First Asia-Pacific Solar Physics Meeting
ASI Conference Series, 2011, Vol. 2, pp 47–53
Edited by Arnab Rai Choudhuri & Dipankar Banerjee

A dual Fabry-Perot based narrow band imager for the National Large Solar Telescope

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Abstract. A large solar telescope is usually equipped with several post-focus instruments deployed to study the dynamics of the solar features at different wavelengths. Indian Institute of Astrophysics (IIA) has proposed to build a 2-m class National Large Solar Telescope (NLST) to be located at a site which is suitable for high resolution observations of the sun. The narrow band imager (NBI) is proposed to be one of the back-end instrument for NLST to provide a spectral resolution of 40 mÅ or better. The NBI comprised of two Fabry-Perot interferometers kept in tandem. The instrument will be capable of observing the solar atmosphere at various wavelength positions of the spectral line with the expected temporal cadence of about one spectral image per second. The instrument will also have the additional capability of making Dopplergrams at very high cadence.The instrument can be combined with a high precision polarimeter to obtain the vector magnetic fields of the solar atmosphere (one or more levels) with good temporal cadence. Several simulations and numerical studies have been carried out to arrive at the optimal design of the instrument. In this paper, we present the important design parameters of the instrument such as wavelength coverage, optimum spacing ratio, parasitic light contribution, field-of-view, spectral and spatial resolution, signal-to-noise ratio etc. The theoretically estimated performance of the proposed NBI is also compared with similar instruments used around the world.

Keywords : Sun: general – instrumentation: interferometers

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1. Introduction

A two meter class National Large Solar Telescope (NLST: Hasan et al. (2010)), is being proposed by the Indian Institute of Astrophysics (IIA) to study the dynamics of small scale magnetic inhomogeneities at a resolution of $0.1''$ or better in the optical and near infrared wavelength regions. The telescope will be placed in one of the best high altitude sites in India and will be equipped with higher order adaptive optics system to correct for atmospheric seeing effects. The scientific output and versatility of the telescope will be driven by the state-of-the-art back-end instruments.

It is well known that features in the solar atmosphere changes very rapidly at a rate of sound speed. Smaller the feature faster its evolution. Hence, the observations made at high spatial resolution always demand high temporal cadence too. To achieve high temporal cadence, it is essential to accumulate large number of photons. Various observational evidences suggest that during the active phenomena on the sun there is a rapid change in velocity, intensity and perhaps even the magnetic fields at various heights in the solar atmosphere. In order to observe various heights in the solar atmosphere, it is essential to observe the sun at different wavelengths since each spectral line forms at different temperature and pressure. The photometric measurements alone are not sufficient for magnetic feature. On many occasions, it becomes necessary to have Dopplergrams and magnetic fields of these regions to obtain full physical information. This is possible by using a high resolution spectrograph or very narrow band imaging system. The basic requirements of such an instrument are: (i) large spectral coverage (4000 Å to 1.5 μm), (ii) high wavelength stability (5 mÅ /hr), (iii) reproducibility of the selected wavelength positions over the long observing periods and (iv) high temporal cadence with large field-of-view (FOV) to cover the full active regions. All these requirements can be achieved by a narrow band imaging (NBI) system capable of high temporal cadence (3 frames/sec), large spectral (30-40 mÅ) and spatial ($0.06''$) resolution without compromising the large FOV (1.5 arcmin) of the target regions.

NBI system is one of the most versatile instruments to study interesting scientific problems in solar physics. Main requirement of the NBI system is that it should be capable of fast scanning at finer spectral resolution without degrading the spatial resolution. There are several NBI systems used in solar observations. For the NLST, a dual Fabry-Perot based NBI system is being planned.

