

Optical design of visible emission line coronagraph on Indian space solar mission Aditya-L1

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Abstract The ground based observations of the coronal emission lines using a coronagraph are affected by the short duration of clear sky and varying sky transparency. These conditions do not permit to study small amplitude variations in the coronal emission reliably necessary to investigate the process or processes involved in heating the coronal plasma and dynamics of solar corona. The proposed Visible Emission Line Coronagraph (VELC) over comes these limitations and will provide continuous observation 24 h a day needed for detailed studies of solar corona and drivers for space weather predictions. VELC payload onboard India's Aditya-L1 space mission is an internally occulted solar coronagraph for studying the temperature, velocity, density and heating of solar corona. To achieve the proposed science goals, an instrument which is capable of carrying out simultaneous imaging, spectroscopy and spectro-polarimetric observations of the solar corona close to the solar limb is required. VELC is designed with salient features of (a) Imaging solar corona at 500 nm with an angular resolution of 5 arcsec over a FOV of 1.05Ro to 3Ro (Ro:Solar radius) (b) Simultaneous multi-slit spectroscopy at 530.3 nm [Fe XIV], 789.2 nm [Fe XI] and 1074.7 nm [Fe XIII] with spectral dispersion of 28mÅ, 31mÅ and 202mÅ per pixel respectively, over a FOV of 1.05Ro to 1.5Ro. (c) Multi-slit dual beam spectro-polarimetry at 1074.7 nm. All the components of instrument have been optimized in view of the scientific objectives and requirements of space payloads. In this paper we present the details of optical configuration and the expected performance of the payload.

Keywords Space instrumentation · Coronagraph · Spectrograph · Optics · Solar physics

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1 Introduction

The observations made for short periods during the occurrence of total solar eclipses [1–3] have provided a large amount of information about the physical nature of the solar corona but are not sufficient to study the detailed physical and dynamics of the different features of the solar corona and their association with features in the photosphere. The ground based observations [4, 5] made with coronagraphs in the visible emission lines gets affected by the scattered light due to earth's atmosphere. The varying sky conditions modulates the coronal signal and makes it difficult to study reliably the small amplitude variations in the solar corona necessary to delineate the role of various processes to heat the coronal plasma to million degrees. The instruments in the space will not suffer from these effects. There are many proposed and existing space missions for spectroscopy in the UV, EUV and X-ray wavelength [6, 7] range but there is no space based mission with spectroscopy capabilities in the visible emission lines.

ADITYA-L1 [8] mission is a space based solar observatory with seven payloads onboard which is planned to be placed in halo orbit around first Lagrangian point (L1) of sun-earth system. It is an enhanced version of ADITYA-I mission which was initially planned in a low earth orbit with VELC as the only payload. VELC [9, 10] on ADITYA-I was an internally occulted [11] solar coronagraph with capabilities of simultaneous narrow band imaging at two coronal emission lines centered at 530.3 nm (Fe XIV), 637.4 nm (Fe X) and continuum imaging at 500 nm. Images of solar corona provide information about the intensity in continuum or emission line only. However, spectroscopic observations in emission lines yield knowledge about the velocity and line-width in addition to intensity. These three parameters are necessary to study the physical and dynamical characteristics of the solar corona. With the enhanced mission, the scientific objectives of VELC payload are re-defined and optics of the VELC payload is re-designed to carry out simultaneous imaging, multi-slit spectroscopy and spectro-polarimetry of solar corona in three emission lines. Scientific objectives [12] of VELC payload on ADITYA-L1 is to delineate the role of different physical and dynamical processes in heating up the plasma, study of dynamics of coronal loops and prediction of space weather through the occurrences of energetic events in the corona.

The proposed VELC on Aditya-L1 mission is designed for carrying out imaging of solar corona at 500 nm, simultaneous spectroscopy of solar corona in emission lines centered around 530.3 nm [Fe XIV], 789.2 nm [Fe XI], 1074.7 nm [Fe XIII] and Spectro-polarimetry at 1074.7 nm [Fe XIII]. These lines represent plasma temperature in the range of 1–2 million degrees and are strong emission lines in the visible part of the coronal spectra. FOV of imaging channel is 1.05–3Ro (Ro-solar radius) and 1.05–1.5Ro for spectroscopy channels. The uniqueness of the payload stems from the fact that observations of solar corona closer to the limb (1.05Ro) with high cadence. Optical design of VELC is discussed in the subsequent sections.

