Proposed instrumentation for PILOT

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ABSTRACT

PILOT (the Pathfinder for an International Large Optical Telescope) is a proposed Australian/European optical/infrared telescope for Dome C on the Antarctic Plateau, with target first light in 2012. The proposed telescope is 2.4m diameter, with overall focal ratio f/10, and a 1 degree field-of-view. In median seeing conditions, it delivers 0.3" FWHM wide-field image quality, from 0.7-2.5 microns. In the best quartile of conditions, it delivers diffraction-limited imaging down to 1 micron, or even less with lucky imaging. The areas where PILOT offers the greatest advantages over existing ground-based telescopes are (a) very high resolution optical imaging, (b) high resolution wide-field optical imaging, and (c) all wide-field thermal infrared imaging. The proposed first generation instrumentation consists of (a) a fast, low-noise camera for diffraction-limited optical lucky imaging; (b) a gigapixel optical camera for seeing-limited imaging over a 1 degree field; (c) a 4K x 4K near-infrared (1-5 micron) camera with both wide-field and diffraction-limited modes; and (d) a double-beamed mid-infrared (7-40 micron) imaging spectrograph.

Keywords: instrumentation, Antarctica, wide-field, optical, infrared, tip-tilt, fast guiding

INTRODUCTION

Dome C offers seeing, isoplanatic angle and coherence timescales all twice as good as the best temperate sites (Lawrence *et al.* 2004, Agabi *et al.* 2006, Trinquet *et al.* 2008), and thermal infrared backgrounds an order of magnitude lower (Walden 2005). PILOT (the Pathfinder for an International Large Optical Telescope) is a proposed 2.4m telescope designed to take advantage of these unique conditions, both as a pathfinder for larger telescopes, and to do unique science in its own right.

The areas where PILOT can outperform 8-m class telescopes on existing sites are (a) diffraction-limited optical imaging, (b) wide-field infrared imaging, and (c) high resolution, wide-field optical imaging. The proposed instrumentation is designed to cover these niches comprehensively.

Fast tip-tilt correction is fundamental to PILOT, both to correct for windshake, and to partially correct for atmospheric turbulence. Fast guiding offers significant gains in image quality when $D/r_0 \sim 1\text{-}10$, where D is the telescope diameter and r_0 is the Fried scale of atmospheric turbulence (e.g. Hardy 1998). For PILOT, $r_0 \sim 0.3\ (\lambda/0.5\mu m)^{6/5}$ m in median conditions, and we are in this regime for all optical and NIR work. The seeing at Dome C from 30m elevation comes in roughly equal parts from residual ground layer turbulence below ~100m, and free seeing above this, according to the French balloon data from Trinquet *et al.* (2008) and Agabi *et al.* (2004). The characteristic linear distance for useful correlation in the turbulence at any given height is the telescope diameter D; given the angular fields of view of seeing-limited cameras (5'-1°), this means we can always correct for the residual ground layer across the entire field, but little of the high level seeing. So in general, we always require multiple guide stars, to average out their individual, uncorrelated motions caused by high-level turbulence. The best distribution of guide stars, for uniform image quality, is distributed in an annulus around the science imaging area.

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There are four obvious guiding options: (a) multiple deployable guide probes; (b) a dichroic beam splitter and a large area acquisition camera; (c) dedicated guiding detectors around the science detectors, large enough to allow acquisition of sufficient guide stars; (d) guiding with sub-windows of the main science detectors. Each of these presents major challenges: (a) is ruled out by complexity and the requirement for large corrective optics to get the necessary wide field; (b) is ruled out by the harmful effects on the image quality caused by the dichroic in the converging beam; (c) involves additional detectors and controllers and causes complications with coatings and filters; (d) means the guide star images are seen through the same filters (losing most of the photons), and with the same read noise, as the science data.

The required frequency and amplitude for fast guiding with PILOT is a factor 2 less than large telescopes on existing sites. Windshake is dominated by the tower, with fundamental frequencies of just a few Hertz; while the Tyler frequency for atmospheric image motion is ~3Hz (vs 7Hz at Mauna Kea). The characteristic amplitudes for both processes are ~0.2". Nonetheless, the guiding requirements are still stringent: we require guide star frames at 50-100Hz rates, for multiple guide stars, each with S/N large enough to determine their centroids to a fraction of the image size.

1 INSTRUMENT SUITE SUMMARY

PILOT's proposed first generation of instruments allows both diffraction-limited and seeing limited imaging from 0.4-40µm. There is one small instrument and three major ones, as follows:

1. High resolution, high speed optical camera for diffraction-limited lucky imaging. The proposed camera is based on an E2V L3-Vision detector (which allows fast readout with very low read noise), with 1K x 1K, ~0.03" pixels.

