THE INFRARED IMAGING SPECTROGRAPH (IRIS) FOR TMT: SIMULATION OF THE ATMOSPHERIC DISPERSION CORRECTOR USING IDL

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ABSTRACT

For the Thirty Meter Telescope, the effects of atmospheric dispersion represent a significant challenge. This paper presents a simulation in the IDL programming language of the atmospheric dispersion corrector (ADC) for the Infrared Imaging Spectrograph (IRIS). This model studies the performance of a crossed Amici prism design operating in the infrared range covered by IRIS (0.84-2.4 microns).

1. INTRODUCTION

IRIS (InfraRed Imaging Spectrograph) is a first light instrument presently being developed for the Thirty Meter Telescope (TMT). IRIS will include an integral field spectrograph and an imaging camera, covering wavelengths from 0.84 μm to 2.4 μm (infrared range). IRIS will work with the Narrow-Field Infrared Adaptive Optics System (NFIRAOS), achieving an unprecedented angular resolution [1], creating the sharpest images ever taken in the infrared.

Because of the high spatial resolution of the TMT, previously minor difficulties, such as chromatic dispersion in the atmosphere, have become major problems [1]. The atmosphere bends the incoming light from an astronomical source, refracting shorter wavelengths more than longer wavelengths, thus elongating the image of the object vertically and creating a rainbow-like effect. This effect is also dependent of the zenith angle, the angular distance between the zenith (the point directly overhead) and the object. For greater zenith angles (i.e. altitudes near the horizon) atmospheric dispersion increases drastically, even across the near infrared range. Across a single passband filter at low elevations, differential dispersions in the order of 100 milliarcseconds (mas) are usual. At the diffraction limit of the TMT such dispersions will lead to significant image blur and for that reason this effect must be largely corrected in order to reach the precision desired of several tens of microarcseconds for astrometric measurements [2].

IRIS will include an atmospheric dispersion corrector that will use real-time information of atmospheric conditions (temperature, pressure, humidity) and optical elements to correct for the atmospheric dispersion over varying elevations. The IRIS ADC will consist on an optical design know as crossed Amici prisms. In this design, a pair of identical counter-rotating prisms produces a variable dispersion to cancel that of the atmosphere [2].

A more detailed explanation of IRIS ADC can be found in Phillips, et al. [2].

2. IDL MODELING

2.1 SIDEREAL MOTION AND ATMOSPHERIC DISPERSION.

The amount of atmospheric dispersion depends on the position of an astronomical source, and thus it is necessary to create a model to simulate the motion of objects in the sky due to Earth's rotation. This is very similar to a tracking system for the TMT itself. Because of its high angular resolution; this tracking system must be as precise as possible. Using IDL, a simple tracking system model has been developed by means of the general sidereal motion formulas.

$$x = -\cos(\textit{hour angle})\,\cos(\textit{declination})\,\sin(\textit{latitude}) + \sin(\textit{declination})\,\cos(\textit{latitude}) \tag{1}$$

$$y = -\sin(\textit{hour angle})\,\cos(\textit{declination}) \tag{2}$$

$$z = \sin(\textit{declination})\,\sin(\textit{latitude}) + \cos(\textit{declination})\,\cos(\textit{latitude})\,\cos(\textit{hour angle}) \tag{3}$$

$$r = \sqrt{x^2 + y^2} \tag{4}$$

$$\textit{azimuth} = \arctan\left(\frac{y}{x}\right) \tag{5}$$

$$\textit{altitude} = \arctan\left(\frac{z}{r}\right) \tag{6}$$

These simple formulas compute the (geometric) altitude and azimuth of an object (e.g. a star) given its Hour Angle (the time elapsed since the object was on the Local Meridian) and declination, and the Latitude of the observer's location, ignoring other effects such as the precession of the equinoxes and the presence of the atmosphere. The latitude for Mauna Kea, Hawaii has been used throughout this paper, since this is the location for the construction of TMT.

Once the coordinates of an astronomical object can be calculated, atmospheric dispersion needs to be accounted for. The formula from Larkin, et al. OSIRIS MANUAL [3], was used to determine the index of refraction of dry air in the infrared:

$$n(\lambda) = 1.0 + \left[0.0000744 \times \left(1 + \frac{0.00563}{\lambda^2}\right)\right] \times \frac{P}{T} \tag{7}$$

where P is pressure in millibars and T is the temperature in Kelvin, and λ is the wavelength in microns. Throughout this paper, a pressure of 620 millibars and a temperature of 273 Kelvin have been assumed for Mauna Kea.
Then the deflection (in radians) at a particular wavelength is calculated by the tangent of the zenith angle times the difference in index between space (n=1.000) and the telescope [3]:

$$\Delta\alpha = (n_{Telescope} - 1.000) \times \tan(\alpha) \tag{8}$$

Adding formulas 8 and 6 gives the correct (apparent) altitude for an astronomical source.

Figure 1 shown below illustrates the deflection of light from its geometrical position at a wavelength of 1 micron.

