The Infrared Imaging Spectrograph (IRIS) for TMT: the Atmospheric Dispersion Corrector

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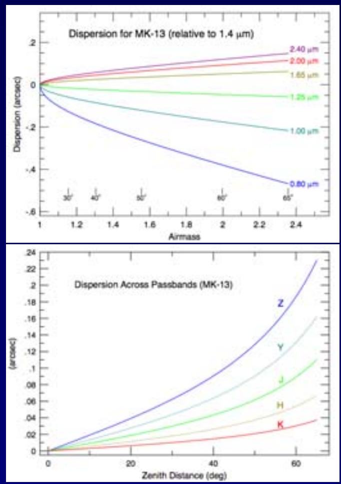
Introduction:

The Infrared Imaging Spectrograph (IRIS)[1] is a fist-light instrument for the Thirty-Meter Telescope (TMT). It sits behind the Narrow-Field Infrared Adaptive Optics System (NFIRAOS)[2], and operates over the wavelength range of 0.84 to 2.4 µm. IRIS has both an imaging mode with a 15″-square field, and integral field unit (IFU) modes employing either lenslet or image slicer beams. In the imaging mode, the goal is to allow astrometry to a few 10s of micro-arcsecond (µas) precision.

Atmospheric dispersion in the near-IR is less severe than in the optical, but the differential refraction across even single passbands can seriously compromise both image quality and astrometric precision of IRIS.

We have explored designs for an atmospheric dispersion corrector (ADC) to compensate for the atmospheric dispersion sufficiently to meet our goals. The major design requirements are given in the table below.

Wavelength Range	$0.84 \le \lambda \le 2.40$ µm in *Z, Y, J, H, K*
Residual dispersion	±1 mas or better in each passband
Zenith Distance	$1° \le Z \le 65°$
Field of view: Imager	15″ × 15″ (r_{max} = 10.8″)
Field of view: IFU	up to 4.4″ × 2.25″ (r_{max} = 2.5″)



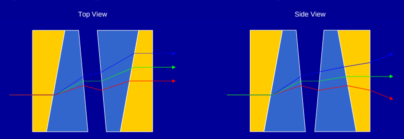
Differential atmospheric refraction relative to 1.4 µm (top), and the edge-to-edge differences across individual passbands (bottom) for the Mauna Kea site chosen for TMT.

ADC Design Choice:

There are two major designs for ADCs. The Linear or Longitudinal ADC design[3] has been used in many modern ADCs[3,4,5]; it works in a converging beam, usually near the focal plane of the telescope, and consists of two identical prisms at 180° rotation with respect to each other. This design essentially restacks the monochromatic images by displacing each by the distance introduced by the atmospheric dispersion. The prism glass or glasses are chosen to mimic the atmospheric dispersion, and the amount of correction is controlled by the prism spacing. The design is mechanically simple, and can be fabricated with large optics. However, this design requires either large prism angles or a large space and is thus impractical for IRIS. Also, because ADCs rotate with respect to the sky/detector, this design has recently been recognized as a potential source of flat-fielding problems[6].

The second design uses crossed Amici prisms, i.e., compound prisms that produce dispersion but have zero-deviation at a particular wavelength. This design works in collimated space. The zero-deviation wavelength is chosen to lie in the wavelength range of interest in order to reduce pupil displacement. Again, glasses are chosen to match the atmospheric dispersion. The magnitude of the correction is controlled by counter-rotating the prisms to go from nulled (prisms 180° out of phase, prism dispersions cancel) to maximum correction (prism dispersions add), as shown schematically in the figure below. This design is usually located near a pupil image, and so does not present flat-fielding risks.

Since IRIS has collimated space available, and the crossed-Amici design is compact, we adopted this design early in the project.



Schematic of crossed-Amici ADC, showing the null configuration (left), and maximum correction (right)

Sensitivities and Non-Correctable Atmospheric Effects:

The degree of correction required for the astrometric goals of IRIS is unprecedented. For the Mauna Kea site and at zenith distances near 60°, the differential refraction across each passband is of order 100 milli-arcseconds (mas). We require the residual dispersion to be within 1 mas, or less than 1 part in 100. This corresponds to an error in pressure of 6 mbar or an error in temperature of 3C according to models of atmospheric refraction. Furthermore, we must assume the models are precise in an absolute (not just relative) sense, and that our temperature and pressure measurements are appropriate, in order to apply the correct degree of compensation.