2. Wide-field optical gigapixel camera, with 40'×40' field of view, ~10µm pixels giving 0.086"/pixel sampling. The detectors may be Orthogonal Transfer Array (OTA) CCD's, or large format traditional CCD's such as the STA 1600A 10Kx10K detectors with 9µm pixels. The design includes two silica corrector lenses, with one aspheric surface.

3. Wide-field NIR (1-5µm) camera with 10.5'×10.5' field of view. The detectors are 4 × 2K × 2K HAWAII-2RG arrays. The plate scale is 0.154"/pixel for 18µm pixels, allowing us to sample the diffraction-limit at K_{dark} and longer. To sample diffraction limited imaging at *zYJH* bands requires a larger plate scale; this is achieved by introducing a Barlow lens doublet and fold mirrors into the optical path. The optics allow the use of 4 of the proposed 4K × 4K HAWAII-4RG15 detectors (expected ~2011) with 15µm pixels. The design includes two CaF2 corrector lenses and an Offner relay cold stop.

4. Mid-infrared camera with Fabry-Perot filters. It is proposed that we have a 7-40µm camera, based on existing detectors, with ~1"/pixel, and allowing grism spectroscopy as well as narrow band surveys of Galactic H_2 emission at 12 and 17µm. This camera could be used during the daytime.

2 LUCKY IMAGING CAMERA

The first and simplest instrument for PILOT is a lucky imaging camera. Lucky imaging involves taking video-rate frames of a field, and selecting, registering and co-adding the best to build up long-integration images with a significant diffraction-limited core to the point-spread function. The field must include a star bright enough to do the selecting and registering, and the field must be small enough for anisoplanatic errors to be small. The target Strehl is ~0.5. The camera would be based on one (or more) E2V L3Vision detectors, which have on-chip amplification and hence allow very fast readout (~20MHz) with low (<1e^-) noise. A drawback with these detectors is that when the signal is of order 1e^-/pixel per frame or higher, the stochastic amplification process doubles (in quadrature) the shot noise.

E2V offer a suitable detector, the CCD201 frame-transfer device with 1024 × 1024 13μm pixels. The frame transfer time is ~1ms, and the transferred image takes 50ms to read out, or less if windowed down. The optimal angular pixel scale is determined by diffraction and by telescope optics to be ~30mas/pixel, giving a 30"×30" field. This is well matched to the 17-30" isoplanatic radius found for lucky imaging by Law *et al.* (2006.)

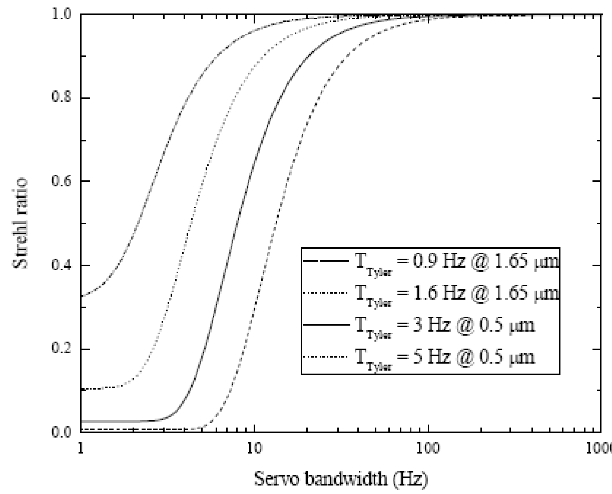

Figure 1. Effect of time delay errors on tip-tilt-corrected Strehl ratio

The required frame rate is such as to 'freeze' the seeing, so the image quality and position does not change significantly during the exposure. In the regime where lucky imaging is useful, image motion is always a large component of the seeing. Hence, since PILOT has a fast tip-tilt capability, the image quality during an exposure can be improved by also using the output frames for fast guiding, and using a predictive guiding algorithm to track the image motion during each exposure. This requires that the Servo bandwidth be a few times faster than the Tyler tracking frequency, and the frame rate a few times higher still, giving a desired frame rate of 20-50Hz. In the best conditions, it may be possible to run with the full detector area without windowing. For useful guiding (and also good frame selection), we need a S/N ~ 5 for the guide star in each frame. Since the shot noise and sky contributions are negligible, we then need ~25e^-/frame. Assuming the diffraction-limited PSF is sampled at a rate ~2.5 pixels/FWHM, we then have the peak pixel intensity ~ 1e^-/pixel/frame, so the detector can be used in Photon-Counting Mode and there is no shot-noise penalty. To get 25e^-/frame at 50Hz , assuming 50% overall efficiency, requires a guide star of brightness AB<18^m. In the *r*-band, there are about 1000 stars/deg^2 brighter than this at the Galactic pole (e.g. Kaiser, Tonry, Luppino 2000). For 30mas pixels and 1K × 1K detector, the coverage factor (fraction of the sky within a detector-diagonal of a guide star) at the pole is then 37%. This could be increased further by using multiple guide stars, or by using shaped filters which leave the guide star uncovered.