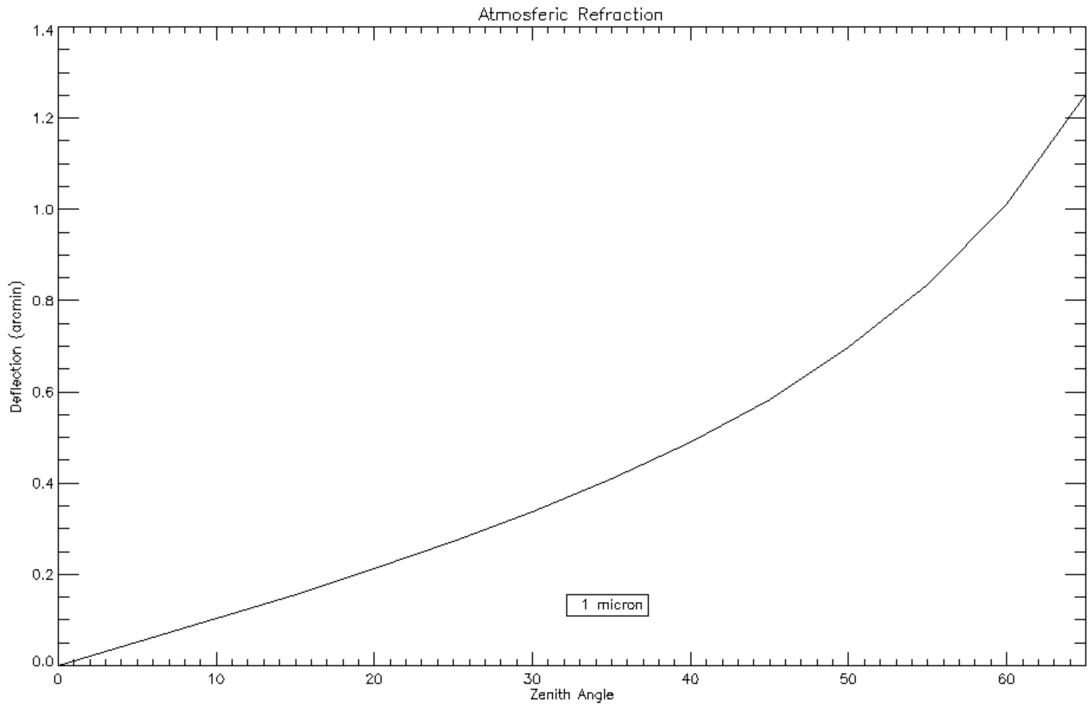

Figure 1.

Moreover, when looking to several stars in the field of view, the distance between stars appear to change due to the atmospheric refraction. The figure below shows a plot of the geometric distance in altitude between two stars (which is constant) and the apparent distance due to the atmospheric effect at 1 micron, over a two hour period.

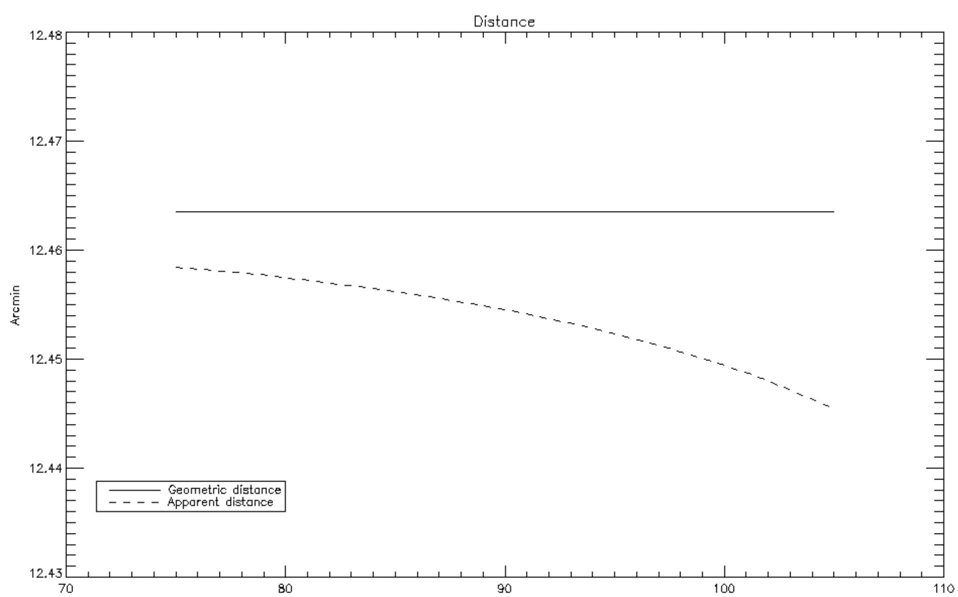

Figure 2.

2.2 DIFFERENTIAL ATMOSPHERIC DISPERSION

Formulas 7 and 8 only calculate the dispersion of light at one particular wavelength. In order to calculate the differential atmospheric dispersion, we need the product of the tangent of the zenith angle times the difference in index between the two wavelengths [3]:

$$\delta\alpha = \Delta\alpha_2 - \Delta\alpha_1 = (n_2 - n_1) \times \tan(\alpha) \tag{9}$$

The figure below shows the displacement in arcseconds of an object at a desired wavelength compared to its position at 1 micron.