2 Optical configuration of VELC

VELC is a reflective internally occulted coronagraph. Light from solar disc and corona enters the instrument through entrance aperture (EA) of diameter 147 mm and is imaged by off-axis parabolic mirror (M1) of diameter 195 mm. Separation between EA and M1 is 1570 mm. Optical layout of VELC is as shown in Fig. 1. M2 is a concave mirror which is

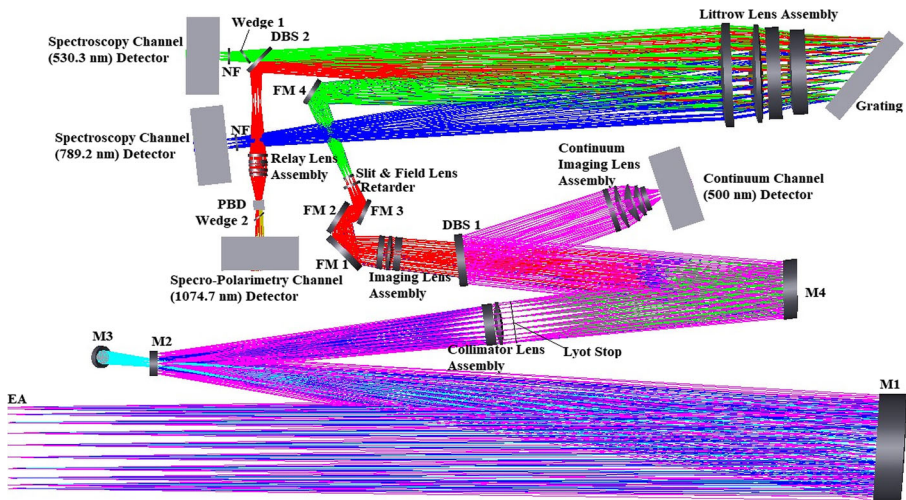


Fig. 1 Optical layout of VELC

placed at the focus of M1 acts as an internal occulter for coronagraph. Disc light and coronal light less than $1.05R_o$ pass through the central hole on M2 and is reflected out of the instrument by a mirror M3 through a small opening on the top of instrument.

Internally occulted coronagraphs demand super polished primary mirror to minimize the scatter light for meeting the signal- to-noise ratio (SNR) requirements. The proposed science goals of VELC demands that the SNR over the FOV of $1.05R_o$ to $3R_o$ should be in the range of 10 to 0.1. This translates into total instrument background of 5 ppm (parts per million) with respect to disk intensity based on aperture size and photon number calculations. Simulations show that RMS surface microroughness of M1 should be $<1.53 \text{ \AA}$ over the spatial scales of 26.8 \mu m to 2.15 mm at 500 nm [13] to keep the instrument background below 5 ppm to achieve the science goals. Distribution of scatter normalized with respect to disk intensity over the FOV due to M1 surface microroughness is shown in Fig. 2.

The coronal light reflected by M2 is collimated by a two-element collimator lens. M1, M2 and collimator together forms the image of EA at a distance of 10.76 mm from the collimator lens assembly. Size of the image at this location is $\sim 74 \text{ mm}$. Lyot stop with a clear aperture 73 mm is placed at the image plane of EA to cut-off the diffraction from EA. Location of Lyot stop is shown in Fig. 3.

The collimated beam will be directed into different channels with the help of M4. Reflected light from M4 is split into two parts by dichroic beam splitter-1 (DBS1) which reflects the light below 515 nm to an imaging channel and transmits the light above 515 nm to the spectroscopy channels. Optical designs of all the channels are discussed in subsequent sections.

