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Optical tests of the LUTIN Fabry-Pérot prototype

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Abstract. The soLar group University of Tor vergata fabry-pérot Interferometer (LUTIN) is a narrow band filter based on an optical cavity resonator with Capacitance-Stabilised Etalon (CSE) control. The prototype, developed at the University of Rome Tor Vergata, is part of the study for the narrow band channel of the ADvanced Astronomy for HELIophysics (ADAHELI) mission designed to investigate the dynamics of solar atmosphere as part of the Italian Space Agency (ASI) Small Missions program. We developed the electro-mechanical control for the optical cavity, necessary for the tuning and the gap control of the instrument. We present the measures of the microroughness of the optical plates, performed with a Zygo interferometer, and the instrument spectral stability behaviour in on-optical-bench open-air mode. The measures refer to the upgraded version of the LUTIN prototype, which mounts the new $\lambda/60$ optical plates.

1. Introduction

The Tor Vergata Fabry-Pérot interferometer [1-2] is a narrow-band tunable filter, optimized in the range $500\text{ nm} - 800\text{ nm}$, designed and realized in the framework of the phase-A study of the ADvanced Astronomy for HELIophysics (ADAHELI) solar mission project awarded by the Italian Space Agency (ASI) small missions program [3-5].

The chromosphere is the region of the Sun's atmosphere in between the photosphere and the corona. Verification of new models for coronal heating requires the capability of observing both the magnetic fields and plasma motions from the photosphere through the chromosphere at high spatial and temporal resolutions [6-7]. Spectro-polarimetric imagers, such as those based on Fabry-Pérot interferometers, provide the necessary time resolution to disentangle magnetic fields and plasma dynamics [8].

The interferometer is based on an optical cavity (OC) where the incoming light undergoes multiple-beam interference bouncing between the two semi-reflective surfaces of the OC. The spectral output has several peaks of transparency at different wavelengths. The peaks are equispaced, resembling a comb. Parallelism, distance control and stability of the OC are crucial parameters of the interferometer, together with the optical quality. In the realized prototype, they are obtained via a double electro-mechanical positioning system, using two kinematic mounts coupled together and controlled with electronic micrometric screws and piezoelectric actuators. The stability is guaranteed by capacitive sensors measuring the position of the



optical housing and performing a closed loop control on the piezoelectric actuators, making the prototype a Capacitance Stabilized Etalon (CSE)[2].

In this work we present first spectral stability measurements obtained in on-optical-bench open-air mode at Solar Physics laboratory in Tor Vergata University. Results are shown in section 3. Absolute measure of the surface of the optical flat plates has been obtained with a Zygo interferometer at the CNR-Istituto Nazionale di Ottica in Florence, results are reported in section 4.

2. The Fabry-Pérot interferometer characteristics

Recently, a couple of fused silica optical plates, 25.4mm of diameter, with a nominal surface quality of $\lambda/60$ and a peak-to-valley (PV) surface error of 10 nm has replaced the initial couple of optical flats installed in the interferometer ($\lambda/30$ at 632.8 nm and PV error = 21 nm). The plates have been realized and characterized by the manufacturer Lightmachinery.

Coarse adjustment of micrometric screws and piezoelectric position control are performed via LabView programs; the programs transform pitch and yaw numerical inputs to signals to the three 120° symmetry actuators. A further procedure regulates the cavity parallelism with a typical resolution of $\simeq 20$ arcsec. To preserve the two plates from accidental contacts there are software safety parameters and a Teflon ring of 0.5 mm thickness on the boundary of the movable optical plate [9].

Capacitive sensors are used to measure the position of the metal ring retaining the movable optical plate with an error less than 0.5 nm. The servo loop provided by the analog electronic controller maintains the movable plate in position using the piezoelectric actuators and the feedback from the capacitive sensors. Piezoelectric actuators are controlled via a digital to analog converter board giving inputs to the analog controller, providing OC gap variations, with a minimum resolution of $\simeq 2$ nm and a maximum stroke of 15 μ m.