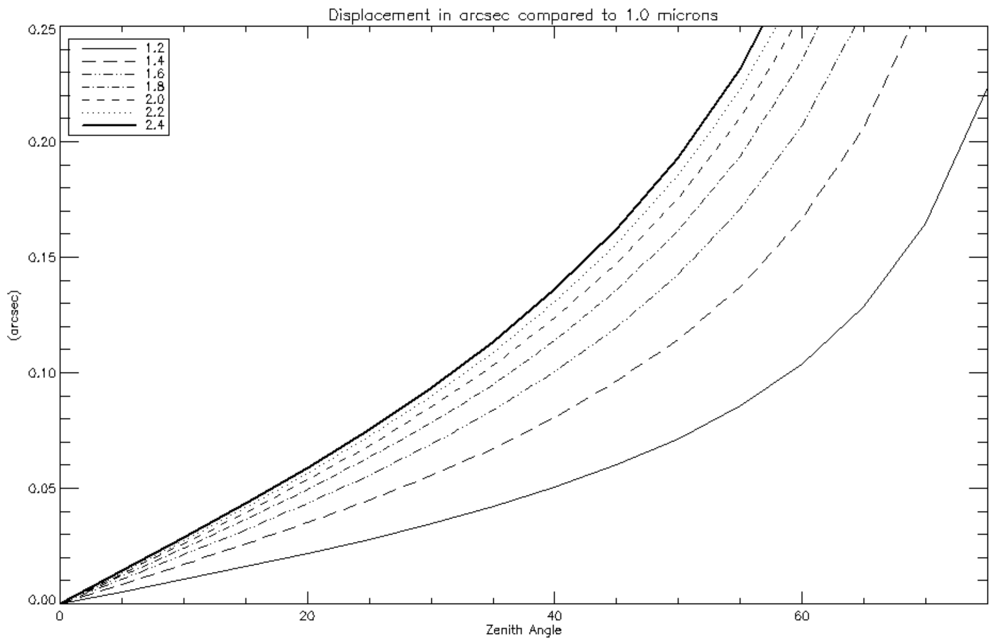

Figure 3.

IRIS will work on the infrared range from 0.8 to 2.4 microns by using several passband filters that cover a portion of the infrared range. Below is a list from of the filters used by the IRIS imager.

Filter	Feature or Central λ	Min λ	Max λ
Z	0.876	0.830	0.925
Y	1.019	0.970	1.070
J	1.245	1.166	1.330
H	1.626	1.485	1.781
K	2.191	2.000	2.400

Table 1. Imager filters (wavelength in microns) [4].

Figure 4 below shows the calculation of the differential atmospheric dispersion across the passbands filters from Table 1. According to the figure, even across the K filter (2.0-2.4 microns) a star position can vary over 20 milliarcseconds at 60 degrees zenith angle (this is five pixels of elongation in the IRIS cameras).

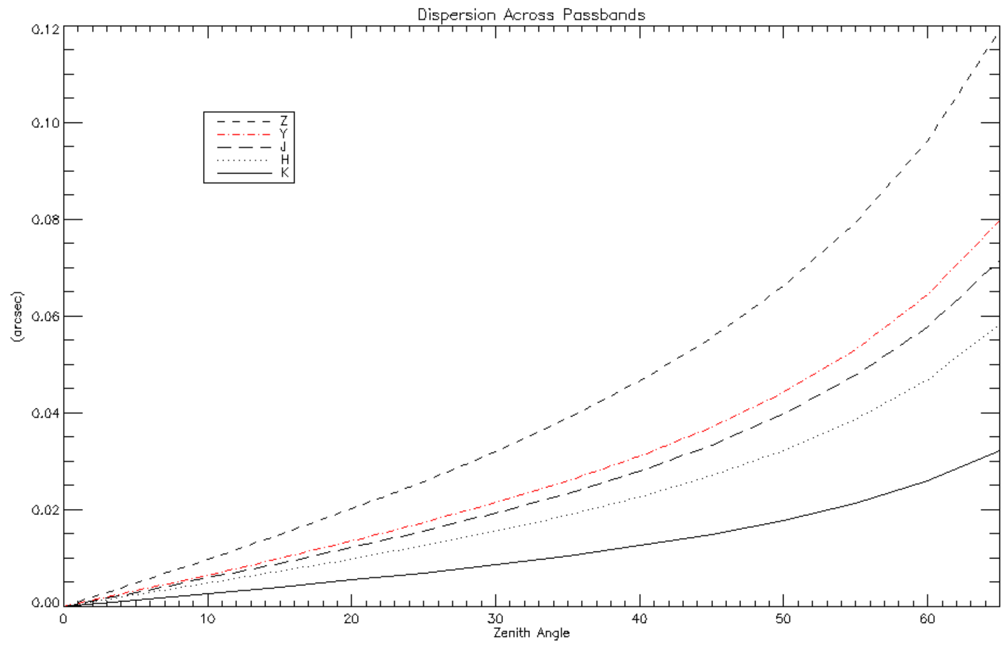

Figure 4. Atmospheric dispersion across different passbands covered by IRIS, as a function of zenith distance.

