Prefilter and LC Polarization Rotator

The prefilter has a measured center wavelength of 530.65 nm at 22° C (530.69 per Andover at 23° C) and a measured full width at half maximum of 1.88 nm (1.89 nm per Andover). Figure 7 shows the measurement of the prefilter transmission.

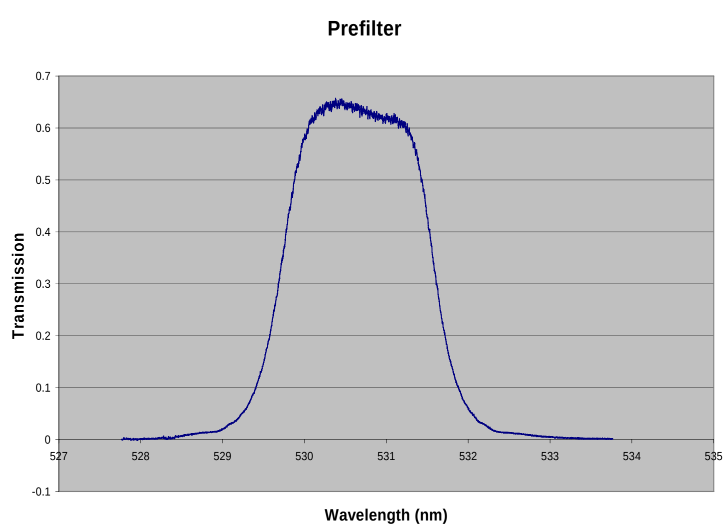

Figure 7 *Measured prefilter transmission profile.*

The linear polarization rotator (LPR) is of the Senarmont design and therefore contains a fixed quarter wave retarder plus an LCVR. The measured rotation vs. the requested rotation by the controller is shown in Figure 8. The 0° direction is defined to be parallel to the direction of the input and exit polarizers of the filter. This direction is at 45° to the edges of the LPR optical assembly.

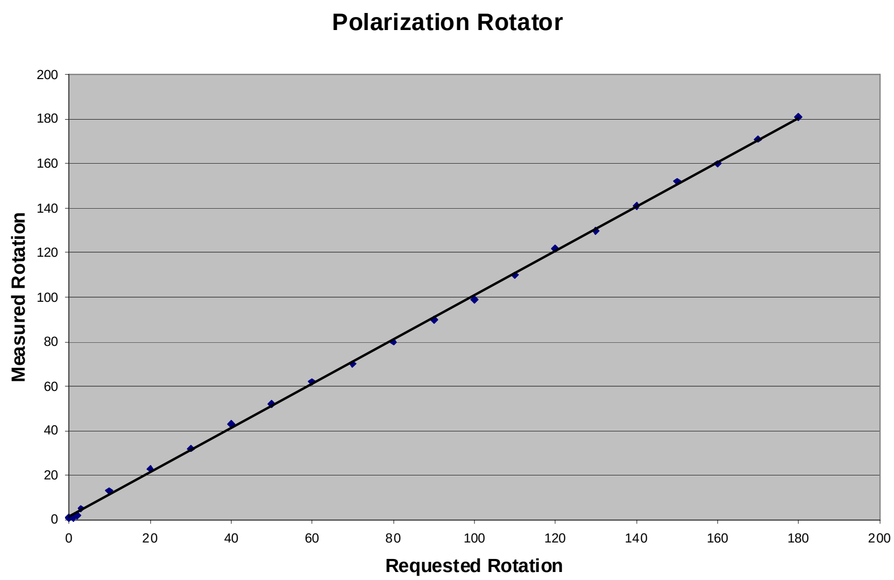

Figure 8 *Measured rotation of the LPR, polarization rotator.*

4. COMPARISON BETWEEN THE LC TUNABLE-FILTER AND THE F-P ETALON

A mechanically tiltable F-P etalon represents the baseline configuration for spectrometry in the ASPIICS coronagraph onboard the formation-flying ESA mission Proba-3. The science goal of ASPIICS is high spatial resolution imaging and two-dimensional spectrophotometry of the Fe XIV, 530.3 nm, coronal emission-line. In order to verify whether a LC Lyot tunable-filter and polarimeter is a better alternative to achieve this goal, the performances of this Liquid Crystal Tunable – filter and Polarimeter (LCTP) were compared with the performances of a classical very high-resolution F-P.

4.1 Characteristics of the LC Tunable-filter versus the F-P Etalon

The baseline configuration for the spectro-polarimeter in ASPIICS is a fixed-gap Fabry-Perot etalon that is spectroscopically tunable by mechanically tilting the angle-of-incidence (AOI). The LCTP is a bandpass filter with a full width at half maximum of FWHM = 0.15 nm at a wavelength of 530.3 nm. The center wavelength of the bandpass is tunable in 0.01 nm steps from 528.64 nm to 533.38 nm. The free spectral range (FSR) between neighboring transmission bands of the filter is FSR = 2.4 nm. This results in a Finesse (= FSR/FWHM) of 17. The wavelength tuning is achieved electro-optically with nematic LCVR's.