2. Fabry-Perot interferometer

A Fabry-Perot interferometer is a device made of two highly polished reflecting parallel glass plates. In combination with order sorting filter, it selectively transmits a particular wavelength of light that corresponds to the resonance of the etalon cavity. The transmitted intensity distribution of the FP fringe pattern is given by Airy's formula (Jenkins & White 1937).

$$I = \frac{I_{max}}{1 + F sin^2(\delta/2)} \quad (1)$$

where $I_{max} = A^2T^2/(1 - R^2)$ is the maximum intensity and $F = 4R/(1 - R)^2$ is the reflective finesse. A, T and R are the amplitude of the absorbed, transmitted and reflected intensities, respectively. δ, the phase difference between the transmitted rays is given by $\delta = (2\mu d cos\theta)2\pi/\lambda$ where, μ is the refractive index of the media between the plates and d is the distance between the plates. The phase between the successive transmitted rays can be altered by changing the refractive index of the material between the plates or by changing separation between the plates. Based on this, two types of Fabry-Perot etalons are available commercially. One is air-gap based and the another is solid-gap based FP system. Each type has their merits and drawbacks [cf: Ravindra & Banyal (2010)]

3. Instrument design specifications

A dual or multiple FPs in tandem have better performance than a single FP. The design specifications of the NBI system that can meet our science goals [cf: Ravindra & Banyal (2010)] are given in the Table 1.

Table 1. The design specifications of the NBI system with two FPs in series.

Spectral Resolution	≥ 200000 at 6000 Å
Spectral Range	5000-9000 Å
Field-of-View	≤ 1.5 arc-min
Maximum Ghost Transmission	$\leq 10^{-4}$
Signal to Noise Ratio	≥ 500
Peak Transmission	≥ 50%
Wavelength Stability	≤ 10mÅ/hr
Tuning Rate	≥ 10 pm/ms
Order Sorting Filter	2-3 Å range
Maximum Stray Light	10^{-3}
Image Cadence	≥ 1 frame per second

4. Parasitic light and optimum plate separation

In the proposed narrow band imager there will be two Fabry-Perot etalons kept in series with a 2-3 Å bandwidth interference filter. If N such FPs are kept in tandem with interference filter then the resulting instrumental profile is given by $I(\lambda) = I_{IF}(\lambda) \prod_{i=1}^{N} I_i(\lambda)$ where, I_{IF} and I_i are the intensities of the transmitted beam through

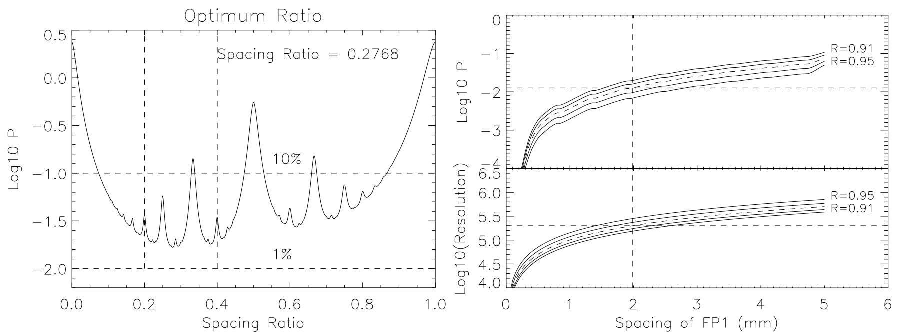

Figure 1. Left: A plot of parasitic light vs ratio of plate separation for dual-etalon system. The two vertical lines define a range where the deepest minima can be found. The two horizontal lines indicate the 10% and 1% level of the parasitic light. Right: A plot of spectral resolution vs plate separation of FPI-I (bottom). The horizontal line represents the desired spectral resolution level. A parasitic light is plotted as a function of plate separation of FPI-I (top). The horizontal line indicates the 2% level of parasitic light.