The optical design of the camera is just camera lens to expand the field from f/10 to f/40, a small ADC, and a filter wheel.

The fraction *F* of data frames which are diffraction-limited has been calculated by Fried (1978) to be $F \sim 5.6\, exp[-0.1557(D/r_0)^2]$. The enormously strong dependences on aperture, seeing and wavelength together mean that PILOT uniquely allows lucky imaging throughout the visible waveband. In good conditions with 0.2" seeing, *F* is 90% at *i*-band, 50% at *r*-band, and 10% at *g*-band.

3 WIDE-FIELD OPTICAL CAMERA

The wide-field optical camera uses the entire 1°, 420mm focal plane of the telescope. Two fused silica corrector lenses are needed for wide-field optical performance; the rear surface of the first lens is strongly aspheric, while the second forms the dewar window. The difficulty of polishing aspherics is determined by differences between meridional and tangential curvature (du Jeu 2004). The original optical design had a maximum of 700μm removed material from spherical. When the du Jeu criterion was included in the merit function (via a simple ZPL macro), this was reduced by a factor of three, and the overall difficulty (taken as the rms difference in curvature) was reduced by a factor 5.6. The original design also had the

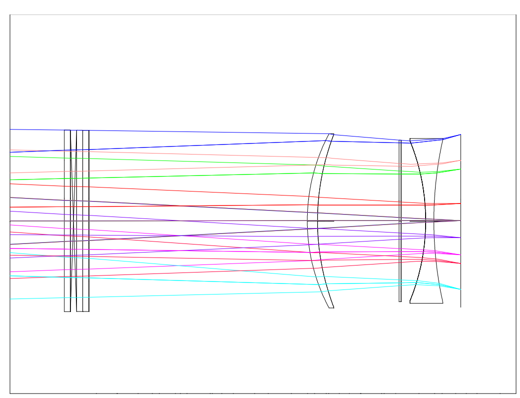

Figure 2. Wide-field camera ADC, filter, and corrector lenses. The right-hand lens also forms the dewar window.

first lens as dewar window. However, this means the filters (which must be outside the dewar) are far from the detectors, making it impossible to have unfiltered guiding detectors (see below).

For optical wide-field imaging, an ADC is required. The best design identified to date uses LLF6 and PK51 glasses, which are very well matched to each other and to atmospheric refraction, in terms of index and dispersion. It gives correction to ZD=70° for all bands. However, the UV transparency of PK51 is less good than it might be (75% for 25mm at 350nm, we have 2 x 15mm central thickness prisms), other combinations may be explored during detailed design. The aberrations from the ADC are minimized by placing it as far from the detectors as possible. The proposed design has it mounted inside the primary mirror cell, just before the Nasmyth bearng (Figure 3); this has the added advantage that the symmetry axis of the ADC remains fixed with respect to its mounting. Designs with curved prism surfaces (Amici prisms) were tried with no significant gain. A design with CaF2 and silica prisms also worked very well, but with additional risk, difficulty and cost.

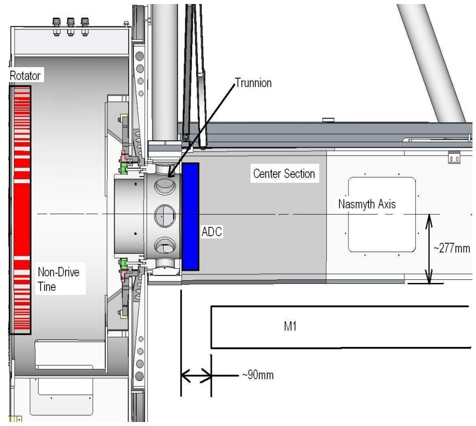

Figure 3. Proposed ADC location on wide-field optical camera

The overall imaging performance is diffraction limited beyond ~450nm, at all elevations > 45° (Figure 4).

