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# The estimation of the instrumental polarization and crosstalk at the focus of the mid-infrared imaging system for the Thirty Meter Telescope


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## ABSTRACT

The Thirty Meter Telescope (TMT) is a proposed future generation telescope which will be located on either Maunakea, Hawaii or La Palma in the Canary islands. A thermal-infrared (TIR) imager and spectrometer (MICHI) combined with an adaptive optics system is being investigated as a possible second-generation instrument for this telescope. MICHI has been designed to also have a polarimetry capability in both imaging and low dispersion spectroscopic modes. Using polarization ray tracing in Zemax, we have estimated the instrumental polarization (IP) and crosstalk introduced at the focus of the near- and mid-infrared imaging system. In our calculations, we find that the IP varies from 1.0-0.54% and 0.54-0.42%, whereas the polarization crosstalk varies between 25-4% and 4-0.7%, in the near and TIR regions respectively at the instrument port of MICHI. These values of IP and crosstalk may cause problems during the high absolute accuracy polarization observations. Here we present the polarization effects for the imaging system of MICHI and it impacts on the polarization observations.



**Keywords:** Instrumental polarization, Crosstalk, Thirty-Meter Telescope, MICHI, MIRAO


## 1. INTRODUCTION

The Thirty Meter telescope which is proposed to be built in Maunakea, Hawaii or La Palma, Canary Islands, has a Ritchey-Chretien optical[1] configuration along with a Nasmyth mirror to feed light to different instruments kept on the Nasmyth platform.[2] The large aperture of the telescope and advanced instrumental facility will make TMT a potentially useful candidate for carrying polarimetric observations of many celestial sources. Currently, none of the first-generation instruments have a polarimetric capability. A polarimetric modeling team[3] was set up in 2014 to investigate the polarimetric capabilities of the TMT. A number of polarimetry science cases were collected with requirements for Instrumental polarization (IP) and crosstalk (CT) from the telescope.[4] An Analytical ray tracing model was developed to determine the IP and CT due to the telescope optics.[5] The Mueller matrices were estimated using the polarization pupil map in the optical design software Zemax. At one of the instruments port (WFOS), the IP of 4.5-0.6% and CT of 70-10% in the wavelength range of 0.4-2.5$\mu$m has been estimated. They were found to vary with the zenith angle of the telescope at all the other instrument ports except at the WFOS port.[4] The high values of IP and CT and their variation would pose challenges for precise polarimetry in TMT in this wavelength domain. Currently, one of the proposed second-generation instrument (in the TIR wavelength region, 3-14 $\mu$m (-25 $\mu$m to be confirmed)) named Mid-Infrared Camera, High-disperser, and Integral field unit (MICHI) for TMT will have the polarimetry capability along with low/ high-resolution spectrometer and with the imager. The science cases/drivers and the instrument specifications


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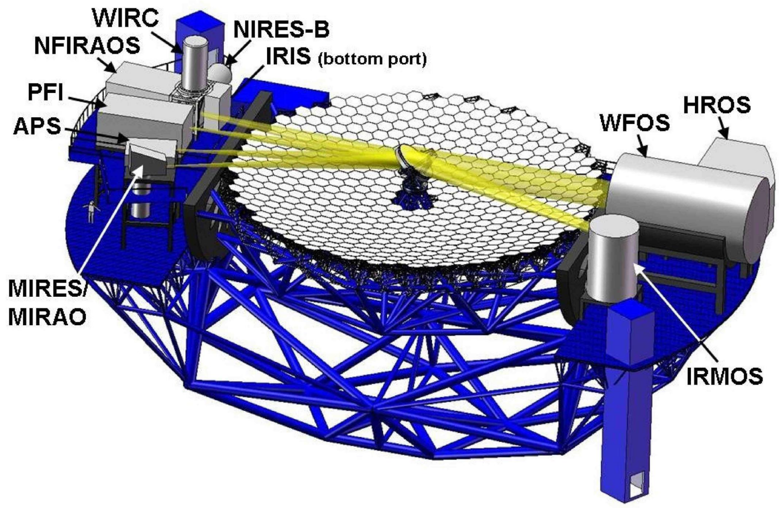


Figure 1. **The Nasmyth platform of the TMT showing the different instrument positions. WFOS instrument port corresponds to the tilt of 45 degrees of the Nasmyth mirror.**

have been discussed by Okamoto et al. (2010) and Packham et al. (2012).[6,7] The preliminary design concepts of the instrument have been presented in Tokunaga.[8] The polarimeter is proposed to be a half wave plate (HWP) and Wollaston prism-based system which can be operated in both imaging and spectro-polarimetric mode in at least the N band (7.3-13.8$\mu$m).