the order sorting filter and the two FPs, respectively. The value of i varies from 1 to N. The best performance of the system can be achieved if we optimize the parasitic light and spectral resolution. The parasitic light is defined as the ratio between the flux outside and inside the instrumental profile. By using the methodology given in Cavallini (2006) we estimated the parasitic light with the following parameters: the refractive index μ =1, the incidence angle θ=0, absorption coefficient A=0.01, coating reflectivity R = 0.93, FWHM$_{IF}$=3Å, centered at 6302 Å, and peak transparency t$_{IF}$=0.3. Figure 1(left) shows the plot of parasitic light vs the ratio of the FPs spacing. The plot shows that lowest level of the parasitic light is obtained for the spacing ratio of 0.277. This being the optimum ratio, now one can adjust the spacing between the plates of FPI-I such that the spectral resolution is optimized. Again by following the method of Cavallini (2006) we optimize the spectral resolution R = 2.0×10^5 (Figure 1(right-bottom)) for a spacing of FPI-I (d= 2.283 mm) at which the parasitic light is 2% (Figure 1(right-top)). So, the dual FPs with a spacing of FPI-I 2.283 mm and FPI-II 0.637 mm and a coating reflectivity R = 0.93 have been considered as the best values for getting the best parameters such as large transparency, low ghosts, low parasitic light, high image quality and high spectral resolution.

5. Size of the Fabry-Perot

The spectral resolution in the telecentric mounting depends on the focal ratio of the beam. The FWHM of the transmitted spectral line can be approximated as, $\Delta\lambda_{FWHM} \sim \frac{\lambda_0^2}{\pi d_1 \sqrt{F(1+\epsilon^2)}}$ where λ_0 is the central wavelength, d_1 is the spacing of the FPI-I in the series and $\epsilon = d_2/d_1$. Also, $d_1 = 2.3$ mm and $\epsilon = 0.277$. With this set up, the FWHM for the 6302 Å line is estimated to be 19.2 mÅ. In order to achieve a required spectral resolution in telecentric beam the required FP size is very large and it is hard to find it in the market. Hence, we changed the spectral resolution by a small amount from the desired value by 1.5 mÅ. Now, with the requirement that $\Delta\lambda$ equal to 33 mÅ, we get a telecentric spread in wavelength as 27 mÅ. The estimated focal ratio is 170.8. Following Darvann & Owner-Petersen (2004), the required size of the FP for a given FOV is $D_{FPI} = F_{no}\alpha_{FOV}D$. Where, the α_{FOV} is the field of view and D is the diameter of the telescope. For 2 m class telescope and a FOV of 1.5 arc-min, the clear aperture of the FP should be 14.9 cm. Hence, the adoption of 15 cm aperture air gap FP will be sufficed for our NBI. At this focal ratio the spectral resolution at 6302 Å is 1.91×10^5 which is little less than the desired value.

6. Exposure time and signal to noise ratio

It is very important to know the exposure time and the signal to noise ratio (SNR) at the detector. These quantities can be calculated by using the reflectance and transmittance of all the optical components in the path of the beam. The solar flux at 6318 Å continuum wavelength (which is close to 6302 Å) is 1.638 W m^{-2} nm^{-1} (obtained from http://lasp.colorado.edu/sorce/index.htm) which corresponds to a photon flux of 5.201×10^{27} photons m^{-2} m^{-1} s^{-1}. For the specific characteristics of the telescope and the imaging instrument, we can relate the photon flux to the number of electrons at the detector per second. We assume the atmospheric transmission is $\tau_{atm} = 0.95$. This is almost close to the quoted value of atmospheric transmission if one neglects molecular scattering and aerosol absorption (Cox 2000). The proposed NLST telescope will have a six mirrors (including the primary) each with a reflectivity of 95%. With 6 reflecting surfaces in series and adaptive optics system in place, a 60% of the original intensity will reach the NBI system. The transmission of the etalon is 80% each and the order sorting filter transmits the light by about 40%. Hence, the final beam will have an intensity of 15% of the original solar flux. The FWHM of the imaging instrument is 33 mÅ. The FOV is 1.5 arcmin circular. For a 2048×2048 pixel CCD camera (pixel resolution of 0.06 arcsec) with 60% quantum efficiency we should be able to detect 6.43×10^6 electrons s^{-1} which corresponds to an exposure time of about 31 ms for a full well pixel capacity of 2×10^5 electrons. To avoid the image saturation, it is sufficient to consider about 95% of the full well capacity with 30 ms exposure time. If the CCD readout time is about 800 ms then we should be able to get at least 1 images per second. At this photon detection level the SNR is about 440. Hence, at 0.06″ resolution there is little less photons to achieve the desired SNR. To increase the SNR we may have to lower the pixel resolution (0.08″ or lower).

