SENSITIVITY OF 3.6m DEVASTHAL OPTICAL TELESCOPE

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ABSTRACT

The 3.6m optical telescope, currently the largest optical telescope in India is being built at Devasthal with an aim to develop an observational facility with spectral and seeing limited imaging capabilities at visible and near infrared bands. Electromagnetic radiation received on Earth are the major carriers of cosmological information. The ability of a telescope to collect the least possible signal describes its sensitivity. The aim of the project was to characterize the photometric and spectroscopic sensitivity of this telescope. A measure of sensitivity is given by the signal to noise ratio of the telescope. The signal to noise ratio for imaging as well as spectroscopy at various zenith angles and observing conditions has been calculated using MATLAB. In imaging, a signal-to-noise ratio of 3.9 has been obtained for a 25mag point source in V band, measured at zenith for an exposure time of 30 minutes, using a 4KX4K CCD camera with a pixel size of 15microns,three days from New Moon. And, in spectroscopy, a signal to noise ratio of 7.5 has been obtained for a 20 mag point source at 0.5 µm, measured at zenith for an exposure time of 10 minutes.

CONTENTS

INTRODUCTION

Devasthal,(located at an altitude of 2420m, latitude 29deg 39 min North and longitude 79deg 68min East) is one of the potential astronomical sites in India, for observations of celestial objects in the optical and near infrared waveband, with a best seeing that can be obtained being around 0.7 arcsec and an availability of around 210 clear nights per year. The 3.6m optical telescope being built, at Devasthal, with an aim to develop an observational facility with spectral and seeing limited imaging capabilities at visible and near infrared bands, is currently the largest optical telescope in India.

It is a Ritchey-Chrétien telescope with an Alt-az mount and seeing limited observations. The primary mirror of the telescope has a clear aperture of 3.6m diameter and an f-ratio of f/2, while the diameter of the secondary mirror is 0.9m.The effective focal ratio of the telescope is f/9. The telescope will be equipped with instruments which can record data of point sources and extended objects at the optical wavebands. The aim of the project was to characterize the photometric and spectroscopic sensitivity of the telescope. The sensitivity of a telescope is determined by the amount of signal collected by it from the source. Hence, a measure of signal to noise ratio give an estimate of the sensitivity of the telescope.

In imaging, the shape and relative brightness of a celestial object is recorded and measured by direct imaging onto a detector and filters are used to control the spectral band pass . Whereas, in spectroscopy the intensity of received light from a celestial object is measured as a function of wavelength. The light or electromagnetic radiation from a celestial source is never obtained on the Earth's surface uninterrupted. The molecules present in the atmosphere absorb, scatter and refract the incoming light reducing its flux, altering its apparent position and so on. Besides these effects, molecules in the atmosphere emit radiation when they de-excite, creating unwanted background signals which add to the noise. The sensitivity of the instrument is enhanced when the signal from the source dominates the noise.

EARTH'S ATMOSPHERE

The atmosphere, though helps in maintaining the temperature of the Earth's surface and protect us from the harmful UV radiations from the Sun, has always been a challenge for the astronomers for ground based observations. It forms a barrier to the electromagnetic radiation from celestial sources and limits the observation to certain windows. The various processes that affects the passage of these radiation through the atmosphere are as follows:

Atmospheric extinction:

The air molecules and aerosols present in the atmosphere absorb and scatter the incoming radiation. This leads to a reduction in the flux received on the Earth's surface from the source. If the absorption of radiation is total, the transmission windows can be defined and the minimum altitude at which the observation can be made possible is determined whereas, if it is partial, the spectra of the sources under observation is modified. In this process, the photons transfers its energy to the air molecules and is hence destroyed. The molecules like H_2O, O_2, O_3 and CO_2 are the primary absorbers. H_2O absorbs mainly in infrared and millimeter wavelengths, O_3 in UV and CO_2 in infrared. As the incoming radiation is scattered by molecules in the atmosphere, their direction and energy are changed without destroying the photons. There are two types of scattering by atmospheric molecules- Rayleigh scattering and Mie scattering. The air molecules exhibit Rayleigh scattering and have a λ^{-4} dependence, while aerosols where the scattering particles are bigger than the molecules exhibit Mie scattering with a λ^{-1} dependence. Both absorption and scattering limits the detection of electromagnetic radiation from the celestial sources to a few spectral regions. The atmospheric extinction also depends on the airmass ,which in turn, is dependent on the zenith angle. Knowing atmospheric extinction coefficient in each band and airmass, the atmospheric extinction can be calculated using the formula,

$$\xi=10^{-0.4\times k\times \chi}$$

where, ξ is the atmospheric extinction, k the extinction coefficient and χ the airmass. For zenith angle less than 60^0, airmass is secant of zenith angle.

Atmospheric refraction:

The atmospheric density and refractive index of air varies with altitude, wavelength and humidity. This alters the apparent position of the source by making it appear higher in the sky than its actual position. In addition, the dispersion of the incoming light also occurs, spreading out the image of the source, which is a function of zenith angle, wavelength, humidity and altitude.

Turbulence:

The mixing of various layers of atmosphere leads to a change in refractive index in these layers which creates a turbulence and varies the intensity and direction of light coming from the extraterrestrial sources. This blurs the image of the source, an effect which is called seeing. The refractive index of air depends on its density, which in turn varies with the temperature fluctuations that may occur in the free atmosphere or near a telescope. Hence, temperature fluctuation is one of the major factors that effects seeing. Seeing can cause image motion as well as image blur. Telescopes with larger aperture have a greater spread of images and hence suffer from image blur compared to those with smaller apertures in which image motion is more relevant. It leads to a loss of detail of the object due to scrambling of light rays. Seeing is characterized by Fried parameter. Choosing a telescope with aperture size comparable to Fried parameter helps to reduce image blur considerably. Seeing is most prominent at lower end of optical range.