2.3 ATMOSPHERIC DISPERSION CORRECTION

As mentioned before, IRIS will require an Atmospheric Dispersion Corrector (ADC) to compensate for the atmospheric refraction. A table of the requirements for the ADC is presented below.

Wavelength Range	$0.84 \leq \lambda \leq 2.4$ µm in passbands Z,Y,J,H,K
Residual dispersion	± 1 mas or better within each passband
Zenith distance	$1^\circ \leq Z \leq 65^\circ$
Field of View: Imager	15 arcsec square (r=10.8 arcsec)
Field of View: IFU	4.4 x 2.25 arcsec (r = 2.5arcsec)

Table 2. Adopted ADC requirements [2]

For reasons described in Philips, et al. [2], the ADC will consist on an optical design called the crossed Amici prisms. In this design, which works on a collimated beam, consists on a pair of counter rotating prisms where the dispersion in the perpendicular axis in internally cancelled. Each prism is a compound prism (Amici prism) composed of two glasses (high and low dispersion) that produces zero deviation at some chosen wavelength. The prisms are counter rotated to produce double the dispersion of a single prism when rotated 0 degrees with respect to each other (maximum dispersion), to no dispersion when rotated at 180 degrees with each other (null configuration). [2]

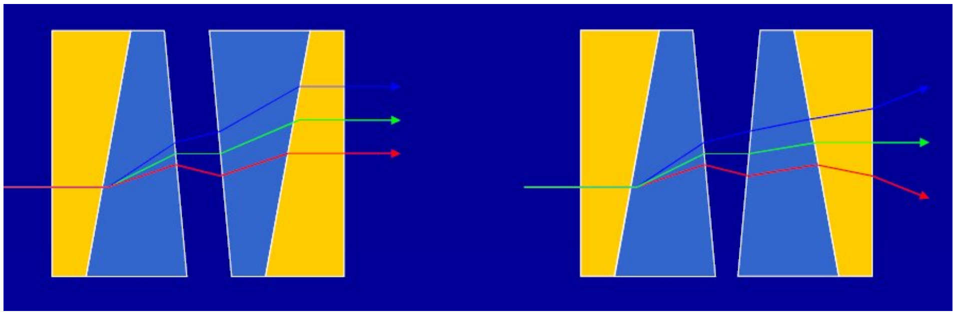

Figure 5. Schematic of crossed Amici prisms, showing null configuration (left) and maximum dispersion (right) [2].

Several glass combinations were analyzed in Philips [2] to determine the best arrangement that can mimic the atmospheric dispersion over the entire range 0.8-2.4 microns sufficiently to meet the ADC requirements. S-NPH2 and Spinel were among the best glass combination and this pair was used as a base to correct the atmospheric dispersion calculated on previous sections.

2.3.1 OPTICAL DESIGN

In order to determine the specific design of the Amici prisms (the prism angles needed for S-NPH2 and Spinel), it is necessary to choose a zero deviation wavelength. It is useful to select the wavelength that is halfway along the dispersion between the maximum and minimum wavelengths that will be used. This minimizes the total amount of dispersion needed from the prisms and so minimizes their wedge angles. Working with formula 9 one obtains:

$$\lambda_c = \frac{\lambda_{min}\lambda_{max}\sqrt{2}}{\sqrt{\lambda_{min}^2 + \lambda_{max}^2}} \tag{10}$$

Using 0.84 and 2.4 microns as the maximum and minimum wavelengths, a central wavelength of 1.12 microns was calculated.

The prisms need to achieve a maximum dispersion at 65 º zenith angle. Therefore, using formula 9 at that elevation, it is determined that 0.84 and 2.4 microns are 0.524 arcseconds apart in the sky. This is the maximum elongation of a star that will ever occur within IRIS.

This means that each compound prism needs to disperse this same wavelength range by plus and minus 0.262 arcseconds and have zero deviation at 1.12 microns. Additionally, there is a large angular magnification (m) in IRIS (~600 for the imager, 4500 for the IFU), which applies to the dispersion produced by the ADC [2]. Consequently, this information was used to determine the required prism angles using the linear combination:

$$\delta = (n_1 - 1)\tan(a_1) + (n_2 - 1)\tan(a_2) \tag{11}$$

Where a1 and a2 are the prism angles, n1 and n2 are the indices of refraction, which were calculated using tables of indices for N-SPH2 and Spinel at 77 Kelvin in vacuum.

Setting the deviation to zero at 1.12 microns, the ratio of the tangents of the prism angles can be calculated. Next, using formula 11 at the maximum (or minimum) wavelength, we can use:

$$m\Delta\delta\lambda = \delta(\lambda) - \delta(1.12) \tag{12}$$

to determine the prism angles. Since the real prisms have large wedge angles and the light is deviated at each of their faces, small adjustments to the calculated prism angles are needed to exactly produce zero deviation at 1.12 microns. The prism angles were corrected using a light ray tracing model written in IDL, described in the next section which calculates all of the correct angles without any approximations.