Here, we estimate and present the polarization effects from the telescope in thermal-infrared wavelengths at the following locations:

1. At the instrument port of MICHI
2. Just before the modulation of the incoming light (HWP)
3. At the focus of the MICHI (imaging mode)

We also show the dependence of IP and CT on the field angles and the Zenith angles at the above-mentioned locations. Section 2 gives a brief description of the polarization ray tracing in Zemax which is used for the determination of the polarization effects. The Mueller matrices are given for the thermal-infrared region at the instrument port of MICHI. Section 3 explains the change in the IP and CT during the tracking of the telescope. The IP and CT for different coatings at the MICHI focus are given in section 4. Discussions and future work are given in section 5.

## 2. POLARIZATION EFFECTS AT THE TELESCOPE FOCUS AT THE MICHI PORT IN NEAR AND MID INFRARED REGION

The optical layout of the telescope is modeled in Zemax with the Nasmyth mirror pointing to the MICHI port. The Stoke's-Mueller formalism[9] is used to determine the polarization effects. We use the polarization pupil map for different input polarizations in Zemax[10] to estimate the Mueller matrices. The polarization pupil map for one of the input polarization states is shown in the Fig 2. The polarization effects depend on the incident angles and the coating of the mirrors. The coating used in our analysis for the telescope mirrors consists of Silver (thickness of 1100Å) as the main reflecting layer and Si3N4 (85Å) as the protective coating. The refractive indices are taken from the handbook of optical constants by E. Palik[11] up to $\lambda = 10\mu$m. For $\lambda > 10\mu$m, it is taken from Hagemann (1975).[12] The Mueller matrices which are estimated for the near and mid-infrared regions is given in figure 3 and figure 4 respectively. The first column of the Mueller matrix corresponds to the instrumental polarization from the telescope. The contribution from $I \rightarrow U$ and $I \rightarrow V$ is found to be less compared to $I \rightarrow Q$. IP reduces 1% to 0.55% in the near infrared region as shown in figure 3. In the case of the mid-infrared

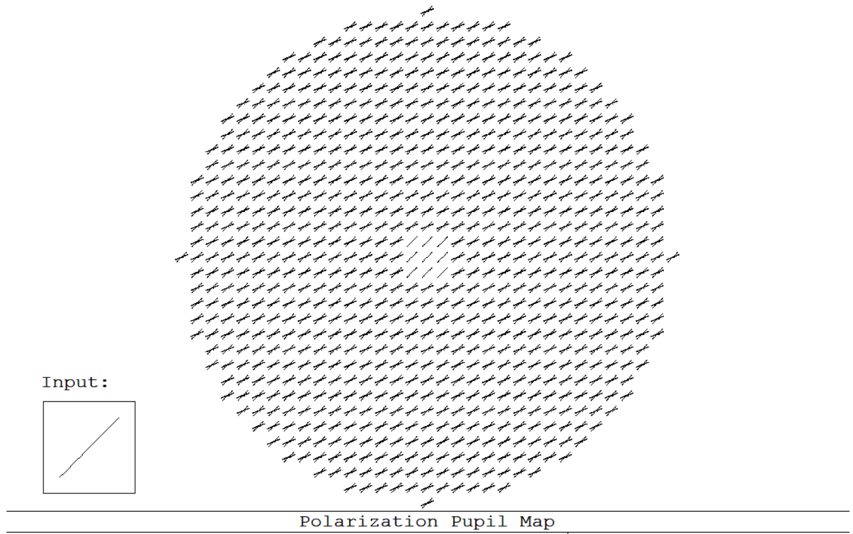


Figure 2. The Polarization pupil map obtained from Zemax at the telescope focus with Nasmyth mirror pointing to the MICHI port. The lighter black line corresponds to the input polarization vectors and the darker line corresponds to the output vectors. The input is the linearly polarized light at 45 degrees. The output polarization vector no longer remains linear after three reflections. It becomes elliptical because of linear to circular crosstalk.

region, in increases from 0.55% to 0.65% from $5\mu$m to $10\mu$m. Beyond $10\mu$m, it decreases to 0.45% at $28\mu$m. The terms $M42$ and $M43$ in the figure 3 and 4 correspond to linear to circular crosstalk. The $Q \rightarrow U$ and $U \rightarrow V$ crosstalk are found to decrease from 25% to 1% from 1-28$\mu$m. The values of crosstalk are high in the near infrared region compared to the mid-infrared region. The IP and CT also show variation with the field angles. For a smaller field of view (1-2'), these variations lie within the error values of the IP and CT.