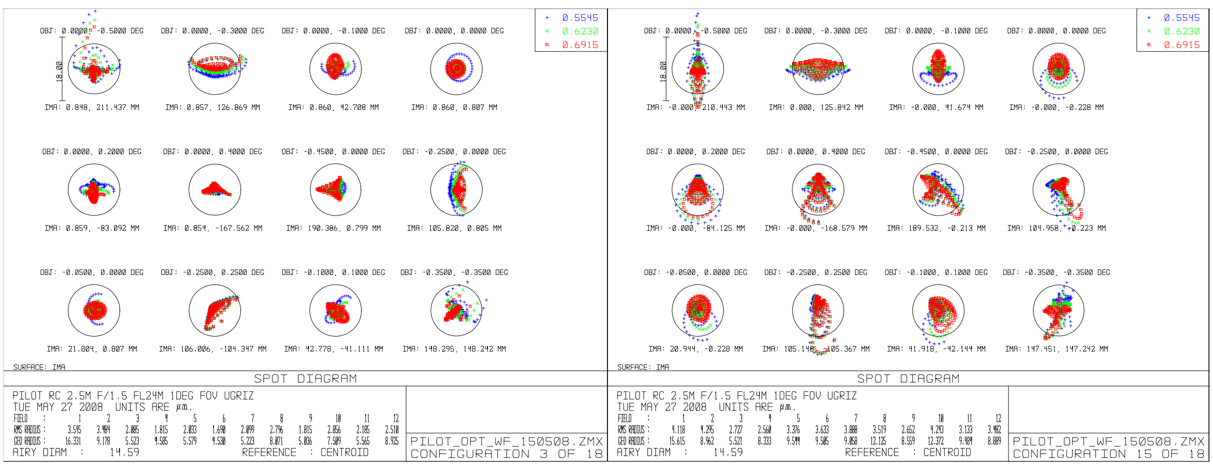

Figure 4. *r*-band spot diagrams at zenith and ZD=70°, showing the Airy disc.

Detectors

The strawman detectors are STA1600A 10.5K x 10.5K detectors with 9µm pixels. There is room for 10 of these on the focal plane (Figure 5), including the required dead space between them), giving a 1.1 gigapixel camera. At f/10, the resulting pixel scale is 0.077"/pixel.

A very interesting alternative option is Orthogonal Transfer Array (OTA) CCD's (Burke *et al*. 2004). These have the advantage of allowing differential fast tip-tilt across the detector area. In Antarctica, the advantages in seeing, isoplanatic angle and coherence timescale mean that there are 20 times as many useable guide stars per isokinetic patch as at Mauna Kea; this means that it is possible to map the entire coherence field over large angles (Kaiser, Luppino and Tonry 2000), to achieve tip-tilt guiding over the whole field with almost no anisokinetic error. The pixel scale is Nyquist sampled with 12µm pixels.

Optical Guiding

The proposed fast guiding scheme for this camera is to use a set of 8 L3Vision CCD201 detectors around the science detectors, as shown in Figure 5. Calculations show that this allows excellent guiding, in the sense that the guiding error is completely dominated by irreducible anisoplanatic effects over the wide-field. The detectors would be preferably single-frame rather than frame-transfer mode, since readout time is not an issue for the very small guiding windows (say 8 x 8 pixels) we would use.

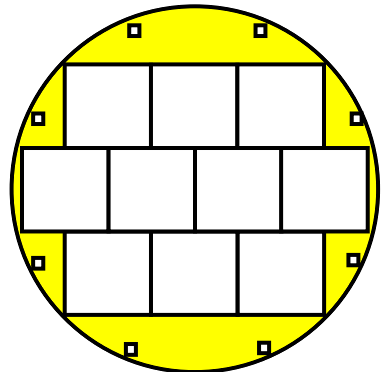

Figure 5. Detector array for the wide-field optical camera, showing science and guide detectors

Optical Image Quality

The expected median image quality is shown in Figure 6. This includes seeing, tip-tilt correction, anisoplanatic error, diffraction and telescope contributions. Also shown is the image quality that is in principal achievable in median conditions with OTA CCD's.

Optical Science Drivers

This camera offers a unique facility whenever high resolution imaging is required over large areas. The primary driver is for weak lensing (Saunders 2008). Other areas with obvious gains are stellar populations in our own or nearby galaxies, and galaxy morphology versus environment at high redshift.