Many of these effects can be considerably reduced by a suitable choice of observational sites. For instance, the particle number density of H_2O becomes negligible at higher altitudes. Similarly, the density of air decrease with altitude and therefore the refractive index also decreases which facilitates a better seeing. Moreover, by keeping the temperature of the dome as close as possible to that of outside temperature helps a great deal to reduce temperature fluctuations and hence, seeing.

SOURCES OF NOISE

The signal from the source is always accompanied by light emitted from various other activities such as thermal emission from the atmosphere, zodiacal light, airglow, thermal emission from telescope and instruments within it and so on. All these signals contribute to the noise, which must be subtracted to extract signal from the source . All these emissions added together forms the sky background. Besides these, detector read out noise and dark current from the CCD also contribute to the noise.

Sky Background:

The major contributors to sky background are scattered moonlight, zodiacal light, diffuse galactic emission, emission lines due to OH airglow etc., which together forms continuum, and thermal emission from atmosphere and from the telescope. The sky background becomes more pronounced in the near infrared regions beyond 10μm, which makes observation in these regions almost near to impossible.

Scattered moonlight:

Moonlight is one of the most prominent sources of sky background in the optical region. Atmospheric gases and aerosols scatter the moonlight by Rayleigh scattering and Mie scattering respectively. Since, the efficiency of Rayleigh or Mie scattering increases towards shorter wavelengths, the blue wavelengths are more effected due to scattered moonlight. Based on Krisciunas & Schaefer (1991),the contribution from the scattered moonlight to the sky background is given as a sum of contributions from Rayleigh and Mie scattering. i.e.,

$$B_{\mathrm{moon}}(\lambda) = B_{\mathrm{moon,R}}(\lambda) + B_{\mathrm{moon,M}}(\lambda),$$

The intensity of scattered moonlight varies as a function of wavelength(λ), lunar phase angle(α), lunar zenith distance (z_{moon}), the zenith distance of the sky position (z), lunar distance or the angular distance between the Moon and the sky position (ρ) and the atmospheric extinction (k) as,

$$B_{moon\ i} = I(\alpha)f_i(\rho,\ \lambda)10^{-0.4k\,\chi(z_{moon})}[1 - 10^{-0.4k\,\chi(z)}]$$

wherein, the subscript 'i' corresponds to either Rayleigh or Mie scattering and χ is airmass which attenuates the moonlight as it travels through the atmosphere. For this model the airmass is computed by,

$$\chi = (1 - 0.96\sin^2(z))^{-0.5}$$

$I(\alpha)$ is the intensity of moonlight, which is a function of lunar phase angle and is given as,

$$I(\alpha) = 10^{-0.4[3.84+0.026|\alpha|+(4\times10^{\wedge}(-9))\alpha4-1.3]}$$

where, phase angle is given in degrees. The angle between the centre of the Sun and that of Earth, as seen from the centre of the moon is called the lunar phase angle. It varies from -180^0 during New moon to 180^0. The phase angle during full moon is 0^0, while the first quarter and last quarter occurs near -90^0 and 90^0 respectively. The surface brightness of the Moon generally increases as the magnitude of phase angle decreases.

$f_i(\rho,\ \lambda)$ is the wavelength dependent scattering function for Rayleigh scattering or Mie scattering and is given by,

$$f_M(\rho,\ \lambda) = 6.2 \cdot 10^7 \rho^{-2}(0.55/\lambda)^{1.3} \quad \rho < 8.$$

$$= 10^{(6.15-\rho/40)}(0.55/\lambda)^{1.3} \quad \rho \geq 8.5$$

And,

$$f_R(\rho,\ \lambda) = 2.27 \cdot 10^5(1.06 + \cos^2\ \rho)\ (0.55/\lambda)^4$$

where λ is in μm and ρ is in degrees.

The contribution from moonlight in units of mag arcsec^{-2} is given by the following equation,

$$V_i = \frac{20.7233 - ln(Bi/34.08)}{0.92104}$$

Zodiacal scattered light:

The dust grains orbiting the sun and concentrated in the ecliptic plane scatters the sunlight. Zodiacal light is the sunlight scattered by these interplanetary dust and is more pronounced in the short wavelength region. It is the brightest component and contributes around 50% to the sky background in a moonless night. Zodiacal light is not uniform. The impact of zodiacal light is reduced when the observations are made at midnight. It is an extended radiation source wherein, the observed intensity is due to light scattered into the line of sight and extinguished emission at the top of the atmosphere in the direction of observation. The intensity of zodiacal light is a function of ecliptic latitude and helio-ecliptic longitude. For wavelength greater than1µm, the following equation gives an estimate of the intensity of zodiacal light (in photons m^{-2} s^{-1} sr^{-1}),

$$Z(\lambda) = \frac{15.1}{\lambda^2} + 6 \times 10^{-8} \times \frac{2c}{\lambda^3} \frac{1}{e^{hc/265k\lambda} - 1}$$

where, the first term is the fall off scatter component and the second term thermal emission of a diluted blackbody at a temperature of 265K.

Diffuse galactic emission:

The scattering of starlight by the interstellar dust grains is the major cause for the diffuse galactic emission and is characterized by highly irregular patches of emission. This scattered starlight produces a diffuse glow concentrated along the galactic plane. It is relevant in the far UV to the near IR regions. It is a function of galactic latitude. The scattering process is more intense at low galactic latitudes since, in these regions the dust column density and integrated stellar emissivity are high. The albedo of the particles and the angular dependence of the scattering function defines or interprets the diffuse galactic light observations. The intensity of starlight passing through the interstellar dust is given by,

$$I = I_0 \, . \, e^{-\sigma n l}$$

where, σ is the cross section of each particle, n the space density of the particle and l is the length of the path.