## 3. POLARIZATION EFFECTS DURING THE TELESCOPE TRACKING

The Nasmyth platform in the figure 1 shows different instrument ports in the TMT. The Nasmyth mirror has to rotate 23 degrees from the Alignment and Phasing system (APS) position to feed the light to MICHI. The tilt ($\phi$) and the rotation ($\theta$) of the mirror changes (as shown in figure 5) during the tracking of the telescope (M3 document). They are found to decrease with the increase in the zenith angle. As a result of this, the incident angle on the Nasmyth mirror also changes during the tracking. The contour plot of the incident angle on the surface of Nasmyth mirror at zenith angle of 45 degrees is shown in the figure 6. It varies from 39 to 35 degrees along the tilt axis of the mirror. The variation of the incident angles with the zenith angle is shown in the figure 7. The curves correspond to the rays falling at the specified pupil positions. The IP and CT are dependent on the incident angle and the coating of the mirror. As the incident angle varies during the telescope tracking, the IP and CT would vary too.

The Mueller matrices are estimated at the instrument port of MICHI when the zenith angle of the telescope varies from 1 to 65 degrees. The figure 8 shows the variation of IP and CT with the zenith angles. IP reduces from 0.6% to 0.3% as the zenith angle varies for $\lambda = 9.19\mu$m and the CT reduces from 2.8% to 2% for $\lambda = 7.293\mu$m. These variations would pose problems during the instrumental polarization correction in the science data.

## 4. IP AND CT AT THE FOCUS OF THE MID-INFRARED IMAGER

Figure 9 shows the optical layout of the proposed mid-infrared imager with the polarimetric capability. The modulator and the polarizer are placed at the beginning of the layout after the initial two mirrors.

### 4.1 Ideal coating for all the mirrors

As the coating recipes for all the optical components in the MICHI are not available, we have used an ideal coating which makes the reflection coefficients $rp$ and $rs$ to be equal. This would give the IP and CT caused

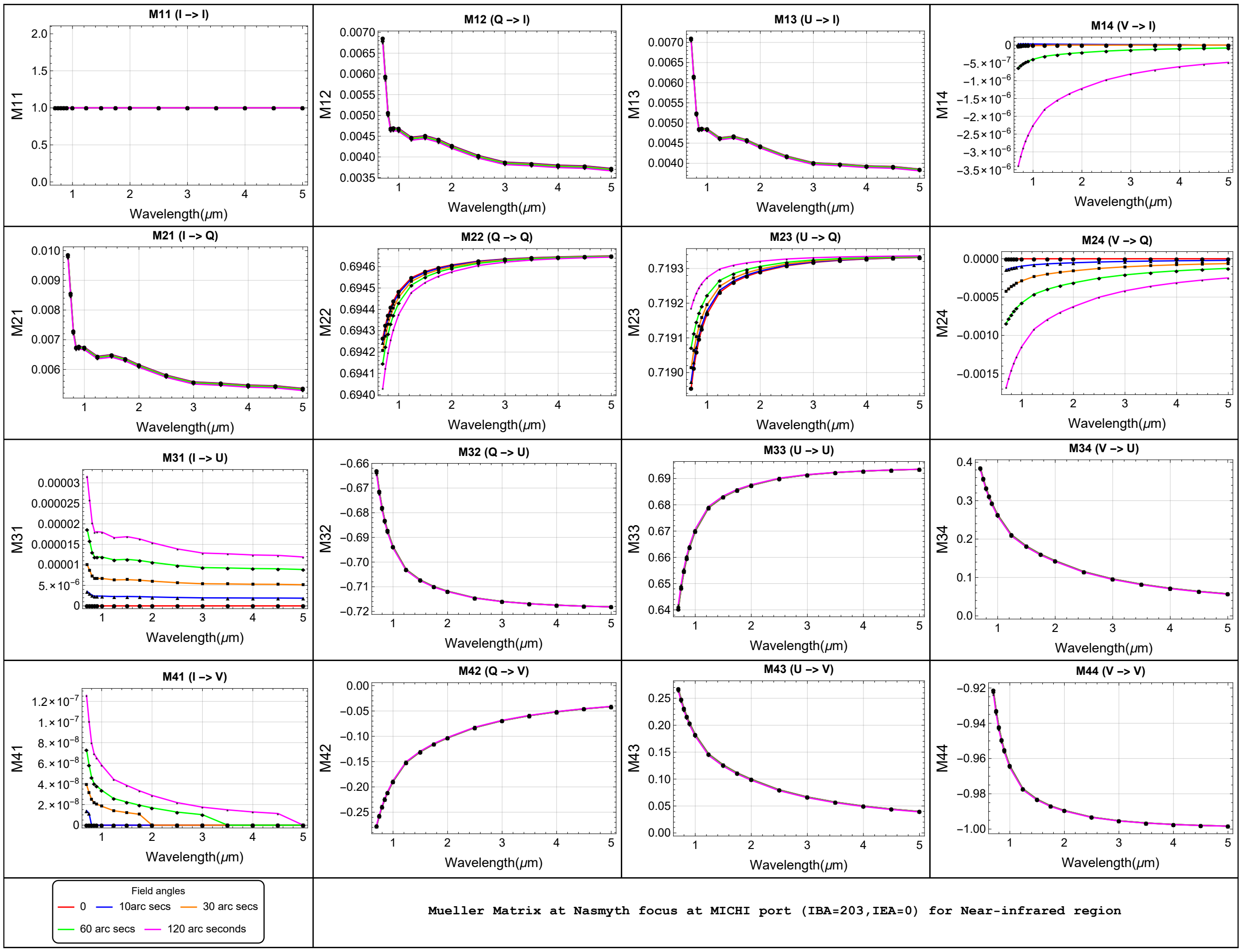


Figure 3. Mueller matrices are shown for the near infrared wavelength region at the instrument port of MICHI. Different colors correspond to different field angles.