2.1 Imaging channel

VELC images the solar corona over an FOV of $1.05\text{--}3R_o$ (0.28° to 0.8°) around 500 nm with an angular resolution of 5 arcsec . A sCMOS sensor of 6.5 \mu m square pixel and of format $2k \times 2k$ is used as a detector. Optical layout of imaging channel is as shown in Fig. 4. Light reflected by dichroic beam splitter (DBS1) ($<515 \text{ nm}$) is collected by a four-element

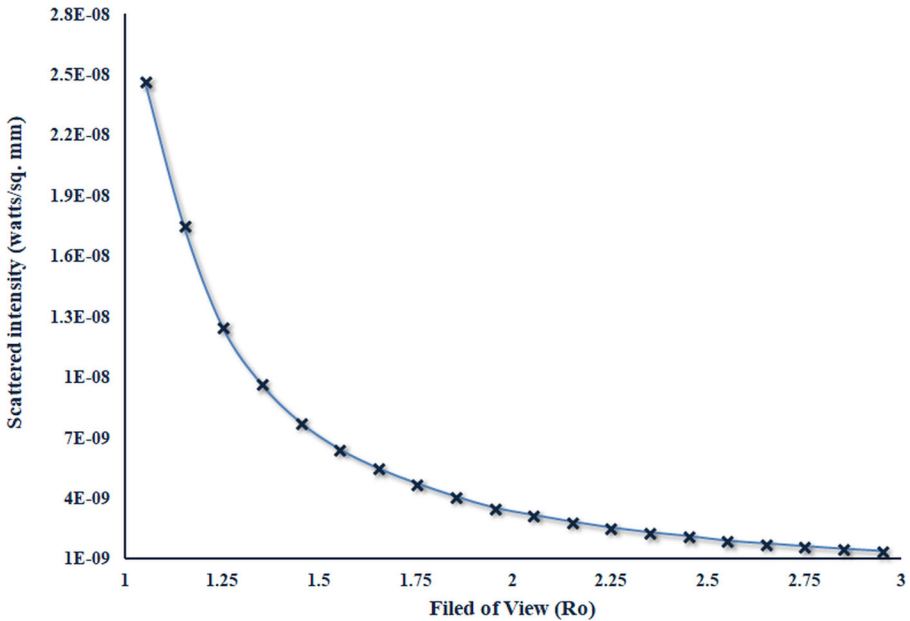


Fig. 2 Distribution of scatter over the FOV of VELC

continuum imaging lens (CIL) and forms an image with F-ratio of $f_{\#}3.6$. A narrow band filter of full width at half maximum (FWHM) of 10 \AA is mounted on CIL assembly to obtain the image over required spectral band. Collimator, M4 and CIL collectively form an aberration corrected image meeting the required optical performance over the FOV. Figure 5 shows the ensquared energy plots of field points over the FOV. About 92% of energy is contained within 3×3 pixels. Considering the efficiencies of reflective coatings on mirrors, anti-reflection coatings on lenses and narrow band filter transmissions, optical efficiency of imaging channel is estimated to be approximately 50%.

2.2 Spectrograph

2.2.1 Imaging at spectrograph slit plane

A three element imaging lens system is designed to collect the transmitted light from DBS1. Collimator, M4 and imaging lens collectively form an aberration corrected image at spectrograph slit plane meeting the required optical performance over the spectral band and FOV. VELC optical layout upto spectrograph