Airglow emission:

The molecules in the excited state when de-excited emits radiation which is the source of airglow in the atmosphere. These are the non- thermal emissions from the atmosphere, OH molecules being the major contributor. It is comprised of both continuum and emission lines and is the brightest component of the night sky. The brightness of airglow varies with solar activity. Besides, airglow emission is a function of airmass and varies with the number of emitters at any given time. It is dominant in the shorter wavelength regions and becomes irrelevant beyond K band. The intensity of emission lines varies with airmass as,

$$I\,(t,z) = I_0(t)\,\chi\,(z)$$

where, t is the time after sunset, $I_0(t)$ is the time dependent intensity specific for each atmospheric molecule, z is the zenith distance and χ (z) is the airmass given by Rhijn function,

$$\chi\,(z) = \left[1 - \left(\frac{R}{R+h}\right)^2 \sin^2 z\right]^{-1/2}$$

where, R is the radius of Earth and h is the altitude.

All these background emissions mentioned above forms the non-thermal atmospheric emission which has continuum as well as emission lines.

Thermal emission from atmosphere and telescope:

The collision between the air molecules is the major source of thermal emission from atmosphere. It peaks at around 10µm and is overtaken by airglow emission of OH at shorter wavelengths. Similarly, the dust particles on the surface of the mirror of a telescope scatters the photons incident on it. The collision of these scattered particles are responsible for the thermal emission from telescope. The intensity of thermal emission is a function of wavelength , temperature as well as the emissivity and is given by,

$$I = \varepsilon_\lambda\, B_\lambda(T)$$

Here, ε_λ is the emissivity and $B_\lambda(T)$ is the Planck's function at the mean temperature.

The flux from the sky background is a sum of all the above processes. In shorter wavelength regions, non-thermal emission from the atmosphere is dominant while the thermal emission from the atmosphere dominates in the longer wavelength regions, the intensity of sky background peaking at around 12µm. This implies that the observation in the infrared region is almost near to impossible. Making use of continuum values corresponding to the broadband brightness as given by the 'standard' ESO ETC sky brightness table for a moon phase of 3 days from new moon ignoring any dependencies on site and airmass, and equating the thermal emission from atmosphere and telescope, a plot between wavelength and sky brightness has been developed using MATLAB. The emissivity of the atmosphere, which almost approximates that of a blackbody was taken to be 0.9 and that of telescope which can be considered as a grey body is taken to be 0.14. The mean temperature of the Earth is 255K and the temperature at the observational site was taken to be around 293K. It is evident from the plot that the sky background peaks at around 12µm.

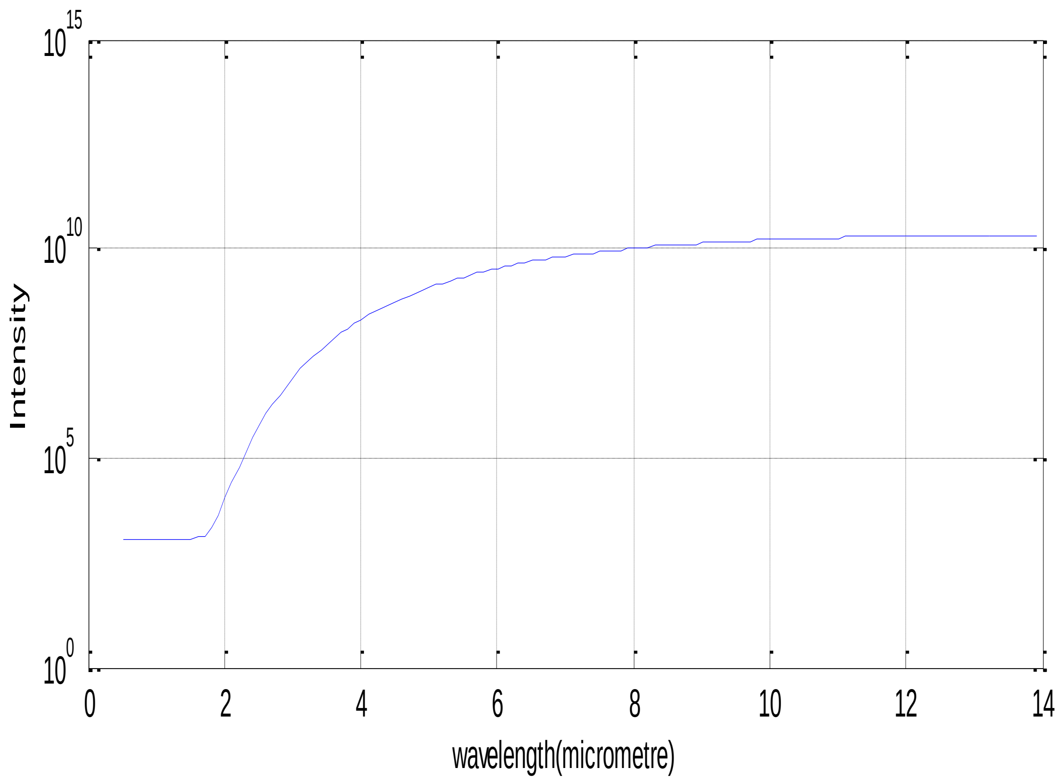

Fig.1

The intensity is given in photons s^{-1} m^{-2} μm^{-1} $arcsec^{-2}$.

PHOTOMETRY

Photometry is the science of measuring the flux that we receive from celestial objects. In other words, photometry involves the measurement of received radiation intensity and the determination of the shape of the object in a specific wavelength band. This is achieved with the help of a CCD camera with filters to define a particular wavelength band.