only due to the variation of the angle of incidences on the mirror surfaces. The IP and CT are shown with the zenith angle at MICHI port, before the modulator, and at the focus of the imager in the figure 10. The IP at the telescope focus varies from 0.22% to 0.15 %. Similarly, it shows a variation of 0.3% to 0.18% and 0.52% to 0.42% at the modulator and focus of imager respectively. The CT values are less than 1% till the modulator, which then increases to 2% at the imager focus.

## 4.2 Metal coating on all the mirrors

To have the comparison with the ideal coating, we have considered Silver+$Si_3N_4$ coating for the telescope mirrors. An unprotected gold coating which is widely used in the infrared wavelength regions owing to its high reflectivity is considered for all the mirrors inside the MICHI instrument. The refractive index for the gold is obtained from Handbook of optical constants of solids.[11] Figures 11 and 12 show the variation IP and CT at the modulator and the focus of the imager. The IP and CT values are higher compared to the values with the ideal coating. The maximum value of the IP and CT are found to be 0.8% and 3.6% at the modulator. Similarly, we see 2.6% IP and 10% CT at the focus of the imager as shown in Figure 12. The effect of coating on the IP and CT is found to be more than the incident angles.

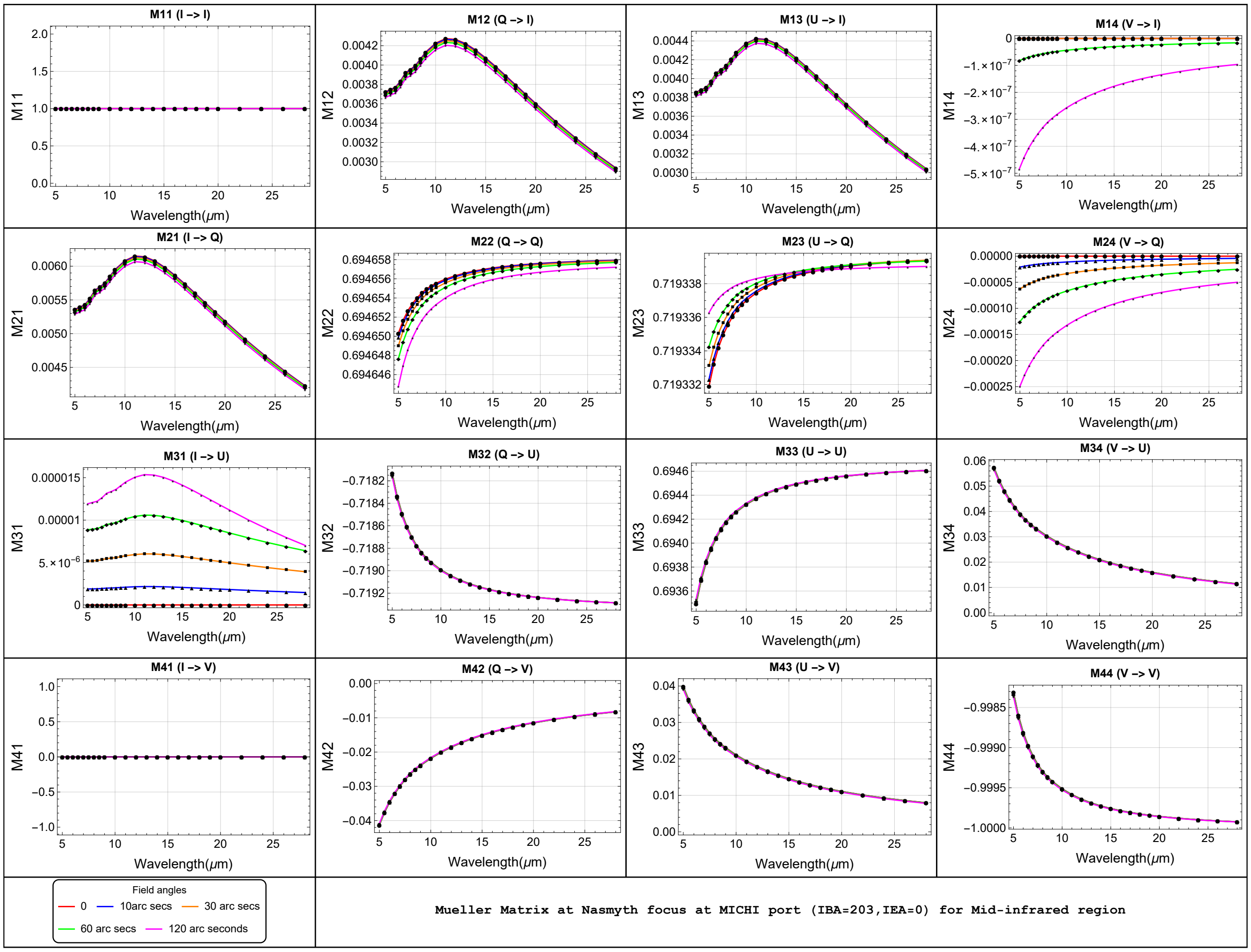


Figure 4. Mueller matrices are shown for the mid infrared wavelength region at the instrument port of MICHI. Different colors correspond to different field angles

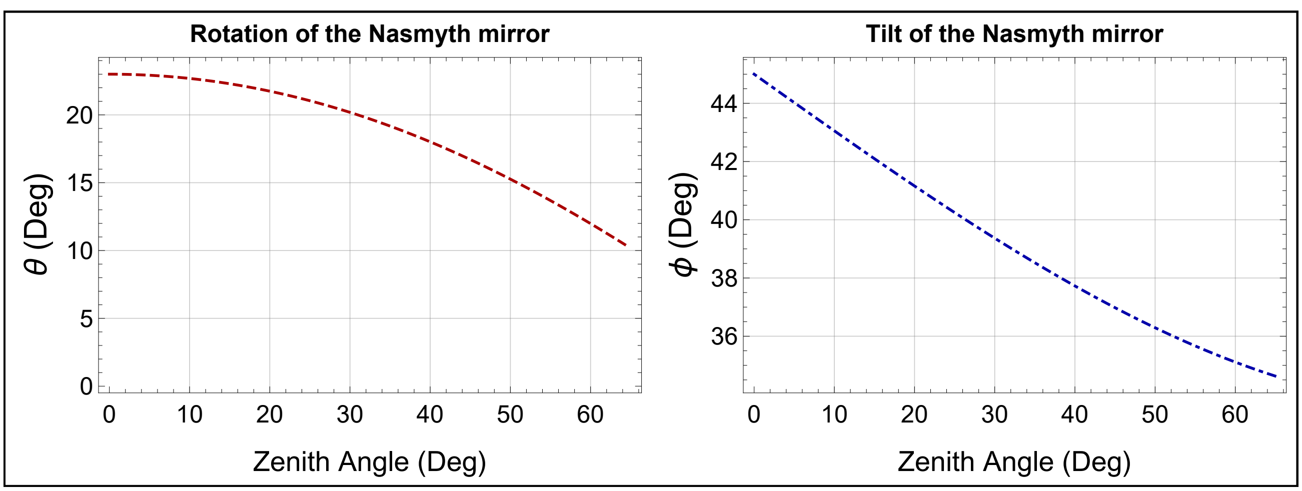


Figure 5. The variation of the rotation ($\theta$) and the tilt ($\phi$) of the Nasmyth mirror with the zenith angle of the telescope is shown in the figure.

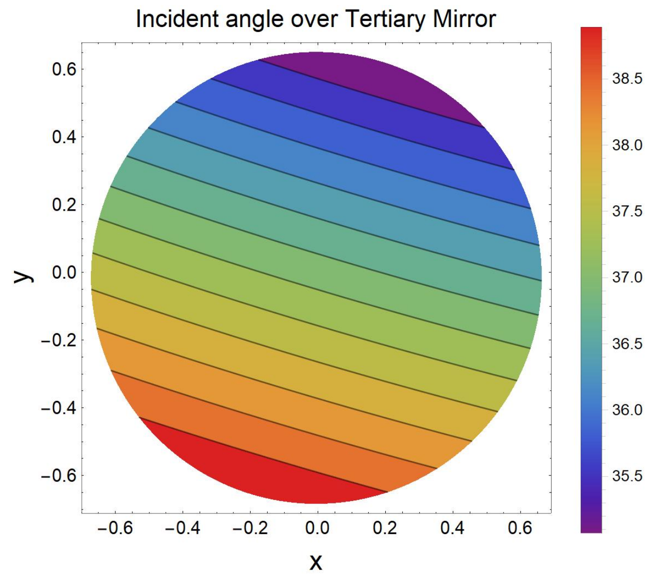


Figure 6. The contour plot of the incident angle on the surface of the Nasmyth mirror is shown. $x$ and $y$ corresponds to the co-ordinates on the mirror surface.