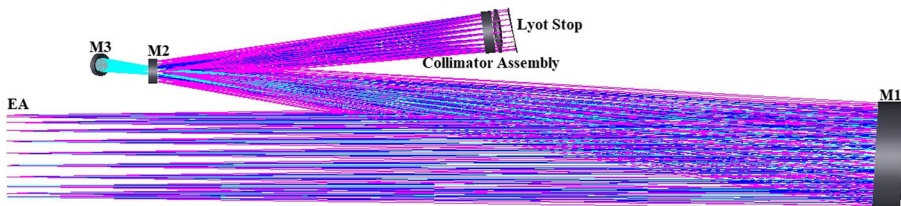


Fig. 3 Lyot-stop location after collimating lens

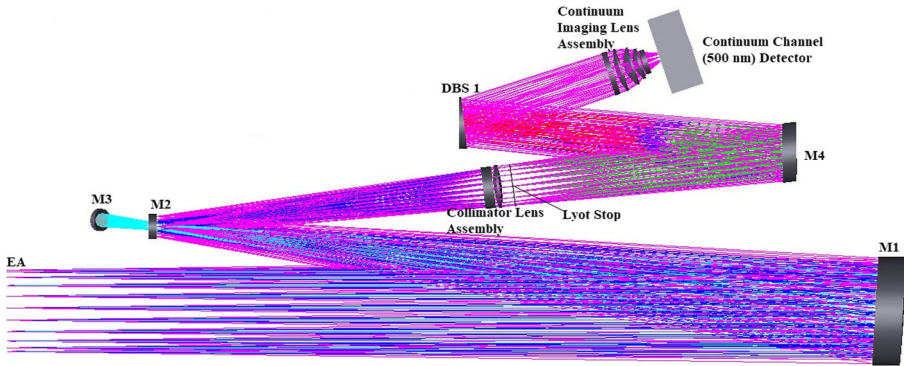


Fig. 4 Optical layout of imaging channel of VELC

slit plane is as shown in Fig. 6. About 90% of the total energy is contained within 20 μm diameter (slit width) as shown in Fig. 7.

2.2.2 Multi-slit spectrograph

VELC contains a multi-slit spectrograph working in Littrow configuration as shown in Fig. 8. It is capable of simultaneous spectroscopic observations at 530.3 nm, 789.2 nm and 1074.7 nm at four positions over the FOV. A polarization modulator and a polarization beam displacer are used for spectro-polarimetric observations at 1074.7 nm. Four slits of width 20 μm each and separated by 3.75 mm is the source for the spectrograph. A field lens mounted along with the slits forms the pupil of the instrument on the diffraction grating. Coronal light through four slits and field lens is