Charge Coupled Devices:

A CCD is a device which converts photons into photoelectrons which are then stored in the form of digital signals. These photoelectrons are stored in the depletion region of a metal insulator semiconductor capacitor. The CCD array consist of several pixels, each of which collects the photons from the source. The charge stored within each pixel is transferred from pixel to pixel during readout via changes in electrical potential between the biased gates. The freed electrons are held in the potential well until the end of exposure with the help of these gate structures. There are various types of CCDs such as surface channel CCDs in which charge transfer occurs across the surface, buried channel CCDs in which the charge movement is enhanced by reducing the number of possible trap sites and decreasing the transfer time, interline transfer CCDs, front illuminated and back illuminated CCDs, anti-blooming CCDs and so on. In back side illuminated CCDs the photons are absorbed directly into the silicon pixel without interference of the gate structure. This increases the quantum efficiency of the detector. Quantum efficiency describes the ability of a detector to convert incoming photons to those actually detected or stored in the device. Quantum efficiency can be increased using high resistivity silicon.

IMAGER OF 3.6m TELESCOPE:

A 15micron 4KX4K CCD camera with an image area of 60mm x 60mm is being mounted on the 3.6m telescope. It is a back illuminated single chip CCD with clocked anti-blooming facility and optional MPP mode operation. MPP design helps to reduce the dark current and if the light levels are sufficient, allows room temperature operation. The CCD has enhanced blue sensitivity and a peak quantum efficiency greater than 95% at 450nm at -100^{0}C. The summing of charge within a few pixels, before they are digitized, in the output register is called on-chip binning. The CCD of imager in 3.6m telescope has an on chip 2x2 and 4x4 binning modes. The operating temperature range of the control electronics in the imager is around -10^{0}C to 30^{0}C and the spectral range of operation is 300nm-1000nm.

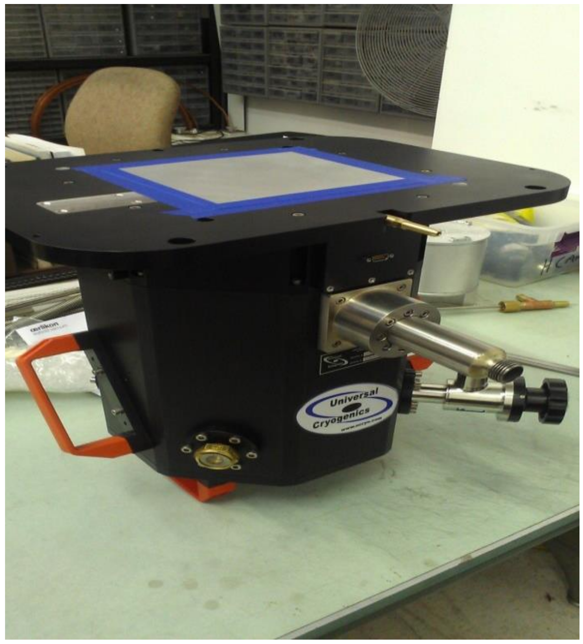

Fig.2

Every material at a particular temperature above absolute zero will be subject to thermal agitation and hence noise within. In a CCD, if the thermal agitation is high enough for the silicon, electrons in the valence band are released and get collected within the potential well of a pixel. These are called dark current and are indistinguishable from the signal. For a CCD, it is generally specified as the number of thermal electrons generated per second per pixel or as the actual current generated per area of the device. CCD dark current is a strong function of temperature and will vary considerably even for a modest change in CCD temperature. Therefore, coolers are used to maintain the temperature of CCD. The dark current produced in the imager is ~ $3x10^{-7}$ electrons/pixel/sec at -110^{0}C and liquid nitrogen cooler is used for cooling mechanism.

The electronics themselves often produces spurious electrons into the entire output adding to the number of electrons from the signal. Moreover, the conversion from analog signal to a digital number is not repeatable. Hence, there is an uncertainty in the final output value for each pixel. In simple words, read out noise is the number of electrons introduced per pixel into the final signal upon readout of the device. Read out noise depends upon the physical size of the on-chip amplifier, the integrated circuit construction, temperature of the amplifier and the sensitivity. The rms values of read out noise for the imager being mounted on 3.6m telescope is 2.5-3.5 electrons at 100kHz and 5-7 electrons at 1MHz which has a user selectable multi-port read out options.

The full well capacity of the CCD being used is greater than 200K electrons. The pixel scale of CCD is around 95.5milliarcsec/pixel i.e., the sky covered per pixel is 95.5 milliarcsecond. The gain of a CCD determines how the amount of charge collected in each pixels will be assigned to a digital number in the output and is determined by the output electronics. The typical gain achieved for the imager is around 1.5 electrons/ADU.

Photometric sensitivity:

The photometric sensitivity of the telescope has been calculated using MATLAB. It is characterized by the ratio of signal to noise collected in various bands of electromagnetic radiation. The model calculates the signal to noise ratio of point sources in a particular waveband as a function of magnitude using filters. A star or a celestial source is often defined by its magnitude in a particular waveband. Magnitude system divides the stars of various brightness into several classes of magnitude. Vega, the brightest star is assigned a magnitude of zero. Stars brighter than Vega have negative magnitudes while those which are fainter have magnitude greater than zero. The magnitude of sun in V band is around -26.8. Knowing the magnitude of the source and flux of Vega in various bands and using photometric zero point ,the flux of the source can be calculated using the equation,

$$F_{obj} = F_0 10^{-0.4\ mobj}$$

where, F_{obj} is the flux of the object, F_0 flux of Vega and m_{obj} magnitude of the object. Flux of Vega in various bands has been calculated using the photometric zeropoints provided in the E-ELT Imaging model and using the equation,

$$F_0 = 10^{-Z}$$

where, Z is the photometric zeropoint in a given waveband.