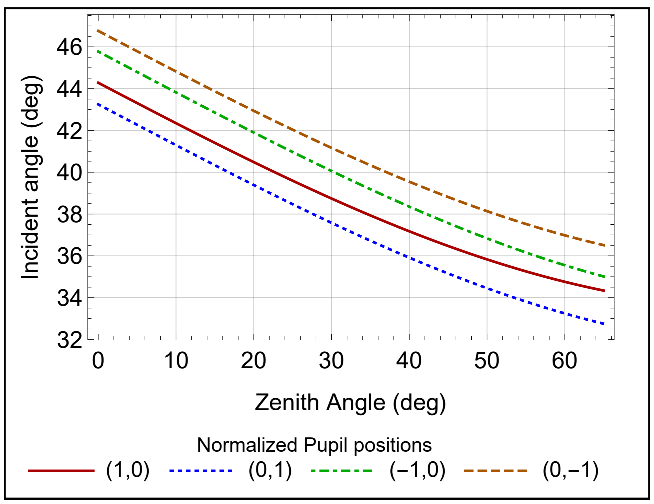


Figure 7. The variation of the incident angle on Nasmyth mirror with the zenith angle of the telescope is shown in the figure. Different curves correspond to different normalized pupil positions.

## 5. DISCUSSIONS AND FUTURE WORK

1. The Mueller matrices are given for the near and mid-infrared wavelength regions at the proposed instrument port for MICHI. They are found to vary with the field of view of the instrument. The IP and CT show variations in these wavelength regions due to the refractive index of the Silver coating.

2. As the incident angles on the Nasmyth mirror changes during the telescope tracking, the IP and CT vary with the zenith angle of the telescope. It would be difficult to accurately correct for these variations without a standard star (unpolarized/polarized) regularly observed.

3. Modulators and analyzers are to be placed at the beginning of the optical layout in MICHI to reduce the IP and CT caused due to the additional mirror surfaces. The IP and CT are estimated before the polarimetry module and at the focus of the imager to show the comparison.

4. As the exact coating information for all the mirrors is not available, an ideal coating is considered which

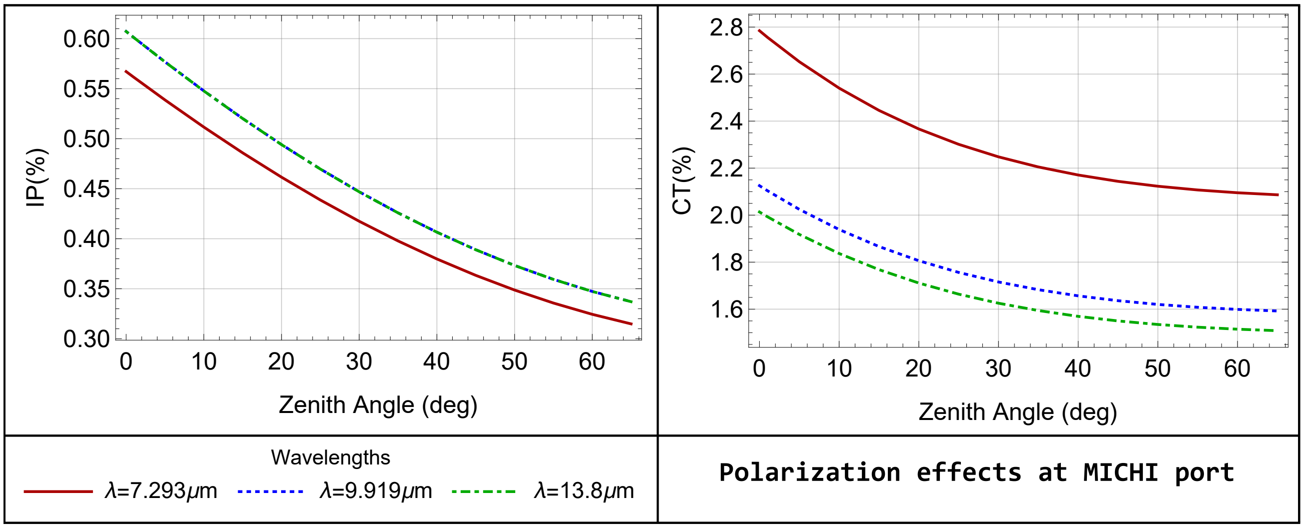


Figure 8. IP and CT estimated at the MICHI port for different zenith angles.