3. The Fabry-Pérot interferometer spectral stability

We present the measures of the spectral stability of the interferometer at the Solar Physics Laboratory in the University of Rome Tor Vergata. A sodium lamp extended source is used to illuminate the prototype, with a lens collimating the light coming from the lamp. The collimated beam passes through the prototype and is then focused by a second lens to obtain an image of the fringe system. The sodium lamp provides an incoherent almost monochromatic source of light at $\lambda_0 = 589$ nm.

Refraction index of the air inside the cavity varies due to changes in temperature, pressure and humidity. We select 10 hours from a 24 hours dataset, searching for a period with maximum air conditions stability. We obtain from different sensors:

$$\begin{aligned} T &= 22.9 \pm 0.2 \text{ }^\circ\text{C} \\ P &= 1016.0 \pm 0.5 \text{ hPa} \\ RH &= 43 \% \pm 3\%. \end{aligned}$$

We use the modified Edlén Equation [10] to compute the refraction index of air obtaining a typical value of $n = 1.000270 \pm 10^{-6}$.

From this calculation we obtain over the 10 hours a maximum drift due to changes in the refraction index:

$$\frac{\Delta\lambda_n}{\lambda} = \frac{\Delta n}{n} = 10^{-6}. \quad (1)$$

The capacitive sensors measure the distance between the sensor itself and a sensing point on the steel ring retaining the optical plate [9]. This measure is based on changes in the capacitance due to a variation in the distance between the two plates. Variations of the air permittivity ϵ result in a spurious signal $\Delta\lambda_\epsilon$. Several effects can affect the wavelength transmitted by the

Fabry-Pérot filter. Summing up all the effects coming from the variation of: refractive index $\Delta\lambda_n$, physical distance between the plates due to thermal expansion $\Delta\lambda_T$ and permittivity of air $\Delta\lambda_\epsilon$, we expect variations in the trasmitted wavelength of the order [11]:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\lambda_n}{\lambda} + \frac{\Delta\lambda_T}{\lambda} + \frac{\Delta\lambda_\epsilon}{\lambda} \simeq 10^{-6}. \quad (2)$$

The observed ring system (shown in fig.1) is the result of the multiple beam interference inside the cavity and optical setup of the experiment. During the test, the cavity gap is set to $d = 8.2 \text{ mm}$, in order to obatain a sufficient number of interference rings inside the field of view of the camera. We use the following interference order:

$$m = \frac{2n}{\lambda_0} d \cos \theta \simeq \frac{2n}{\lambda_0} d \quad (3)$$

where θ is the incidence angle and is nearly zero. In our case we have $m = 27851$.

The Free Spectral Range (FSR) is defined as the distance between two peaks in the comb pattern of the spectral response of the instrument [12]. This quantity is equal to:

$$FSR = \frac{\lambda_0^2}{2nd \cos \theta} = \frac{\lambda_0}{m} = 21.15 \text{ pm}. \quad (4)$$

During the experiment several images of the fringe system, one every 5 minutes for 10 hours, were obtained. In order to identify the peaks, we compute associated profiles from the center (corresponding to the optical axis of the system) in a chosen radial direction. Then we performe a simple parabolic fit on the first two maxima, as shown in the right panel of fig.1 and we compute the distance between them, expressed as the physical distance in μm on the sensor, obtaining the value:

$$D = 2.92 \cdot 10^{-4} \text{ m}. \quad (5)$$

We measure the position of the first ring in every image and, subtracting the value from the previous image, we obtain the variation in the radius Δr . To compute the spectral shift we convert this value in wavelength shift:

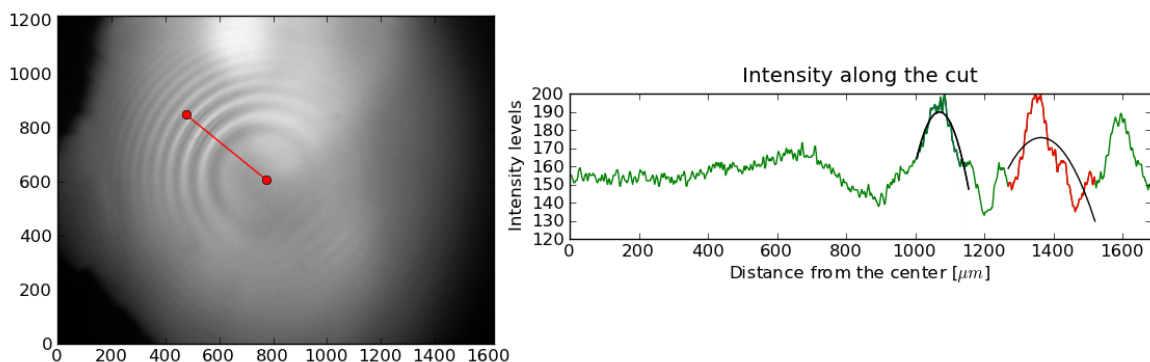


Figure 1. Interference Fabry-Pérot pattern. Cut along the red line is shown as an intensity profile in the right panel. We find the radius of the first two maxima rings in every frame using a parabolic fit with a moving window based on previous image (data shown in a different colour). In some images this results in a poor fit of the gaussian width of the second peak, but with a still robust estimation of its position. Nevertheless only the position of the first peak is used for Δr calculation.

$$\Delta\lambda = \frac{2n}{m} \frac{\Delta r}{D} \frac{\lambda_0}{2n} = FSR \frac{\Delta r}{D}. \quad (6)$$

We can now obtain the spectral response shift as a function of the radius variations. We plot the relative spectral variations $\frac{\Delta\lambda}{FSR}$ in fig.2. We obtain:

$$\langle\Delta\lambda\rangle = 8.7 \cdot 10^{-14} \text{ m}. \quad (7)$$

The typical RMS over one hour is:

$$RMS = 9.5 \cdot 10^{-13} \text{ m}. \quad (8)$$

We thus obtain a typical $\frac{\Delta\lambda}{\lambda_0} = 1.6 \cdot 10^{-6}$ in agreement with the expected value. The PV relative shift does not exceed 0.24 over one hour. If we multiply by the FSR , see eq. 4, the absolute shift in lambda does not exceed a PV error of 5 pm/h over 10 hours.

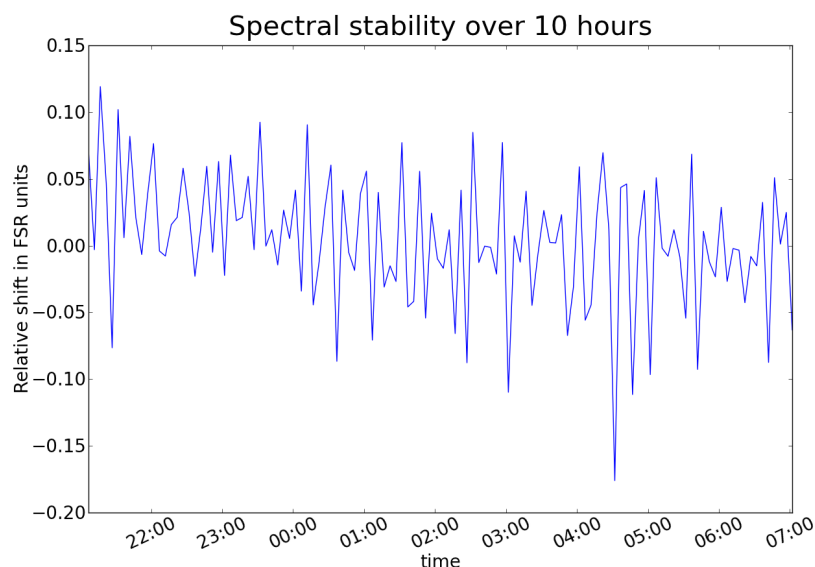


Figure 2. Spectral stability over 10 hours. The relative shift in lambda is shown as a function of time. The cadence is 5 minutes.