As already mentioned in earlier sections, the flux from the object when received on the detector is reduced due to atmospheric extinction which is a function of airmass. Airmass can be defined as the thickness of the air traversed by the signal before reaching the detector and is, in turn, a function of zenith angle. For zenith angles less than 60^0 it is the secant of zenith angle. The atmospheric extinction has been calculated for the values of atmospheric extinction coefficients in each band at Devasthal. Thus, the flux of the object received at the telescope entrance is

$$\dot{F}_{obj} = \xi \, F_{obj}$$

The imaging performance of an optical system is characterized by its PSF. PSF or Point Spread Function describes the two dimensional distribution of intensity of light from the point source in the focal plane. It approximates a Gaussian function and depends on the diffraction effects and the instrumental effects. The point spread function which has a FWHM of 1arcsec has been plotted using Gaussian function in MATLAB as a function of angular distance. FWHM is the width of the PSF at half the maximum intensity and is a good measure of image size. But a better interpretation of the image is given by the encircled energy, which describes the energy contained in a given angular diameter. Mathematically, it is obtained from the error function of the Gaussian distribution. The encircled energy in various angular diameters has been calculated using MATLAB and the following plot was obtained.

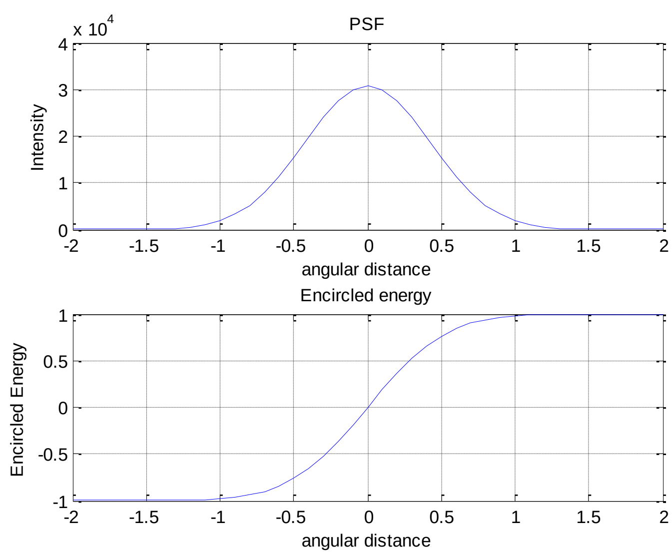

Fig.3

The sky surface brightness in various bands at Devasthal has been obtained from studies done earlier , using which the flux due to surface sky brightness has been calculated at the telescope entrance. Using the parameters of telescope, CCD and sky brightness the signal-to-noise ratio for various bands as a function of magnitude at various zenith angles, three days from New Moon and on Full Moon has been calculated in MATLAB, for pointed sources, using the formula,

$$\frac{S}{N} = \frac{N\text{obj}\sqrt{n\text{exp}}}{\sqrt{N\text{obj} + N\text{sky} + N\text{pix}\,\mathrm{r}^2 + N\text{pix}\,d\,T}}$$

where in, N_{obj} is the number of detected electrons from the object in S/N reference area, n_{exp} is the number of exposures, N_{sky} the number of detected electrons from the background in the S/N reference area per exposure, N_{pix} is the number of pixels in the S/N reference area, r is detector read-out noise, d, the detector dark current and T, the detector exposure time for one exposure and the following plots has been obtained.

The signal-to-noise-ratio has been determined in V band at various zenith angles for sources of different magnitudes, three days from New Moon, for an exposure time of 30 minutes and the following plot has been obtained.

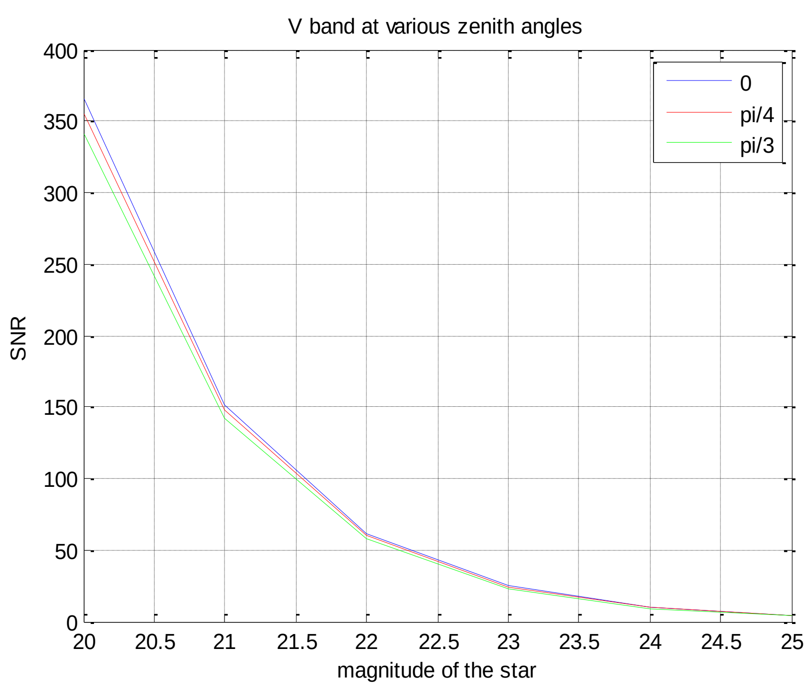

Fig.4

For an exposure time of 30 minutes signal-to-noise ratio has been calculated in UBVRI band, measured at zenith angle of 0^0, three days from new moon and the following plot has been obtained.