Table 3 and 4 summarize the ADC optical design.

Mode	**Magnification**	**Atmospheric disperision (0.84-2.4)**	**Dispersion per prism (0.84-2.4)**
Imager	600	0.523 arcseconds	0.0872 degrees
IFU	4500	0.523 arcseconds	0.327 degrees

Table 3. Optical requirements

Mode	**Glass 1**	**Glass 2**	**Angle 1 (degrees)**	**Angle 2 (degrees)**
Imager	SNPH-2	Spinel	2.939	3.67081
IFU	SNPH-2	Spinel	19.085	24.04207

Table 4. Adjusted angles

2.3.2 LIGHT RAY TRACING

The papers by Larkin [5] and De Greve [6] were used to calculate the propagation of rays through the ADC. As in those papers, the z-axis is defined as positive in the opposite direction of the incoming light ray, which will force all the normal vectors to have a positive z component and the incoming light rays a negative z component. Normal and incoming ray vectors and the propagations equations are listed below.

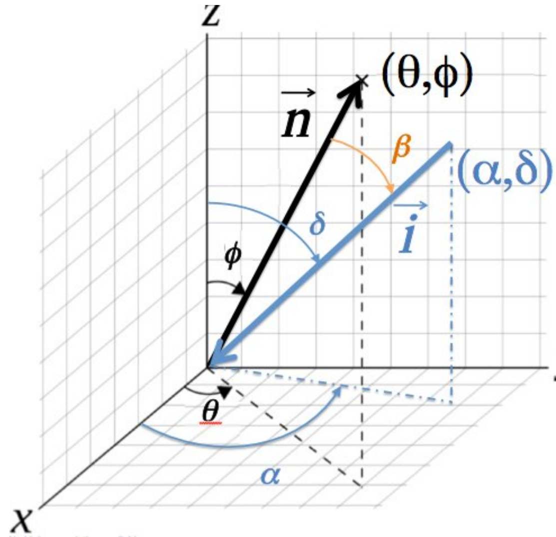

Figure 6. Combined diagram showing definitions of incident and normal vectors [5].

$$\vec{n} = [\cos(\theta)\sin(\phi), \sin(\theta)\sin(\phi), \cos(\phi)] \tag{13}$$

$$\vec{i} = [\cos(\alpha)\sin(\delta), \sin(\alpha)\sin(\delta), \cos(\delta)] \tag{14}$$

$$\cos\beta_i = \vec{i} \bullet \vec{n} \tag{15}$$

$$\sin^2\beta_t = \left(\frac{n_1}{n_2}\right)^2 \left(1 - \cos^2\beta_i\right) \tag{16}$$

$$\vec{t} = \frac{n_1}{n_2}\vec{i} - \left(\frac{n_1}{n_2}\cos\beta_i - \sqrt{1 - \sin^2\beta_t}\right)\vec{n} \tag{17}$$

The vectors are normalized to a length of 1, and these equations were used to calculate the residual dispersion of the prisms, repeating the calculations several times using the transmitted vector as the incoming vector of the next surface. The prism angles were used to calculate the normal vectors of each surface on the prisms following the drawing of figure 5. The space to the sides and in between the prisms is assumed to have an index of refraction of 1.0.

The residual dispersions are shown graphically in figures 7-12

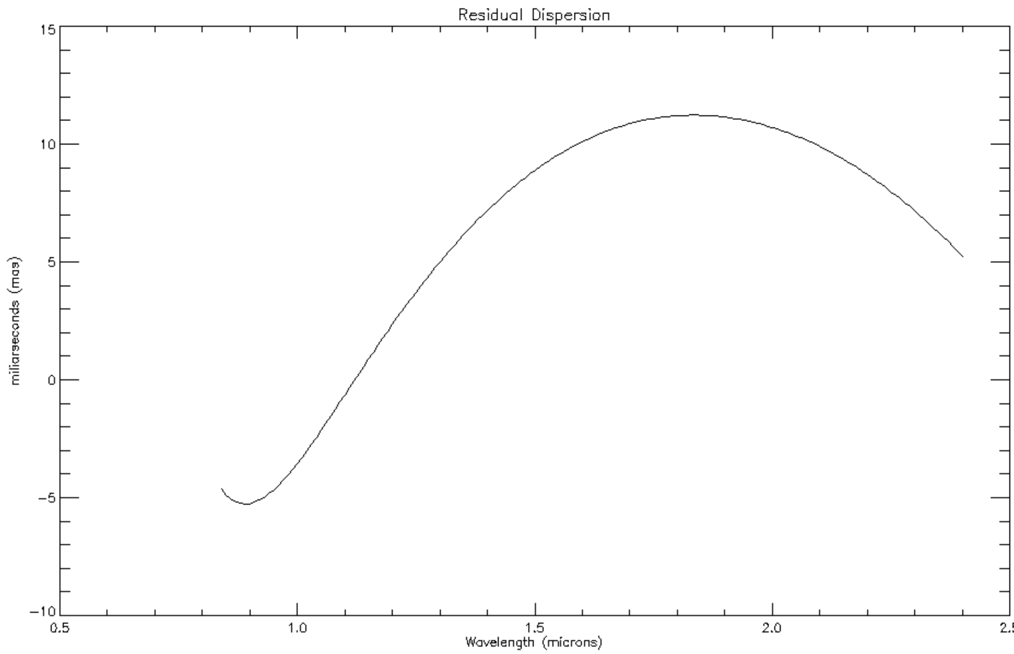

Figure 7. Residual dispersion at 65 zenith angle for the S-NPH2 /Spinel combination across the range 0.84-2.4 microns.