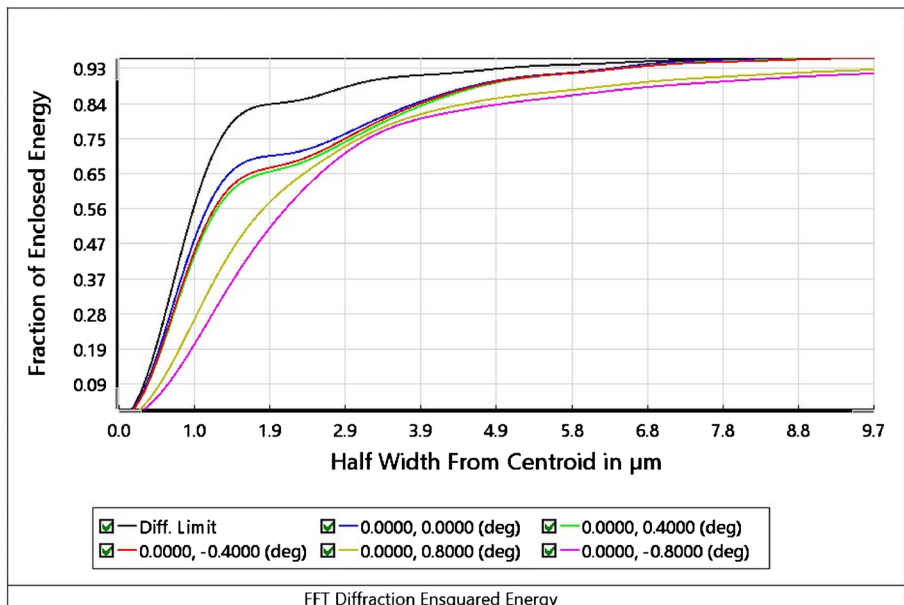


Fig. 5 Ensquared energy of imaging channel over the FOV

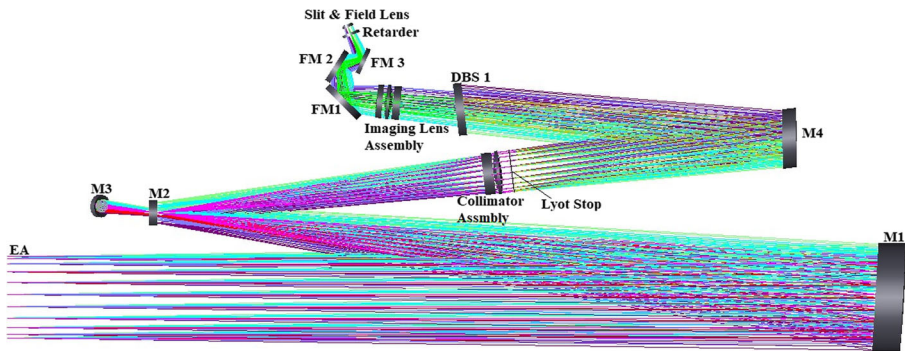


Fig. 6 Optical layout of VELC upto spectrograph slit plane

reflected by FM4 onto the Littrow lens. A combination of plane reflective diffraction grating (600 grooves/mm, blazed at 42°) and a four-element Littrow lens system (focal length ~780 mm) constitute the spectrograph. The diffraction grating is designed to obtain maximum diffraction efficiency at wavelengths of interest 530.3 nm, 789.2 nm and 1074.7 nm in 4th, 3rd and 2nd order respectively. The Littrow lens system corrects the aberrations in three spectroscopic channels operating in different diffraction orders.

As 530.3 nm and 1074.7 nm are dispersed in same direction a dichroic beam splitter-2 (DBS2) is used to reflect 1074.7 nm and transmit 530.3 nm. A finite wedge on DBS2 and a small tilted wedge plate introduced after DBS2 corrects the astigmatism in the transmitting channel (530.3 nm). 1074.7 nm image plane is in between 530.3 nm and 789.2 nm image planes as shown in Fig. 8. A four-element relay lens is designed to relay the image to a convenient location for mounting the IR detector (InGaAs, 24 μm pixel).