4. The Fabry-Pérot interferometer optical characterization

The two $\lambda/60$ optical plates are fully characterized using two Zygo interferometers at the Istituto Nazionale di Ottica (INO) in Arcetri.

First the two plates have been extracted from the prototype for an absolute measure of their relative surface errors. We use a phase-shift Zygo interferometer operated with a laser source @632.8 nm. The absolute shape of the reference plate is measured with the three-planes technique [13] and is subsequently subtracted from the relative measures. We show in fig.3 the surface errors of the two plates. The full diameter is 25.4 mm for both the plates. Measures are referred to a useful diameter of 23 mm. For the movable plate, we measure a PV error of 9 nm and an RMS error of 1.603 nm, once we subtract the reference. For the fixed plate, we measure a PV error of 8 nm and an RMS error of 1.504 nm, once we subtract the reference. The two plates are therefore, respectively, a $\lambda/70$ and a $\lambda/80$ optical quality plates, slightly better than what declared by the manufacturer.

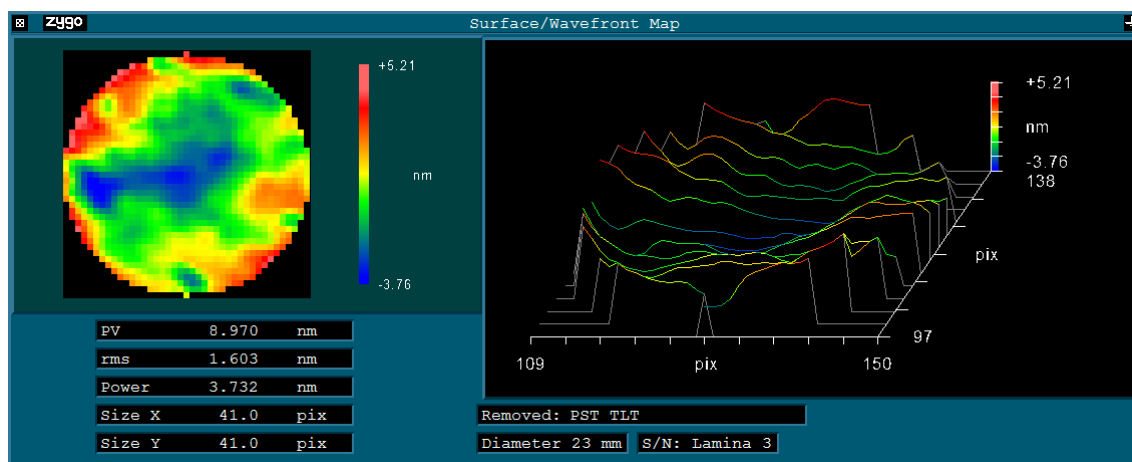


Figure 3. Zygo output of the phase-shift analysis. Surface errors and shape measured of the movable optical plate. PV errors refer to the measures obtained without subtracting the absolute shape of the reference plate.

5. Conclusions

We obtained the spectral stability characteristics of the LUTIN prototype over a period of 10 hours. We also characterized the two surfaces of the optical cavity, measuring the absolute shape of the two plates.

In order to measure the dynamics of the solar photosphere and taking into account the typical doppler shift due to Earth motion, it is necessary to have an instrument able to discriminate a velocity signal of 50 *m/s* [14]. This implies a spectral stability of at least 1 *pm/h*. In this open-air configuration, the typical RMS shift for the passband of this prototype @ 589 *nm* is 0.95 *pm* over an hour and it does not exceed a PV error of 5 *pm/h* over 10 hours. Furthermore, it can be inserted in a vessel able to control temperature, humidity and pressure, in order to improve the stability. After the construction of the stabilized vessel, more spectral tests are planned.

Acknowledgments

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