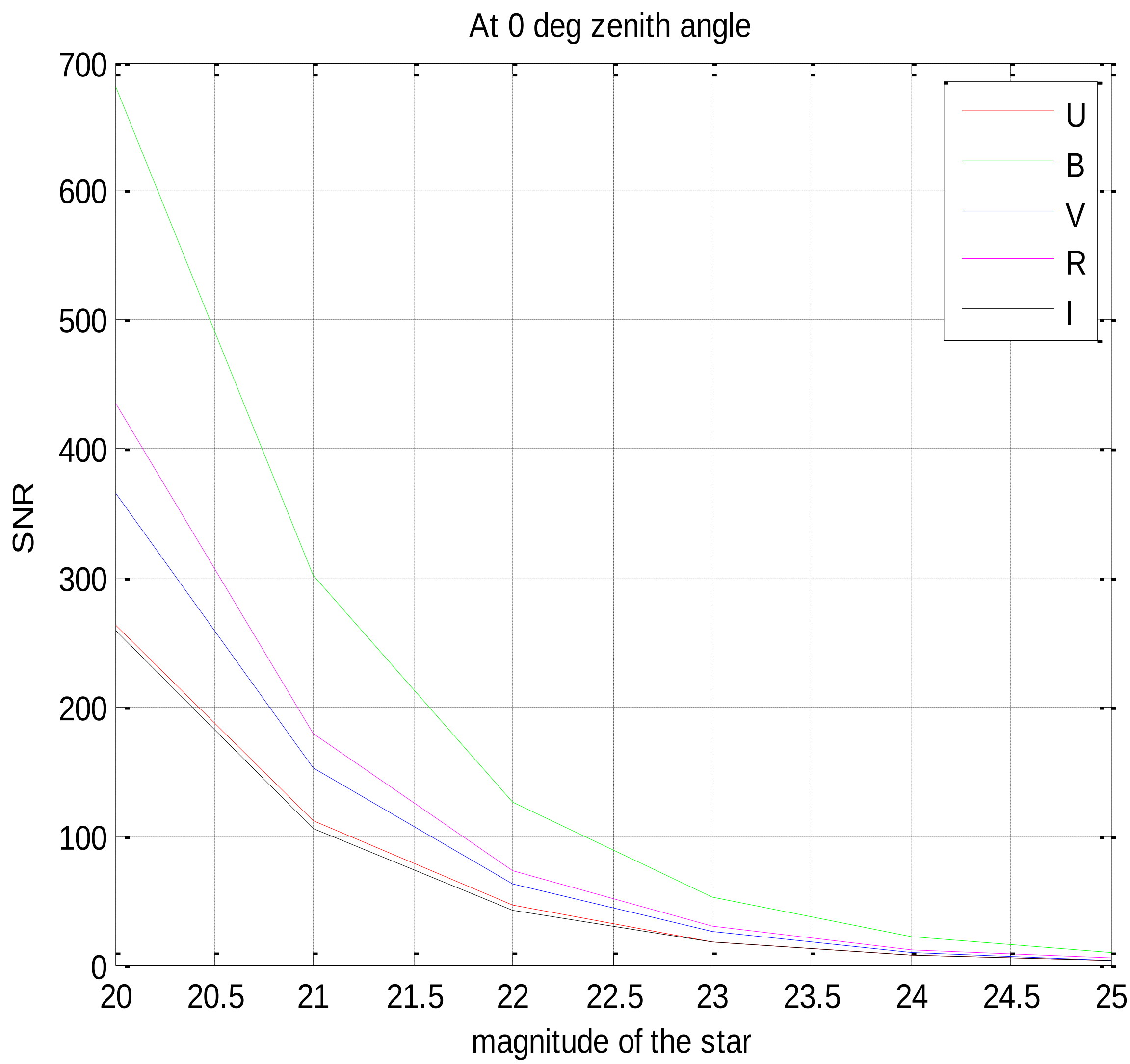

Fig.5

The magnitude of sky brightness varies with varying lunar phase angles. Signal to noise ratio in V band at zenith for an exposure time of 30 minute has been calculated during three days from New Moon and on Full Moon and the plot obtained is the following

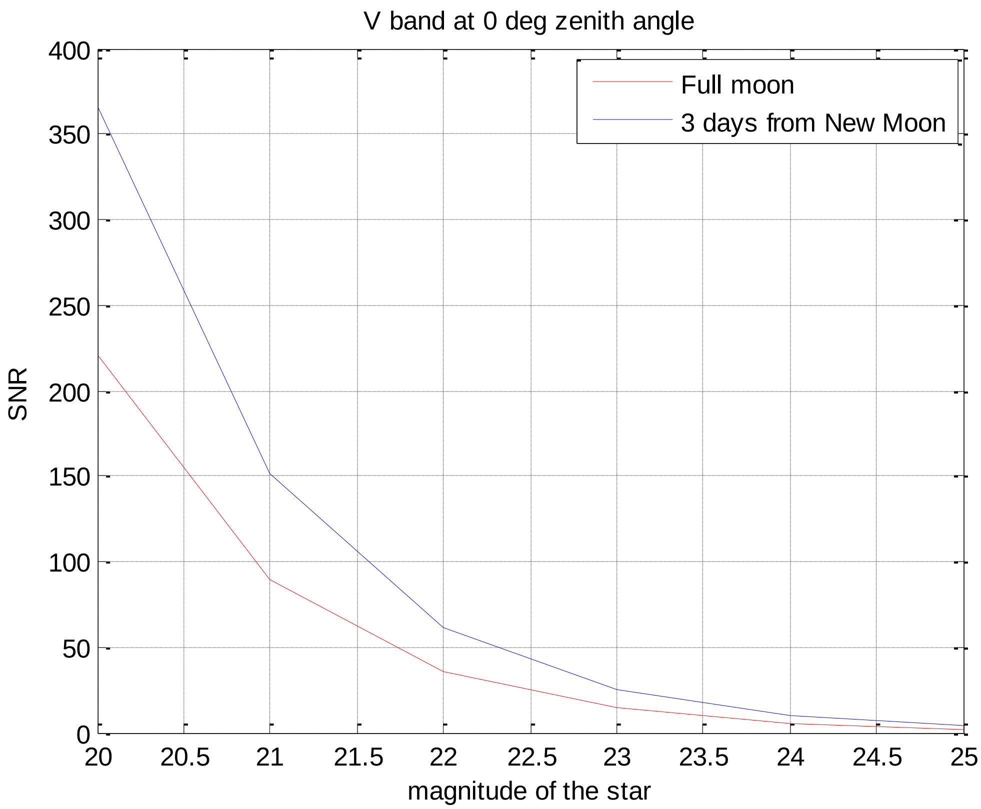

Fig.6

SPECTROSCOPY

In spectroscopy the incoming light is dispersed in order to measure the intensity of received light as a function of wavelength. A spectrograph is used to obtain the spectrum of the incoming light at various wavelengths.