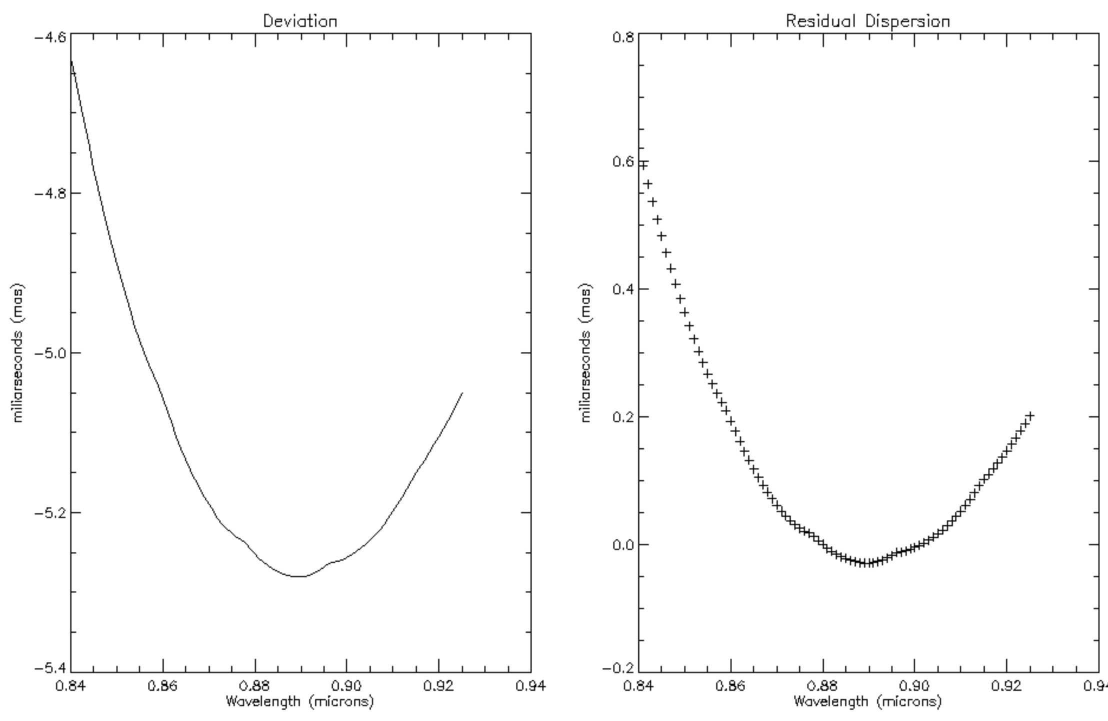

Figure 8. Residual dispersion at 65 zenith angle for the S-NPH2 /Spinel combination across the range 0.84-0.925 microns (Z filter).