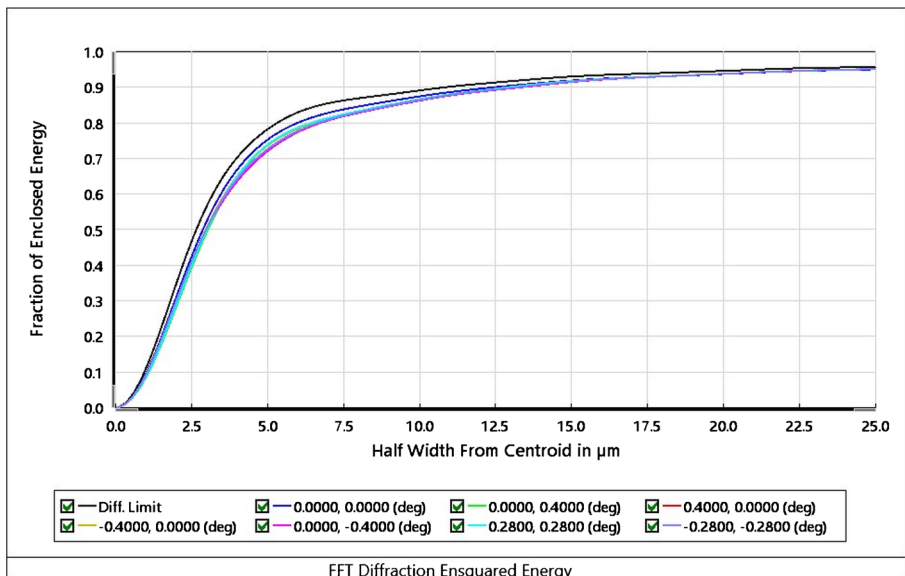


Fig. 7 Polychromatic ensquared energy at slit plane over the FOV

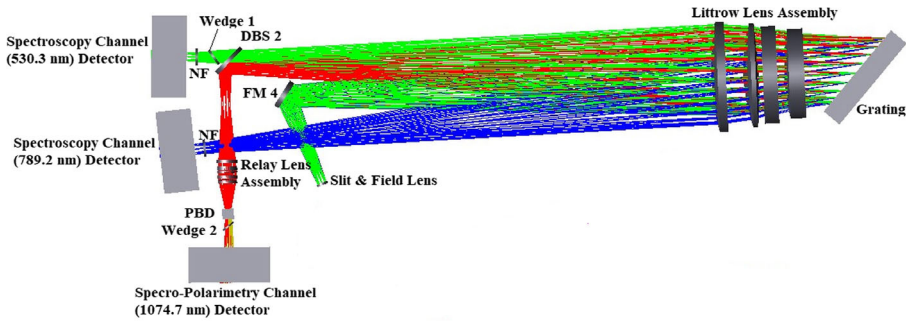


Fig. 8 Optical layout of spectroscopy channels of VELC

At any given point of time, VELC can obtain the spectra of four locations within the FOV through four slits as shown in Fig. 9(a). To obtain a raster scan of the complete FOV, a field scanning mechanism is incorporated in the instrument. Two folding mirrors FM1 and FM2 with an angle of 102° between their front surfaces are mounted on a linear scan mechanism. Scanning direction is along the double headed arrow as shown in Fig. 9(b). Spectrograph slits are separated by 3.75 mm and the total scan required to cover the full FOV is ± 1.875 mm in steps of slit width ($20 \mu\text{m}$). This scan mechanism enables coronal image to shift laterally on the slit plane to cover the complete FOV.

Spectral dispersion of the spectrograph is $28\text{m}\text{\AA}/\text{pixel}$, $31\text{m}\text{\AA}/\text{pixel}$ and $202\text{m}\text{\AA}/\text{pixel}$ at 530.3 nm, 789.2 nm and 1074.7 nm respectively. Narrow band filters of FWHM 5 \AA , 8 \AA and 10 \AA are used to avoid the cross talk between spectra of adjacent slits and the light from any higher orders falling on the detector at 530.3 nm, 789.2 nm and 1074.7 nm channels respectively. Ensquared energy plots of 530.3 nm, 789.2 nm and 1074.7 nm channels are shown in Figs. 10, 11 and 12. About 80% of total energy is contained within 3×3 pixels.

2.3 Tolerance analysis

Thorough tolerance analysis is carried out on the optical design. Fabrication of optics, opto-mechanics, alignment of optical assemblies, thermal expansion of supporting