7. Optical configuration and design

Figure 2(left) shows the typical optical layout for the dual FP based NBI in a telecentric configuration. A set of collimator and imaging lens before the FPs form an intermediate image near the first FP and then another set of collimator and re-imaging lens

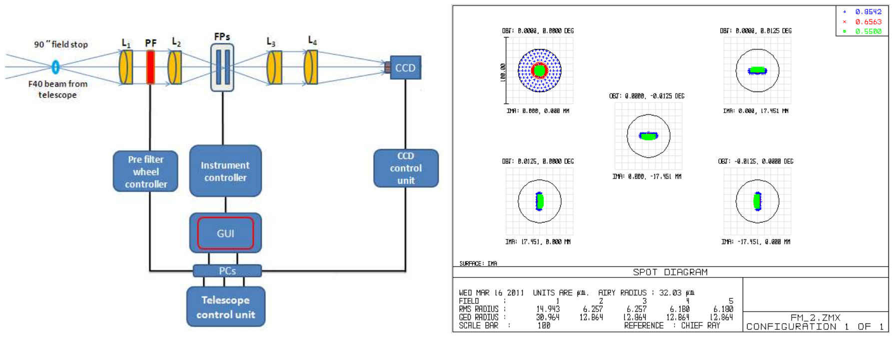

Figure 2. Left: Schematic of a dual FP based narrow band imager. Right: Diffraction limited spot diagram of the optical design.

forms the final image on the CCD camera. A prefilter of size 5 cm with a 3 Å passband will be used in the collimated beam as the large size filters are not readily available. Also by using the prefilter in the collimated beam avoids the shift in the passband. The field stop at the focal plane of the telescope restricts the FOV and it also prevents the scattered light from the telescope entering into the FP optical system.

Zemax software was used to make the preliminary optical design of the NBI instrument. Fig.2(right) shows the spot diagram for the telecentric NBI system for three optical wavelengths. From the diagram it is clear that aberrations are minimized and the configuration is optimized for the diffraction limited performance. Most of the tasks for the etalon will be automated and synchronized with the temperature controller, CCD camera and the prefilter assembly. The whole setup has a length of about 5 m. The beam foldings may be required to assemble the entire instrument at the focal plane of the telescope on an optical bench.

8. Other contemporary instruments

There are many other working NBI systems built by various observatories at different places. Most of them are associated with large solar telescopes. Table 2 gives a brief overview of various NBI systems operating at different observatories around the world.

9. Summary

We have proposed a dual Fabry-Perot based narrow band imager for NLST to study the solar atmosphere at different wavelengths. The proposed FP design is supported by detailed studies comprising stray light modeling, ghost transmission, optimum plate spacings, mounting configurations etc. The instrument will be capable of achieving a 40 mÅ spectral resolution with commercially available FP's of size 15 cm. A one

Table 2. Comparison of FP based narrow band imaging system around the world. TESOS, IBIS, VTT and NLST correspond to Telecentric Etalon SOlar Spectrometer, Interferometric Bidimensional Spectrometer, Vacuum Tower Telescope and National Large Solar Telescope, respectively. In the Table, $\Delta\lambda$ corresponds to spectral resolution, Pixel Res corresponds to spatial resolution in terms of arcsec/pixel and FOV is the field-of-view. TS indicates the telescope size (m) and RF represents the references for the different NBI system.

System	$\Delta\lambda$	Pixel Res arcsec	FOV arcsec	TS	RF
TESOS	320000/160000	0.15	100	0.7	Kentischer et al. (1998)
IBIS	200000	0.2	80	0.76	Vecchio, Cauzzi & Reardon (2009)
VTT	160000	0.11	78×58	test	Puschmann et al. (2006)
NLST	200000	0.06	90	2	

image per second can be achieved with this system as per the desired requirement in design of the NBI for NLST.

Acknowledgments

We thank the anonymous referee for his/her fruitful comments. We would like to thank Drs. Sankarasubramanian, Shibu Mathew and Raja Bayanna who have helped us at various stages of this work.

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