Differential atmospheric refraction across the field produces an apparent compression of the field in the direction of the zenith; this compression is a function of elevation and changes rapidly at lower elevations. Near 65° zenith distance and at 1 mm wavelength, this distortion is 10 mas over a 10^2 field. If the field rotates with respect to the parallactic angle, or the elevation changes rapidly, image blurring will occur with longer integrations. While such effects can be modeled, they cannot be removed.

References:

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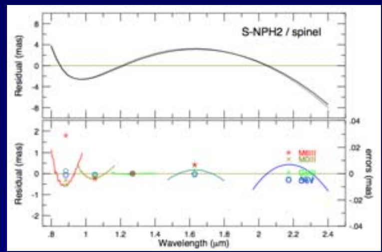
Choice of Glasses:

Choosing the pair of optical materials (hereafter "glasses") is the most crucial task in the ADC design, as we must match the atmosphere to ±1 mas residual dispersion within each (and every) passband. To look for candidate pairs, we compiled a list of high-dispersion and low-dispersion glasses with good NIR transmission. We then calculated best-fit linear combinations of high- and low-dispersion glasses to match the atmosphere at 65° zenith distance over the entire wavelength range from 0.8 to 2.4 µm. We then took the best glass pairs and "tuned" them (by scaling by a constant amount) to produce the minimum residual dispersion across each passband. The results for the best glass pair is shown in the figure at right. Roughly six glass pairs give acceptable results. To verify that they meet our astrometric goals, we weighted the residuals within each passband by the relative flux of stars of five spectral types. The flux-weighted integrated residual represents a spectrum-dependent astrometric error. These are also plotted as symbols in the lower panel of the figure at right, and we see than in general there is less than about 30 µas variation.

Another consideration for the glass choices is transparency. This is shown in the figure below right.

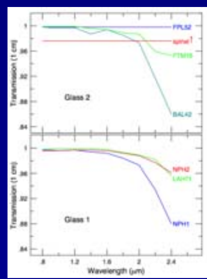


Residual dispersions for S-NPH2/spinel: top panel shows best fit residuals to full wavelength range; lower panel are residuals after tuning to individual passbands. Symbols in the lower panel are flux-weighted integrated residuals within each passband for five different spectral types, representing color-dependent astrometric errors (scale at right). Other glass pairs are shown in the paper.

Specific Optical Design:

The identification of glass pairs is a necessary first task, but it must be shown that actual prisms are also viable. Extreme prism angles could produce variable behavior across the field, or glass thickness that could impact the throughput. Fortunately, the actual angles are not very severe for the imaging mode; in IFU mode, the angles are fairly steep but the positional requirements are less severe. Thicknesses required are also reasonable. The values for three glass pairs are shown in the table below; see the paper for other pairs.

mode	glasses	angle1 (deg)	angle2 (deg)	thickness (mm)
imager	S-NPH2/spinel	2.92	3.63	7.0,7.5
imager	S-NPH1/BAL42	4.59	6.20	8.2,9.3
imager	S-NPH2/BAL42	3.23	4.93	7.3,8.4
IFU	S-NPH2/spinel	18.2	23.0	9.1,10.3
IFU	S-NPH1/BAL42	23.1	32.2	10.3,12.9
IFU	S-NPH2/BAL42	18.3	29.0	9.1,11.9



Transmission of selected low-dispersion (top) and high-dispersion glasses (bottom).

The fact that the ADC is in collimated space means there is little impact on image quality. There is, however, a small amount of distortion that is produced when the prisms are not nulled; this amounts to less than 1 mas maximum and is easily modeled. We have examined changes in dispersion across the field and found them to be negligible.

Acknowledgements:

The authors wish to acknowledge the support of the TMT partner institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the California Institute of Technology and the University of California. This work was supported as well by the Gordon and Betty Moore Foundation, the Canada Foundation for Innovation, the Ontario Ministry of Research and Innovation, the National Research Council of Canada, Natural Sciences and Engineering Research Council of Canada, the British Columbia Knowledge Development Fund, National Astronomical Observatory of Japan (NAOJ), the Association of Universities for Research in Astronomy (AURA) and the U.S. National Science Foundation.