FOSC:

A Faint Object Spectrograph and Camera has been designed for the telescope. In a spectrograph light from the source is made to enter through a slit and then collimated. The collimated beam is then made to pass through the dispersing material, a prism or a grating, which is then captured by a lens that forms the image on the detector. The instrument that is being used in this telescope converts f/9 beam from the telescope into f/4.3 beam. Chromatic aberrations has been minimized by the use of low dispersion glasses such as CaF_2. With FOSC, spectroscopy can be done in the wavelength range 350-900 nm with a resolution in the range of 250-2000 using various grisms and slits. The overall transmission of the instrument is around 75% at 350 nm and greater than 95% at wavelengths larger than 400nm. The detector used in FOSC is the same CCD that is being used for imaging.

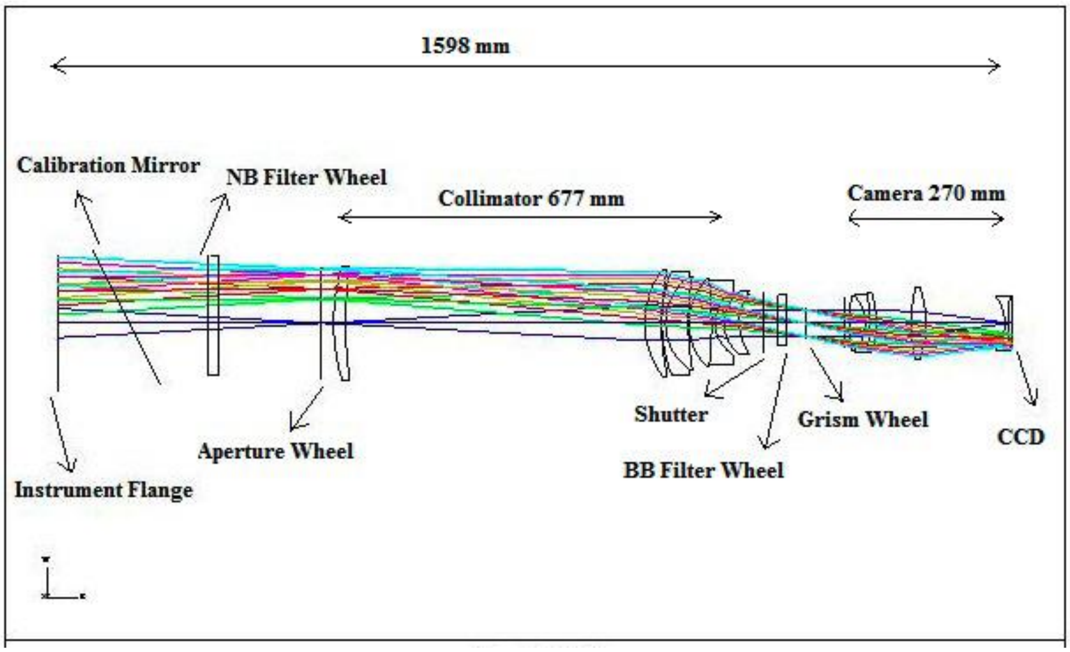

Fig.7

Spectroscopic Sensitivity:

The spectroscopic sensitivity of the 3.6m Devasthal optical telescope has been calculated using MATLAB. The signal-to-noise ratio was calculated for a point source as well as extended source of magnitude and surface brightness 20mag arcsec^{-2} with a spectral resolution of 2000 using the formula,

$$\frac{S}{N} = \frac{N\mathrm{obj}\sqrt{n\mathrm{exp}}}{\sqrt{N\mathrm{obj} + N\mathrm{sky} + N\mathrm{pix}\,\mathrm{r}^2 + N\mathrm{pix}\,d\,T}}$$

where, parameters are the same as in photometry. The number of detected photons from the sky has been calculated from the flux of the sky background calculated earlier. The plots of signal-to-noise ratio as a function of wavelength obtained for point and extended source are given below.