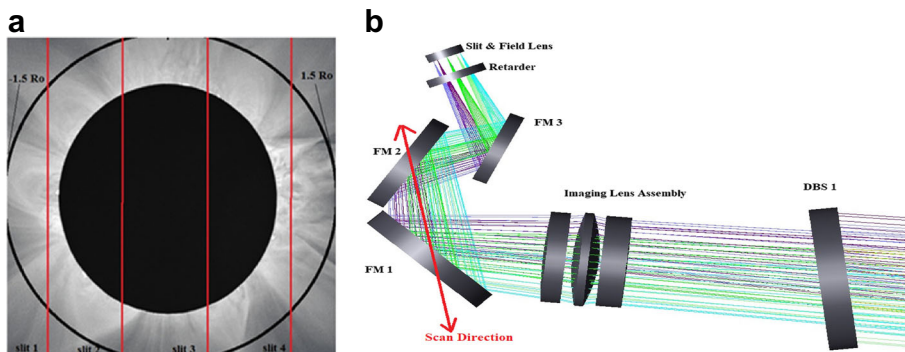


Fig. 9 a Typical positions of slits over FOV, b Two mirror field scan mechanism

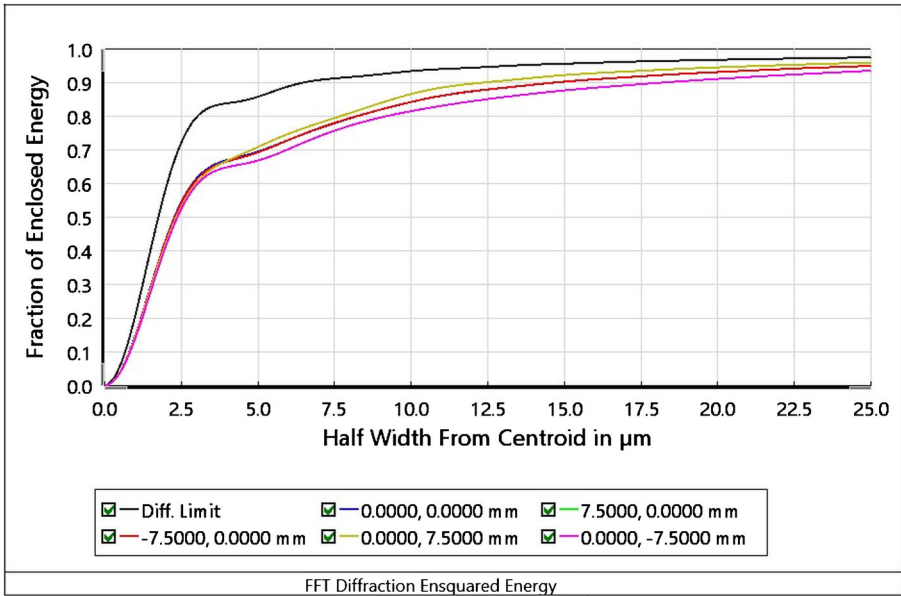


Fig. 10 Ensquared energy at 530.3 nm image plane

structure and appropriate compensators are considered in the analysis. Sensitivity of each tolerance is analyzed in Zemax optical designing software and found that two lens elements in collimator assembly are the critical elements in terms of fabrication and alignment. Alignment of M2 at the focal plane of M1 is another critical tolerance as M2

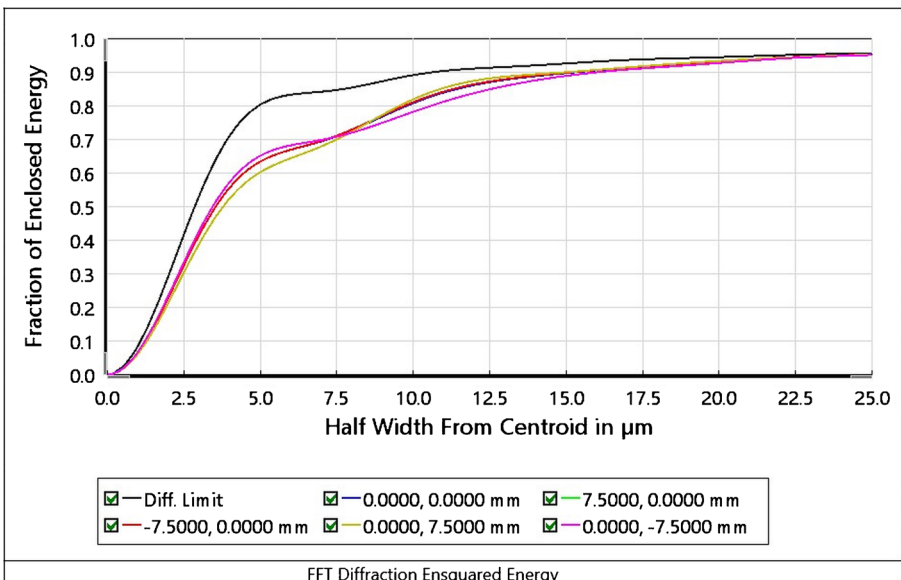


Fig. 11 Ensquared energy at 789.2 nm image plane

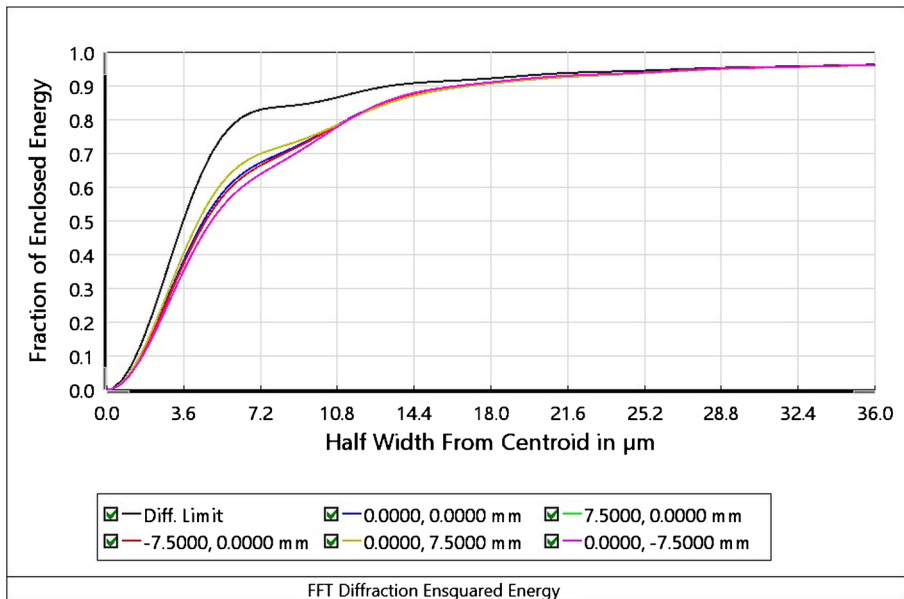


Fig. 12 Ensquared energy at 1074.7 nm spectro-polarimetry channel

is the internal occultor of the system. A Monte-Carlo analysis is carried out by applying all the fabrications and alignment tolerances simultaneously to simulate combined effect of all errors. Tolerances of all the optical components are generated and the design meets the requirements with all tolerances applied simultaneously.