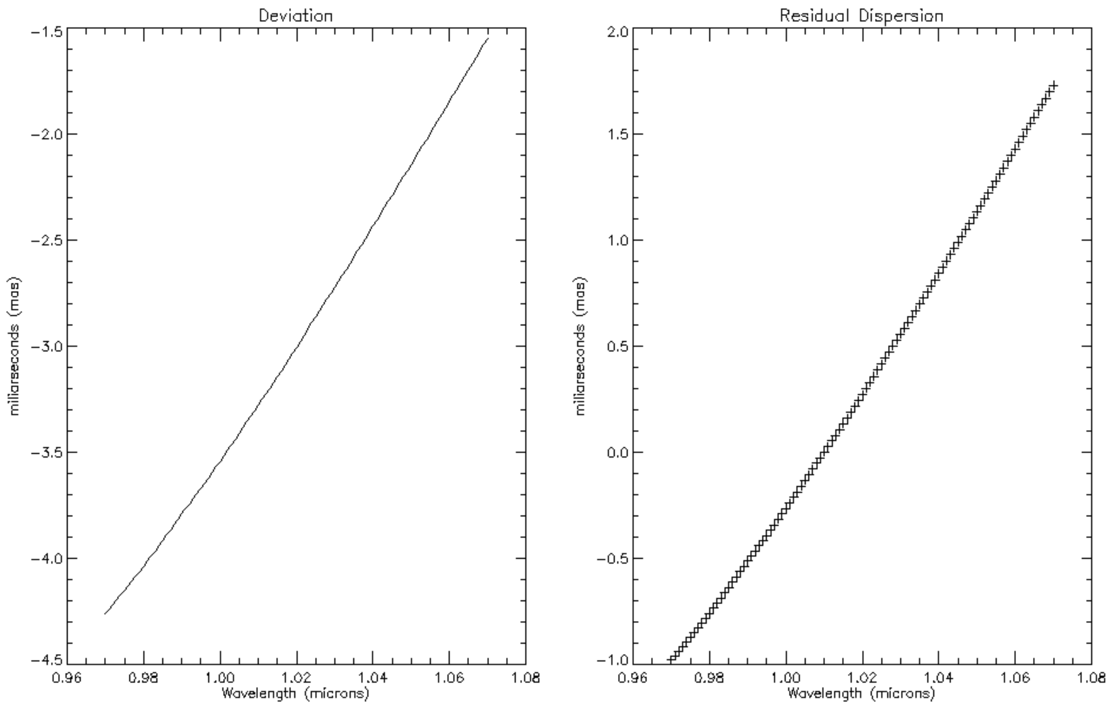

Figure 9. Residual dispersion at 65 □ zenith angle for the S-NPH2 /Spinel combination across the range 0.97-1.07 microns (Y filter).

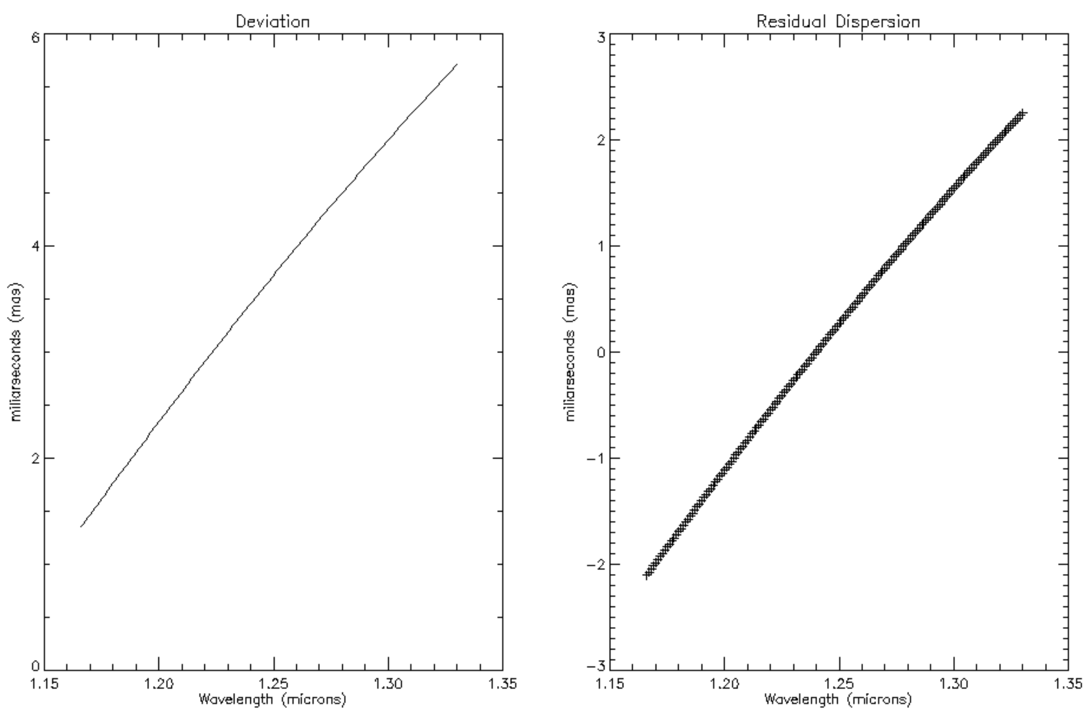

Figure 10. Residual dispersion at 65 □ zenith angle for the S-NPH2 /Spinel combination across the range 1.166-1.33 microns (J filter).