Table 1 summarizes the respective characteristics of the LC Lyot filter and the F-P etalon. The higher spectral resolution (and Finesse) of the F-P etalon is compensated by the finer spectral tuning step of the LCTP. The lower transmissivity of the LCTP balanced by the broader bandpass, resulting in a signal-to-noise ratio (SNR) twice that of the F-P. The aim of the tests reported in this paper was to assess the spectroscopic capabilities of the LCTP and F-P etalon in retrieving the center wavelength (CW) and spectral width (FWHM) of visible-light radiation dispersed by a monochromator and representing a "synthetic" spectral line of known characteristics.

Filter	F-P Etalon	LCTP
Spectral Resolution (nm)	0.02	0.15
Spectr. Tuning step (nm)	0.02	0.01
Free Spectr. Range (nm)	0.5	2.5
Finesse	25	17
No. of fringes at AOI = 20°	40	900 (Effective)
Spatial Res. (arcsec)	120	5
Transmissivity	70%	30%
SNR/SNR$_{F-P}$	1	2

Table 1 *Characteristics of the LC Lyot filter and the Fabry-Perot etalon.*

4.2 Experimental Set-up

Figure 9 shows the schematic layout of the experimental set-up used for the tests of imaging spectroscopy. The source is a quartz – tungsten halogen (QTH) lamp. The light is dispersed by a monochromator with 0.1 nm bandpass. A diffuser (D) and a f_1 = 140 mm collimating lens (L1) ensure a uniform collimated beam illuminating the spectro-polarimeter (either F-P or LCTP). A f_2 = 1131mm camera lens (L2) forms an image of the slit, reflected by a folding mirror (FM), on the detector. The linear polarizer is mounted only for the calibration of the LCTP (for polarimetric tests). The F-P etalon is mounted on a rotation stage, a fixed mount is used for the LCTP. The detector is a 1024×1024 pixels CCD camera.

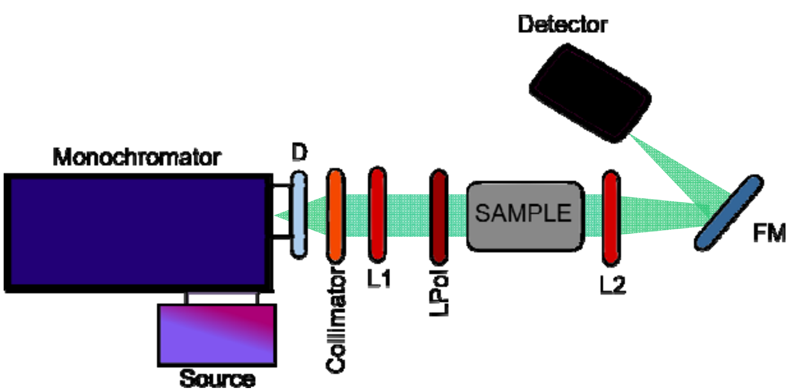

Figure 9 *Schematic diagram of the experimental set-up*

4.3 Test Procedure

The objective of the tests is the comparison of the performances of the LCTP and of the F-P etalon in identical experimental conditions. The set-up's monochromator was calibrated in order to have the required accuracy in wavelength identification and bandpass setting. The F-P is initially set at an in angle of incidence of 20° with respect to the incident, collimated beam. The wavelength scanning is then performed by mechanically rotating the etalon in steps of 26 arcsec, corresponding to a wavelength shift of 0.025 nm. In the case of LCTF, the wavelength is electrically tuned in steps of 0.05 nm around the central wavelength of 530.3. LCTP polarimetric tests are also performed by changing the rotation value of the LPR. The spectroscopic performances of the two devices are assessed by evaluating their respective spectral images of the diffuser illuminated by the scanning monochromator .

4.4 Imaging Spectroscopy Performances : LC Tunable-filter versus F-P etalon.

The first five insets in Figure 10 show the fringes generated by the F-P etalon for 5 tilt angles: 20°± (26, 104, -260) arcsec, corresponding to 5 wavelengths: 530.3 nm ± 0.025 nm, +0.1 nm, -0.2 nm. The last inset shows the five intensities across the spectral profile, for a given point in the images (white asterisk), that are used for a Guassian fit to recover the "synthetic" profile from the monochromator (FWHM = 0.1 nm). Table 2 shows the accuracy – Δ(CW), Δ(FWHM) – in recovering the profile's parameters (i.e., center-wavelength; width) for a given statistics of the 5 measurements.