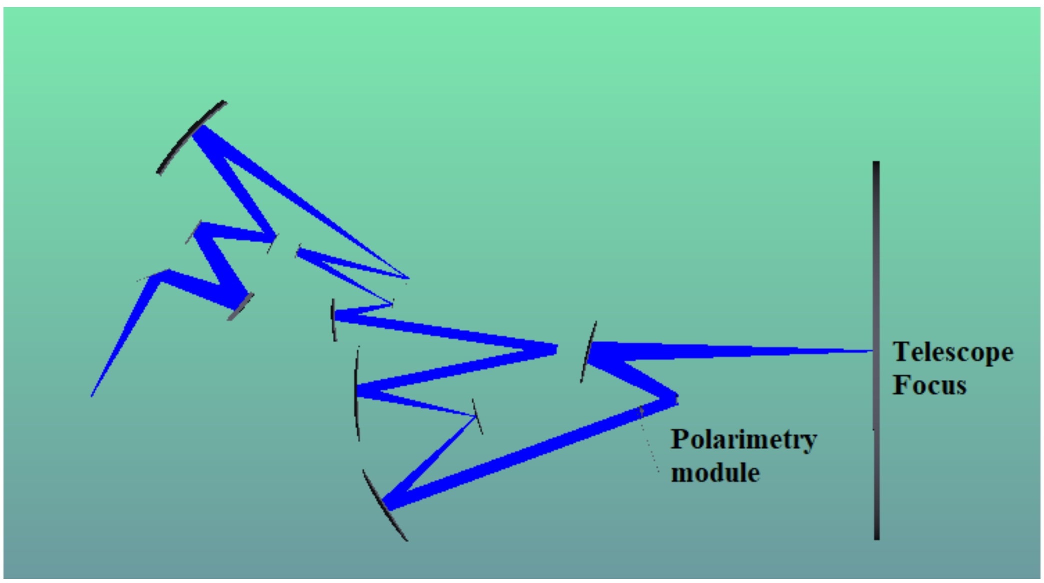


Figure 9. The optical layout of the MICHI imager is shown in the figure. The polarimetry module shows the position of the modulator and the polarizer.

gives IP and CT only due to the variation of the incident angles.

5. The comparison of the obtained IP and CT values with the science requirements has to be done to understand the need for the mitigation technique.

6. The coating imperfections, non-uniformity are not considered in our analysis. Hence, the values obtained are to be considered as the lower bounds of IP and CT.

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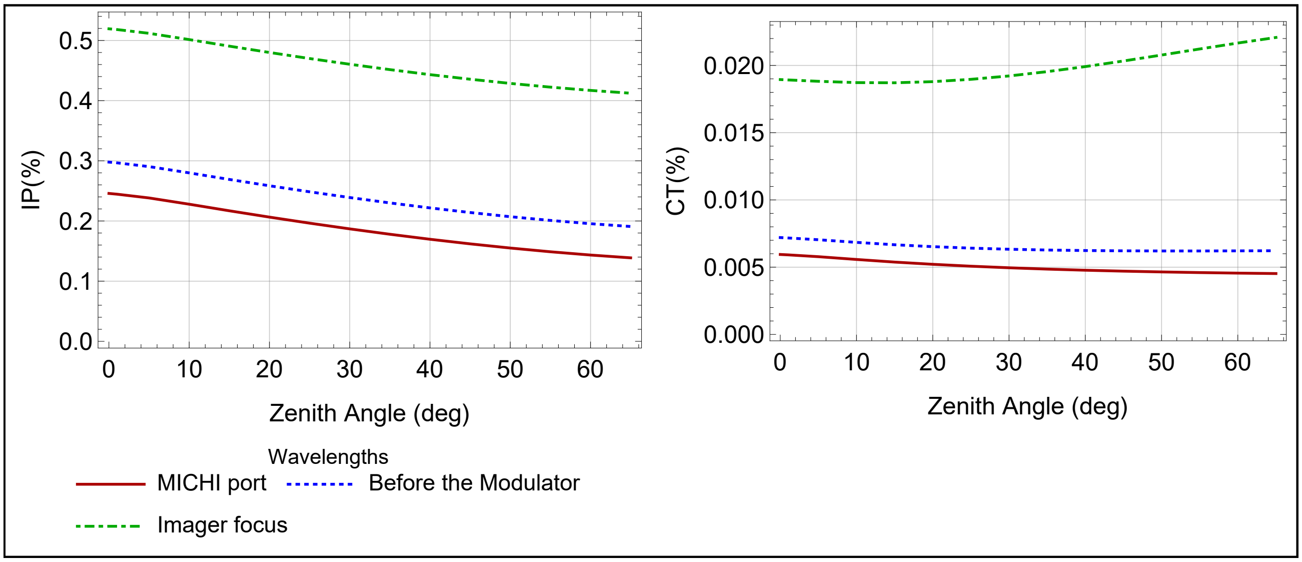


Figure 10. The IP and CT is shown at the MICHI port, before the modulator and focus of the imager for the ideal coating on all the mirrors.