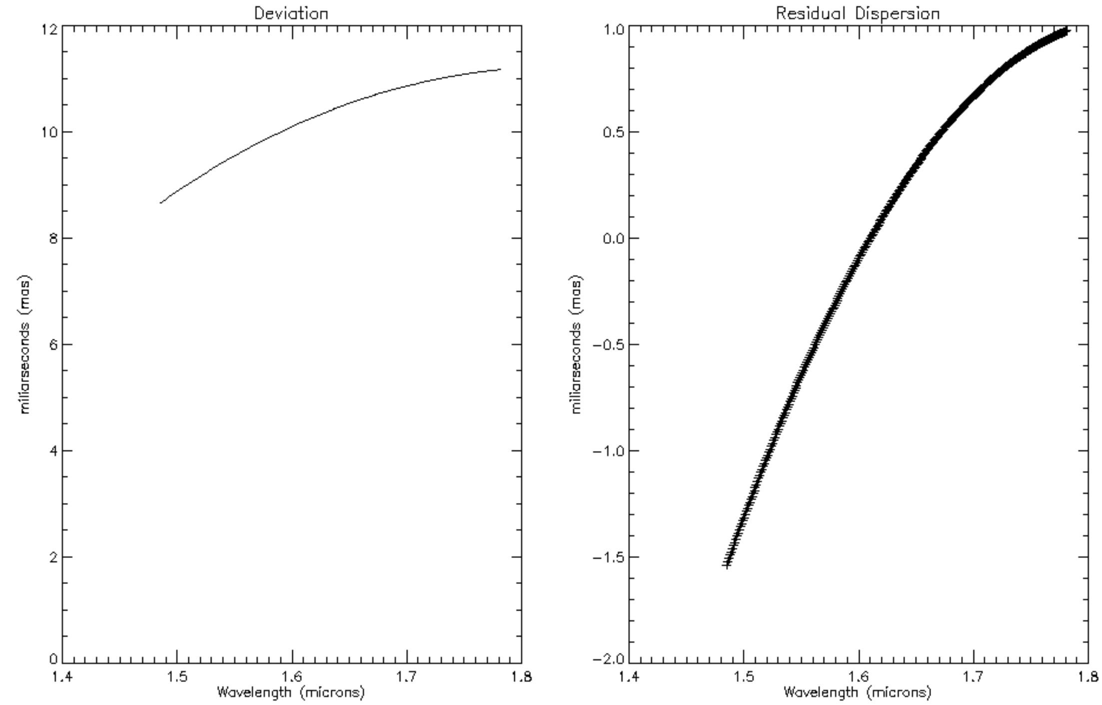

Figure 11. Residual dispersion at 65 zenith angle for the S-NPH2 /Spinel combination across the range 1.485-1.781 microns (H filter).

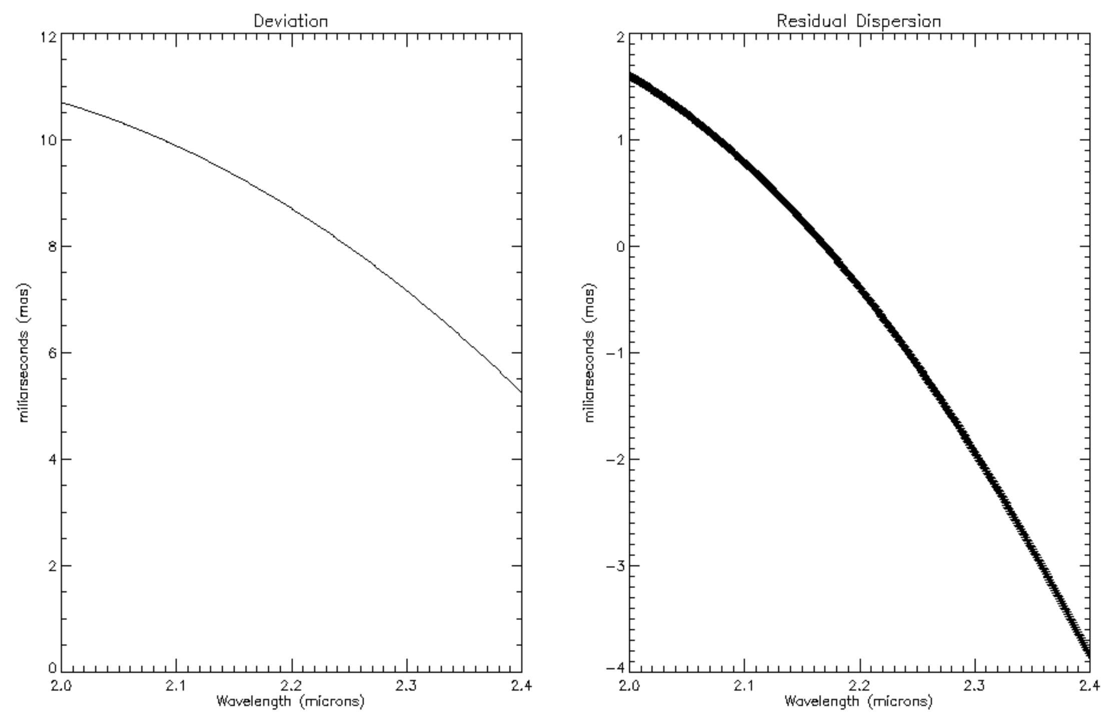

Figure 12. Residual dispersion at 65 zenith angle for the S-NPH2 /Spinel combination across the range 2.0-2.4 microns (K filter).

The residual dispersion is close to the ADC requirements of ±1 mas within each passband.

LIMITATIONS

Due to time constraints, only the S-NP2/Spinel combination was tested with this model. It is important to verify the performance of other glass combinations in order to find the best pair that can meet the ADC requirements.

It is important to draw attention to the precision limitations in the IDL programming language. Although all the calculations were executed using double precision numbers, they were subject to rounding errors due to conversions between degrees and radians and due to manipulations of very small numbers. These rounding errors appear to be negligible, but a more detailed study needs to be done to determine the effects of internal machine precision and formatting precision on these computations.

CONCLUSION

This paper discussed an analysis of the IRIS Atmospheric Dispersion Corrector using the glass combination of S-NPH2/Spinel, which according to the results, is capable to correct for the atmospheric dispersion across the IRIS filters close to the adopted requirements, but is necessary to analyze different glass combination to determine the best suitable pair for the ADC. Also, IDL's internal precision needs to be study in more detail in order to achieve a highest performance of the model.

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