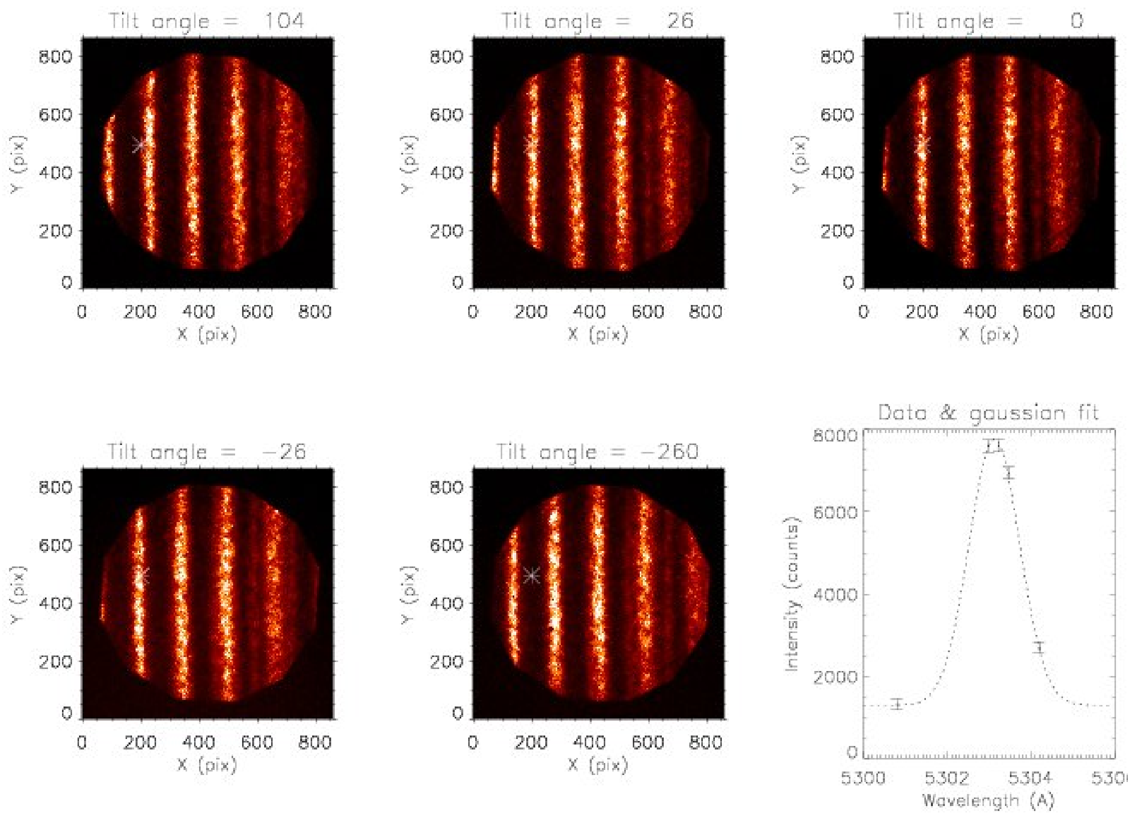

Figure 10 *The first five insets show the fringes formed by the F-P etalon for 5 tilt angles: 20°± (26, 104, -260) arcsec, corresponding to 530.30 nm ± 0.025 nm, +0.1 nm, -0.2 nm. The last inset shows the five intensities across the spectral profile, for a given point in the images (white asterisk), that are used for a Guassian fit to recover the "synthetic" profile*

The first five insets in Figure 10 show the 5 chromatic images formed by the LCTP when it is electro-optically tuned to 5 wavelengths: 530.55 nm ± 0.05 nm, +0.1 nm, +0.2 nm. The last inset shows the five intensities across the spectral profile, for a given point in the images (black asterisk), that are used in a Guassian fit to recover the "synthetic" profile from the monochromator (FWHM = 0.1 nm). Table 2 shows the accuracy – Δ(CW), Δ(FWHM) – in recovering the profile's parameters (i.e., center-wavelength, CW; width, FWHM) for the same statistics as in the 5 F-P measurements.

From Table 2, both the LCTP and the F-P show similar accuracies in recovering the "synthetic" (i.e., monochromator's) line profile when intensity measurements with similar statistics are fit with a Gaussian. Indeed, thanks to its spectral fine-tuning capability (i.e., 0.01 nm), the LCTP has demonstrated the possibility of retrieving Gaussian profiles' widths of the same order of its instrumental profile's width (e.g., "synthetic" profile FWHM = 0.1 nm; LCTP FWHM = 0.15 nm).