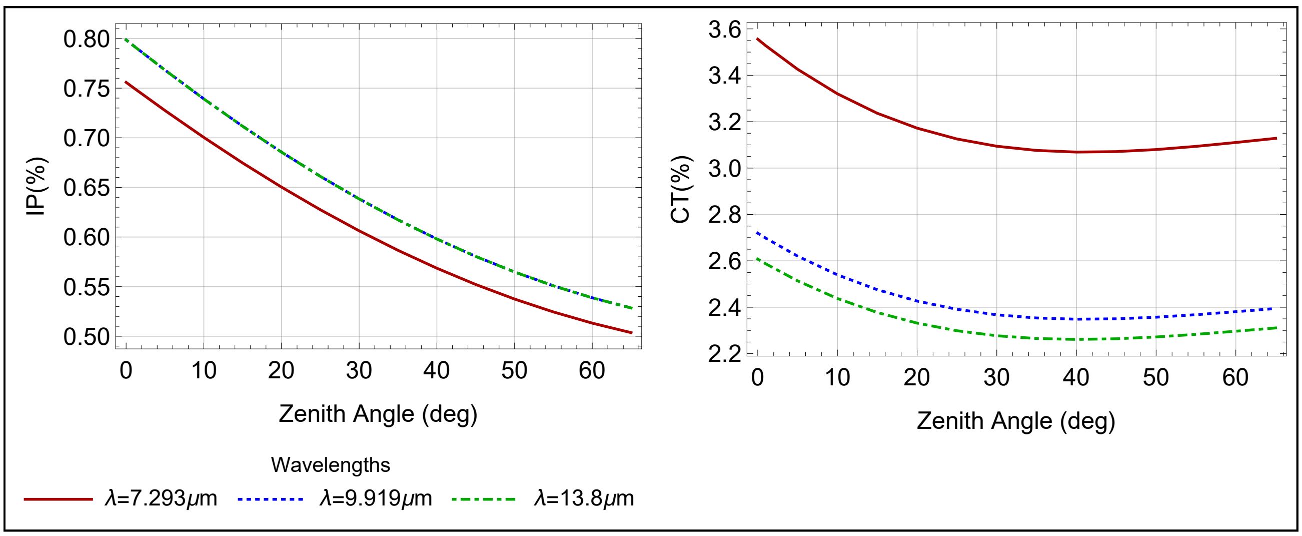


Figure 11. The IP and CT is shown at the modulator with varying zenith angle. The unprotected gold coating is used for the mirrors in the MICHI instrument.The values are shown at three different wavelengths in the $N$ band.

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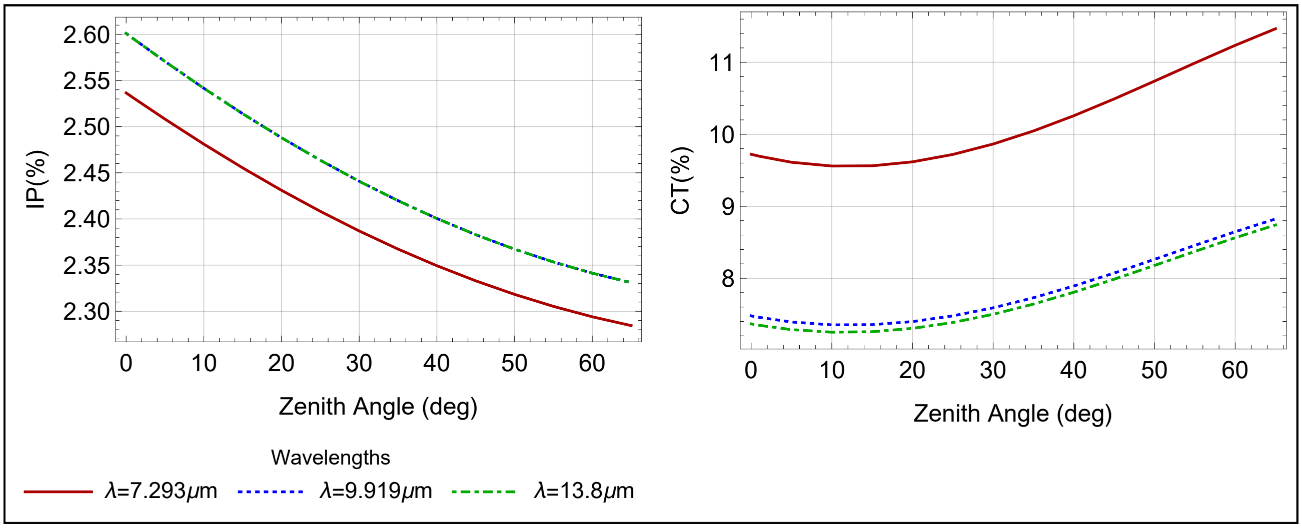


Figure 12. The IP and CT is shown at the focus of the imager with varying zenith angle. The unprotected gold coating is used for the mirrors in the MICHI instrument.The values are shown at three different wavelengths in the $N$ band.


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