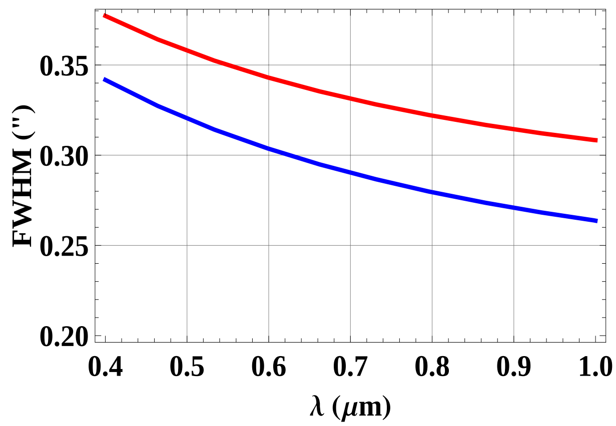

Figure 6. Median wide-field optical image quality with traditional (red) and OTA (blue) CCD's

4 WIDE_FIELD NEAR-INFRARED CAMERA

The wide-field near-infrared camera uses 4 Hawaii-2RG detectors and on-chip guiding using small sub-windows. Detector technology and available atmospheric windows lead to a wavelength range of 1-5μm. To block stray thermal radiation requires a cold-stop within the camera. The strawman design uses a reflective Offner relay-type cold stop with two spherical mirrors within the dewar. These would be silver coated, with 99% reflectivity throughout the 1-5μm design range. The reimaging of the telescope pupil (M1) onto the 75mm cold stop is imperfect (Figure 8), with a maximum spot size of 750μm. The cold stop will need to be undersized to prevent any stray light reaching the detector; this implies an additional 6% light loss.

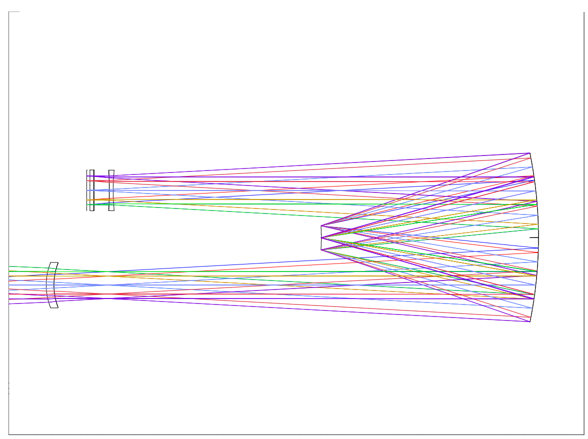

Figure 7. NIR camera, showing Offner relay cold-stop design. The cold stop is the smaller mirror. Both mirrors are spherical. The first (right-hand) lens also acts as dewar window.

There are two CaF_2 corrector lenses with all-spherical surfaces. Coatings for these lenses is a challenge, because of the 5-fold range in wavelength. Coatings would be optimized for the thermal region, 2.4-5μm, where emissivity .is paramount. There is no ADC, since the images remain diffraction-limited at the design wavelength of 2.4μm even at ZD=70°. Even at *Y*-band (1μm), the atmospheric dispersion is only 0.15" at ZD=70° (Figure 9).

Although the dewar is large, it does just fit into the proposed 8m dome of the minimum size required to fit the telescope. If this turns out to be a problem, it would be possible to add a fold mirror (at the cost of adding another warm mirror), to put the dewar vertical. The design is capable of being stretched to accommodate 4 x 4K x 4K Hawaii 4RG15 detectors, though the dewar is even larger and would definitely require folding. In any case, the entire dewar will need to be rotated to compensate for Nasmyth rotation.

The detectors are assumed to be 4 × 2K× 2K Rockwell Hawaii-2RG's with λ_C=5.3µm (as for JWST) and 18µm pixels. We assume ASIC Sidecar controllers, inside the dewar with the detectors at ~50K.

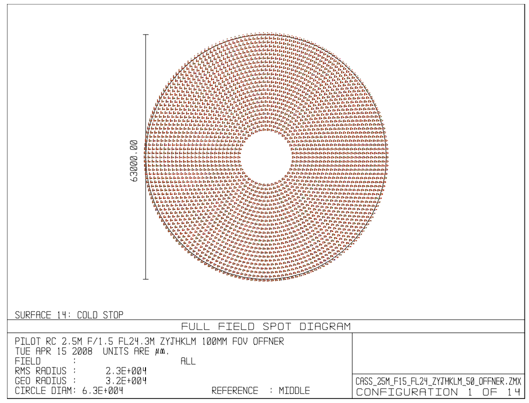

Figure 8. Cold stop surface, showing light-loss due to imperfect re-imaging of the pupil.