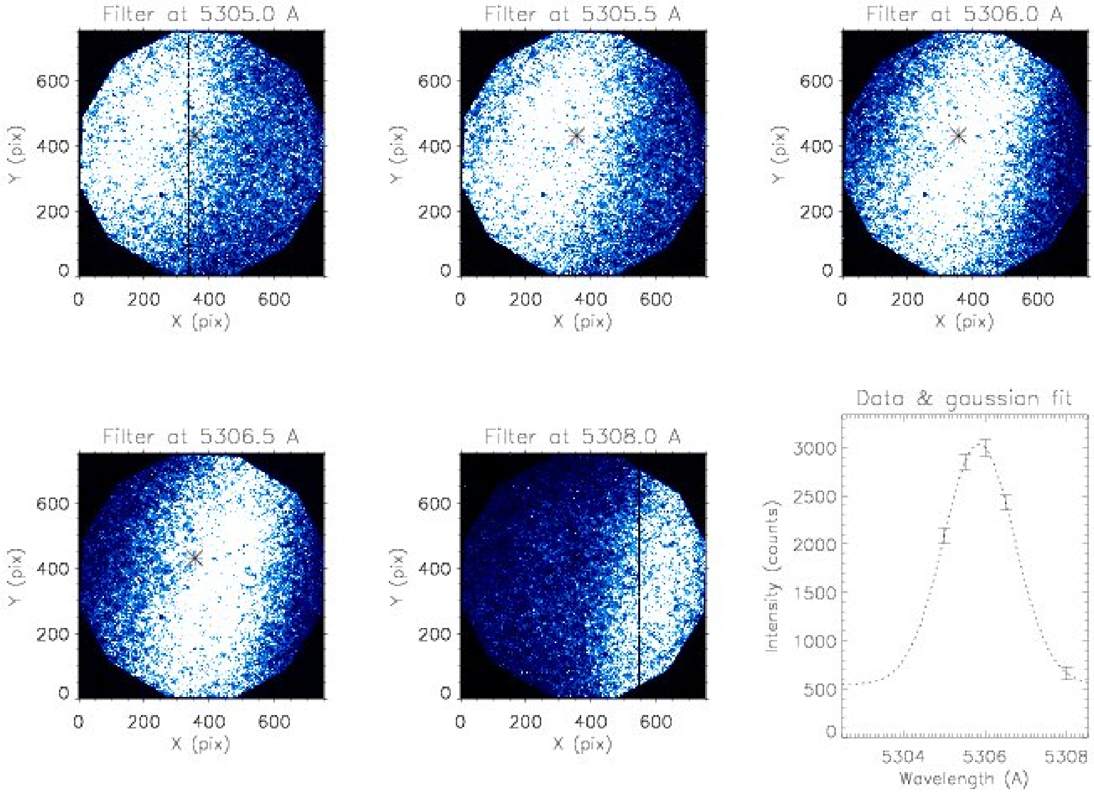

Figure 11 *The first five insets show the 5 chromatic images formed by the LCTP when it is electro-optically tuned to 5 wavelengths: 530.55 nm ± 0.05 nm, +0.1 nm, +0.2 nm. The last inset shows the 5 intensities across the spectral profile, for a given point in the images (black asterisk), fit a Guassian to recover the "synthetic" profile (FWHM = 0.1 nm).*

Instrument	**Fabry-Perot interferometer**		**Lyot filter**	
N. of data	5	7	5	7
Δ(CW) (%)	~ 0.001	~ 0.0005	~ 0.001	~ 0.0005
Δ(FWHM) (%)	9-10	4-6	10-15	4-6
S/N range	~ 10-50		~ 8-40	
Countrate (s^{-1})	1.2 e+2		1. e+2	
*Dwell time (s)	~ 40-50		~ 50-60	

NB: uncertainties are 2-σ errors (95.4% confidence level)

* To derive the Gaussian profile's parameters with the above accuracy (i.e., above S/N range)

Table 2 *Measured performances of the F-P and LCTP. Intensity measurements with similar statistics yield similar accuracies, for both the LCTP and F-P in recovering the "synthetic" (i.e., monochromator's) line profile using a Gaussian fit.*

5. CONCLUSIONS

The performances of the high-resolution ($\lambda/\Delta\lambda$ = 3.5E+3), Liquid Crystal Tunable – filter and Polarimeter (LCTP) were compared with those of a classical very high-resolution ($\lambda/\Delta\lambda$ = 2.5E+4) Fabry – Perot (F-P) etalon. The results of the tests show even if the F-P etalon has a higher instrumental resolution, the LCTP has the same effective spectral resolution thanks to its electro-optical fine-tuning capability in wavelength. In addition, the LCTP has the advantage over the F-P etalon of no mechanically moving parts, and polarimetric and imaging capabilities. In view of these results and of recent advances in the space validation of imaging optics based on liquid crystals [10], electro-optically tunable filters and polarimeters may prove a viable choice for future space-based solar telescopes that, like ASPIICS, have a requirement for high spatial resolution imaging and two-dimensional spectrophotometry and polarimetry.

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