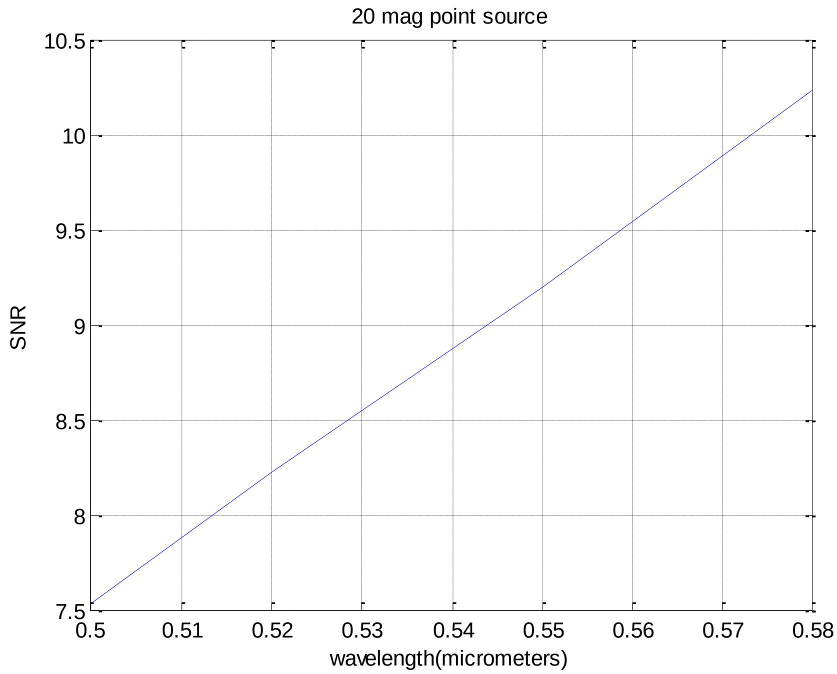

Fig.8

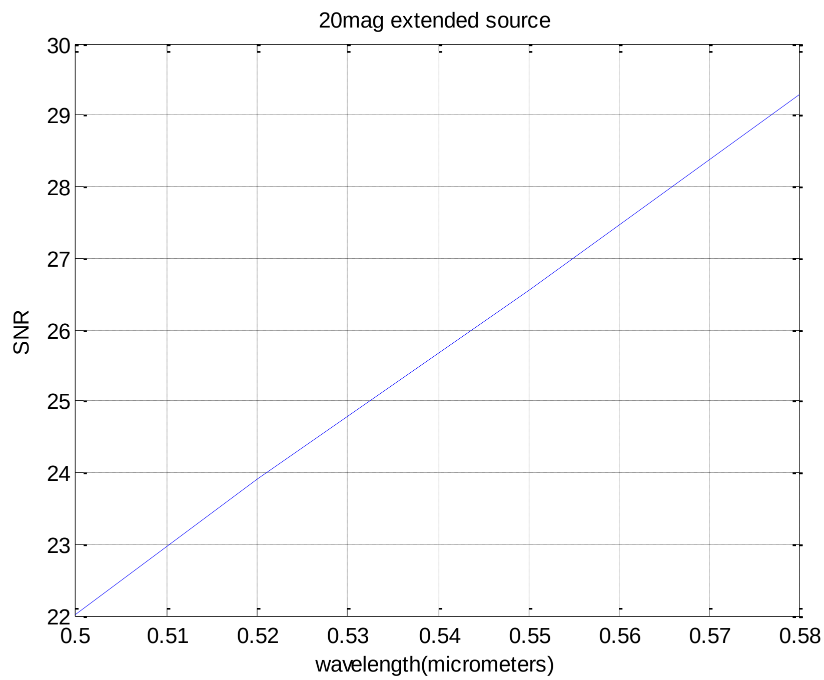

Fig.9

RESULTS:

In photometry, a signal-to-noise ratio of 3.9 has been obtained in V band for a point source of magnitude 25mag arcsec^{-2} ,measured at zenith for an exposure time of 30 minutes, three days from new moon. When calculated with the sky brightness on full moon the signal-to-noise ratio was found to be reduced to 2.2 for the same source under same conditions. Similarly, signal-to-noise ratio was found to decrease with an increase in zenith angle. In spectroscopy, a signal-to-noise ratio of 7.5 has been obtained for a point source of 20 magarcsec^{-2} at 0.5μm for an exposure time of 10 minutes, three days from new moon. With the same parameters a signal-to-noise ratio of 22 has been obtained for an extended source.

DISCUSSION:

As per the calculations, the sensitivity of the 3.6m telescope being installed at Devasthal is appreciable for observation of faint objects in the optical and near infrared wavebands. A comparison has been made between the existing large optical telescopes in India (2m and 2.3m) under the same conditions and the signal-to-noise ratio obtained for 3.6m Devasthal optical telescope was found to be almost twice that of the other telescopes.

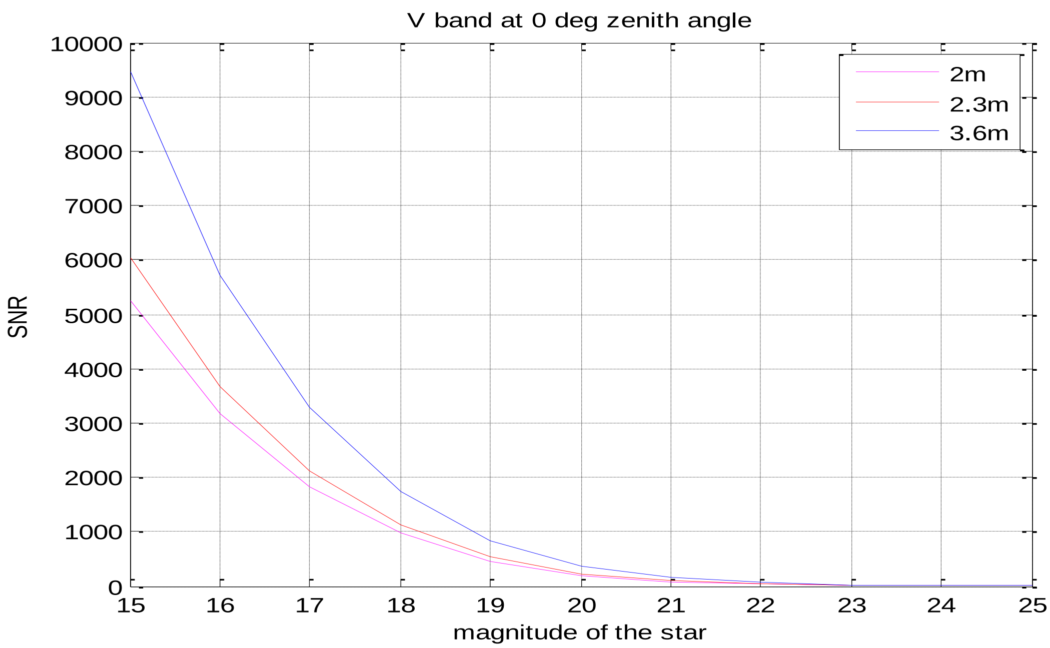

Fig.10

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