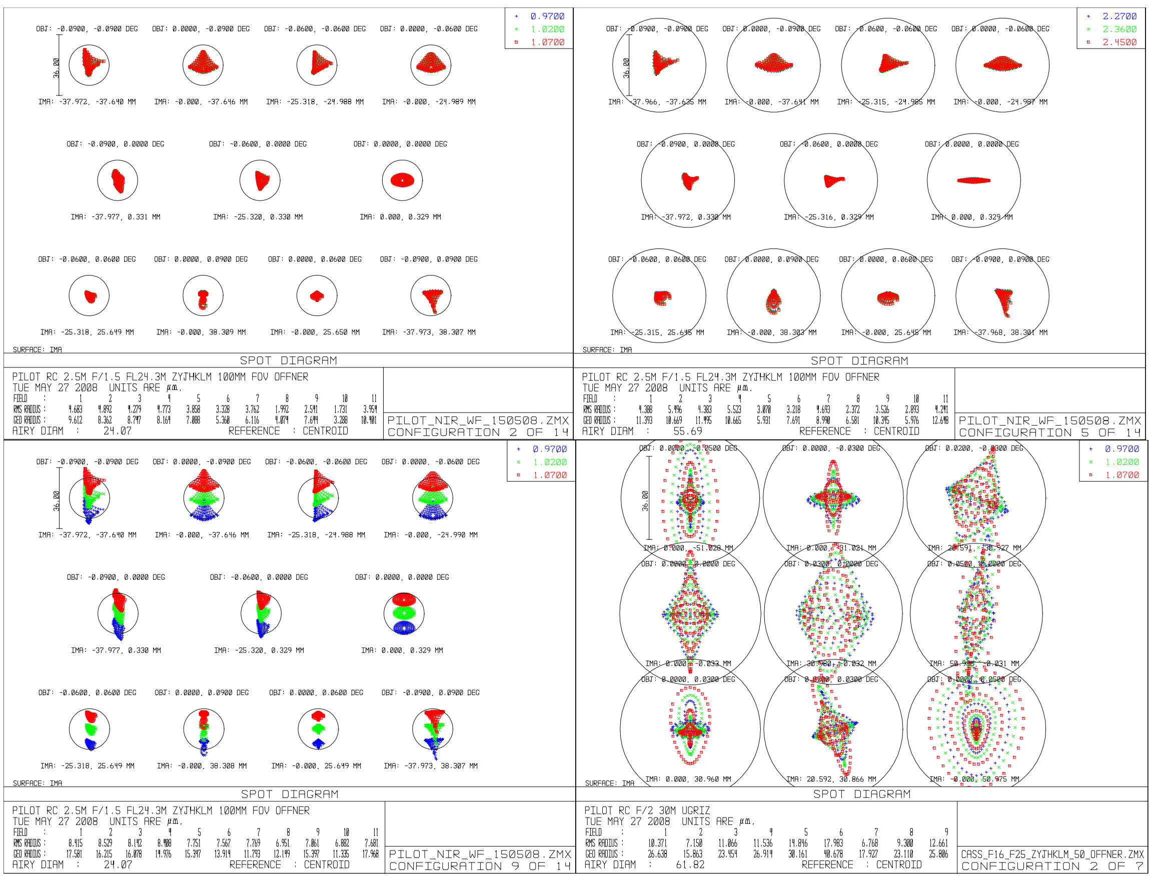

Figure 9. NIR image quality for (in order) *Y* and K_{dark} -band wide-field use at zenith; *Y*-band use at ZD=70°; *Y*-band use with the Barlow lenses. Airy disc and 2 pixel scale bar is shown in each case.

NIR camera in narrow-field use

The NIR camera is designed for wide-field use, with pixellation set by Nyquist sampling of the diffraction pattern at K_{dark}. As such, it undersamples the PSF expected in the best conditions at *zYJH* bands. However, by replacing the final lens with two additional lenses in the beam, below the cold stop, a larger plate-scale can be achieved, with an overall focal ratio of f/25 (Figure 10). Four fold mirrors would also be required to keep the longer path-length within the dewar and imaging onto the same detectors. The resulting image quality is diffraction-limited over the whole detector in all bands.

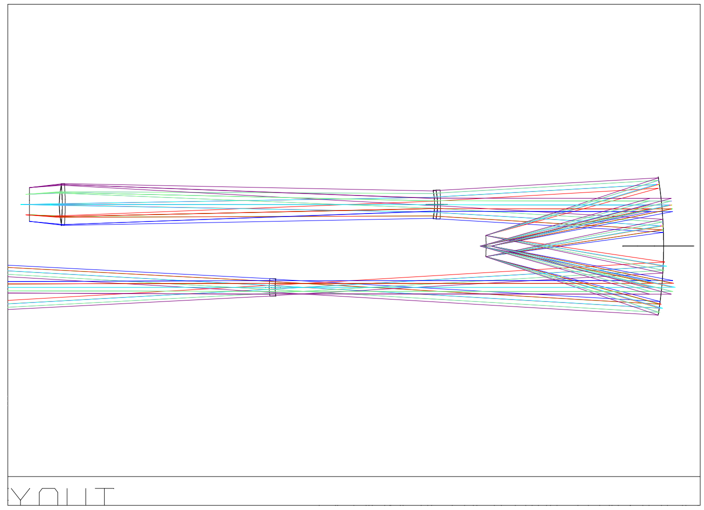

Figure 10 NIR camera optical design for diffraction-limited use at *zYJHK*. Not shown are the 4 fold mirrors required to keep the overall path length and detector placement the same as for wide-field use.