2.4 Ghost image analysis

An analysis is carried out on the optical design to study if any ghost images are formed on the detectors due to the back reflections from different optical surfaces. Back

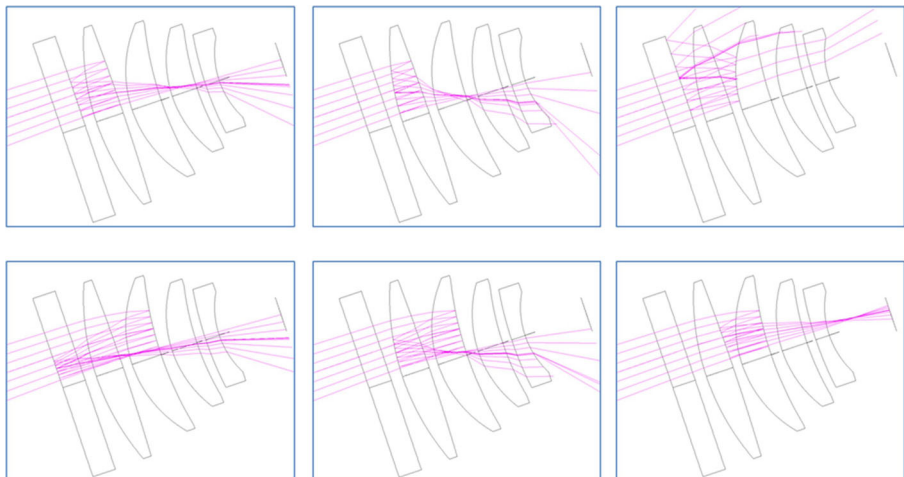


Fig. 13 Some of the safe back reflections between optical surfaces studied during the analysis

Table 1 Expected optical performance of VELC payload

| Sl. No | Channel Name | FOV | Wavelength (nm) | Plate Scale | Efficiency (%) |
|--------|-----------------|------------|-----------------|------------------|----------------|
| 1 | Imaging channel | 1.05–3Ro | 500 | 2.5 arcsec/pixel | 25 |
| 2 | 530.3 nm | 1.05–1.5Ro | 530.3 | 28 mA/pixel | 5.5 |
| 3 | 789.2 nm | 1.05–1.5Ro | 789.2 | 31 mA/pixel | 6 |
| 4 | 1074.7 nm | 1.05–1.5Ro | 1074.7 | 202 mA/pix | 4.5 |

reflections between all possible pair of optical surfaces are studied to find out if any ghost image is formed close to the focal plane. Ghost images formed between the surfaces of narrow band filter in imaging channel is focused at 650 μm before the image plane making it to spread over ~ 750 pixels on the detector. Considering a reflectivity of 10% on surface1 and 1% on surface2 the ghost image counts per pixel is 10^{-6} times the actual image intensity. Other back reflections are out of focus by ~ 10 mm making the ghost image intensity negligible and are shown in Fig. 13.

3 Discussions and conclusions

Optical design of VELC payload with the capabilities such as simultaneous imaging, multi-slit spectroscopy and spectro-polarimetry at three emission lines of solar corona are discussed in this paper. Optical configuration of the payload and expected performance at imaging and spectroscopy detectors are presented in terms of ensquared energy. A detailed tolerance and thermal analysis is carried out on the design considering fabrication and alignment tolerances over the operating temperature range. Ghost image is carried out to study the formation of ghost images on the detectors. The expected optical performance of the payload in terms of ensquared energy is given in Table 1. The optical performance of VELC meets the observational requirements to realize the proposed science goals. Currently, the payload development is in progress.

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