Guiding in NIR use

For fast guiding with the NIR camera, we propose to use sub-windows of the main detectors, as implemented on WIRCAM on the CFHT (Albert *et al.* 2005). On WIRCAM, this successfully suppresses image motion at frequencies less a few Hz.

The main problems are read noise, and the requirement to guide through the same filters as the science data. The intrinsic read noise for Hawaii-2 detectors is $16e^-$ with ASIC controllers. This can be beaten down by non-destructively reading each pixel many times during each integration; for 8 x 8 pixel windows and 10-20ms integrations, we can get close to the $3e^-$ limit imposed by correlated read noise. The error in fast guiding is caused by a combination of read-noise, photon statistics, time delay and anisoplanatic error. We have modeled the error in each band (Figure 11) and also in narrow-field configuration, and in poor conditions. We find that (a) the guiding error is dominated by irreducible anisoplanatic errors in all cases, (b) the centroiding error per frame is read-noise limited, (c) the optimal integration time is always 10-20ms, and (d) the optimal number of guide stars varies from 1 (at *M*-band) to 10 or more at shorter wavelengths. Therefore, it seems that this approach will work well enough. The guiding is significantly worse at *M*-band, but the diffraction limit is starting to dominate there in any case. This approach does mean that high resolution narrow-band imaging is in general ruled out at high Galactic latitudes.

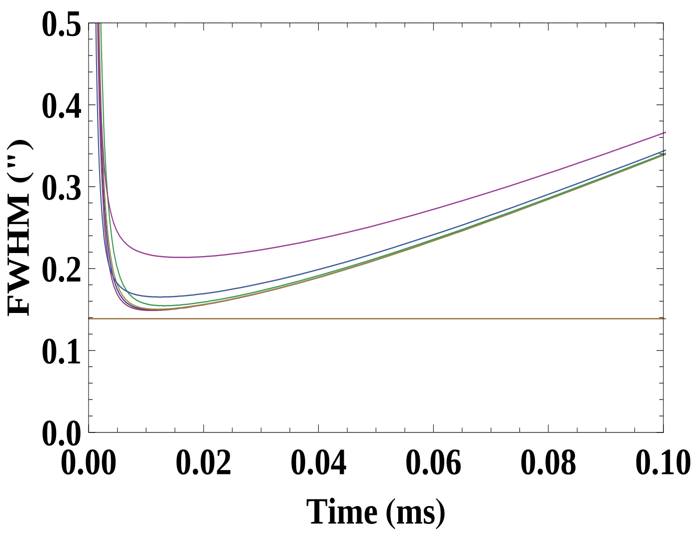

Figure 11. Residual tip-tilt error vs integration time, in median conditions for wide-field use, for *Y*, *J*, *H*, K_{dark}, *L*, *M* bands, in that order, from best to worst. The horizontal line is the irreducible anisoplanatic error.

NIR image quality

The median image qualities, in both wide- and narrow-field use, are shown in Figure 12. The difference is small, because most of the tip-tilt gain is already realised in wide-field use. However, in good conditions, the narrow-field mode gives dramatic improvement.

Hawaii-4RG detectors

Both optics and cost limit the camera to 4 × 2K × 2K Hawaii-2RG detectors. However, the optics do allow the use of 4 of the proposed 4K × 4K HAWAII-4RG detectors with 15µm pixels. These detectors are expected to be of comparable individual cost to Hawaii-2RG's, and should be available fro 2011. If this option is decided upon during detailed design, the speed of the telescope would likely be increased to preserve the pixel scale. This could also benefit the wide-field optical camera, which is currently oversampled with 9µm pixels.

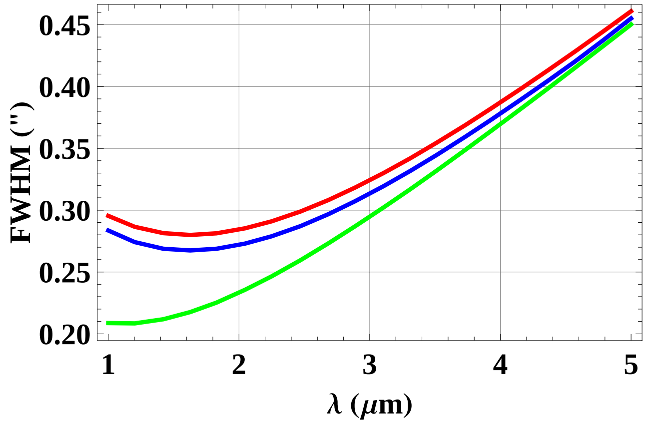

Figure 12. NIR Image quality for wide-field (red) or narrow-field (blue) use in median conditions, and for narrow-field use when the boundary layer is entirely below 30m (green).

NIR Science Drivers

The NIR camera offers sensitivity, wide-field resolution and photometric stability much better than any existing ground-based facility. The background is a factor 30-40 times darker in the *K*-band than any existing site, and the seeing more than twice as good after tip-tilt correction. Together, these lead to an order of magnitude gain in *K*-band sensitivity over existing 8m-class telescopes. There is a similar gain in overall K-band survey speed over VISTA, once the effects of cold-stopping are accounted for. It thus offers the only possibility to get NIR data matched in depth to the great optical surveys now underway. The science drivers identified to date include detecting planetary transits at *L* and *M* bands, determining the stellar populations of our own and nearby galaxies; finding the oldest gamma-ray bursters; finding supernovae at very high redshifts, and finding the first evolved stellar populations at z=6-7.

5 MID INFRARED CAMERA

Several European institutions have recently started a conceptual design study for a mid-IR camera-spectrograph for PILOT, which will last until December 2008. The main scientific drivers for such an instrument reside in the following fields: embedded protostars, crystalline silicates, exoplanet secondary transits, galactic plane survey for molecular hydrogen, extended gas emission in star formation, starburst galaxies and supernovae.

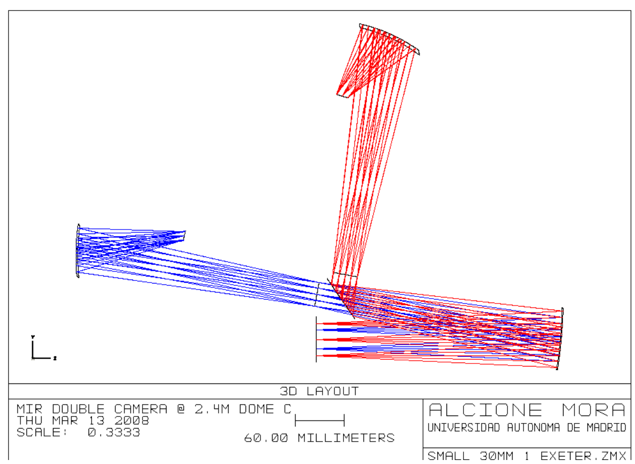

Figure 13. Mid-IR camera-spectrograph optical design

Dome C is currently the best available mid-IR observing site on the ground. Three are three features that make it unique. First, the low temperature, which reduces the telescope emission by more than an order of magnitude in the *N* window (8-13µm) compared to temperate sites. Second, the extreme dryness (~250 µm of precipitable water vapour during much of the winter time, Minier *et al.* 2008), which improves the transmission in the *Q* window (17-40µm), extending it up to ~50 µm. Third, the overall atmospheric stability, which reduces mid-IR flux fluctuations and permits deep, large scale, mosaic imaging surveys (full characterization ongoing, see Smith *et al.* (1998) for results at the South Pole).

The initial Strawman input concept for the PILOT mid-IR instrument is outlined in the following. Figure 13 shows the initial input optical design layout and Strehl ratio diagrams. Several important questions that the conceptual study will address are: overall feasibility of the instrument, possibility of extending the blue-arm (7-25 µm) field of view using the new generation Si:As megapixel arrays, possibility of adding a cryogenic Fabry-Perot unit, and winter time cryogenic system requirements.

The instrument is optimized for Q window (17-40 µm); it is a dual camera design, with one arm for 7-25 µm (blue channel), and another one for 25-40 µm (red channel). The blue channel has a Raytheon Si:As IBC 320x240, with 50 µm pixels, plate scale 0.84"/pixeland field of view 4.5'x3.4'. The red channel has a DRS Si:Sb BIB 256x256, with 50 µm pixels, plate scale 1.31"/pixel, and field of view 5.6'x5.6'. The collimator, blue camera and red camera are all off-axis aspherical mirrors, giving diffraction limited performance throughout. The cold stop diameter is 30mm. Low to medium resolution grism spectroscopy ($R = \lambda/\Delta\lambda \sim 100\text{-}1000$) would be possible with this design.

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