PILOT: a wide-field telescope for the Antarctic plateau

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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 telescope is 2.4m diameter, with overall focal ratio f/10, and a 1 degree field-of-view. It is mounted on a 30m tower to get above most of the turbulent surface layer, and has a tip-tilt secondary for fast guiding. 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 major challenges have been (a) preventing frost-laden external air reaching the optics, (b) overcoming residual surface layer turbulence, (c) keeping mirror, telescope and dome seeing to acceptable levels in the presence of large temperature variations with height and time, (d) designing optics that do justice to the site conditions. The most novel feature of the design is active thermal and humidity control of the enclosure, to closely match the temperature of external air while preventing its ingress.

Keywords: telescopes, Antarctica, wide-field, optical, infrared

1 INTRODUCTION

Conditions at Dome C on the Antarctic Plateau are known to be exceptional for astronomy. The free seeing, coherence time and isoplanatic angle are all twice as good as the best existing observatories, while the water vapour column, and sky and telescope thermal emission are all an order of magnitude better. PILOT (Pathfinder for an International Large Optical Telescope) is a proposed 2.4 metre optical/infrared telescope for Dome C, with target first light at the end of 2012, as a key step to a major international observatory. A year-long feasibility design study, by the AAO and UNSW, is now almost complete. The primary aims of the design study are to produce a viable design and implementation plan, and a realistic costing. As part of the study, we are actively seeking partners in the PILOT project, and input into the design and the scientific requirements. Further information on the PILOT project can be found at http://www.aao.gov.au/pilot/ .

2 SITE CONDITIONS

Site conditions at Dome C have been extensively reported by Lawrence *et al*. (2004), Kenyon *et al*. (2006), Agabi *et al*. (2006), Trinquet *et al*. (2008a); they are only summarized here insofar as they affect the design and performance of PILOT. The dominant weather pattern consists of a katabatic wind flowing off the plateau. Cooling of this wind by the surface ice causes a very strong temperature inversion in the lowest 200-300m, while surface drag causes a strong wind speed gradient. Together, these factors create poor seeing in the turbulent surface

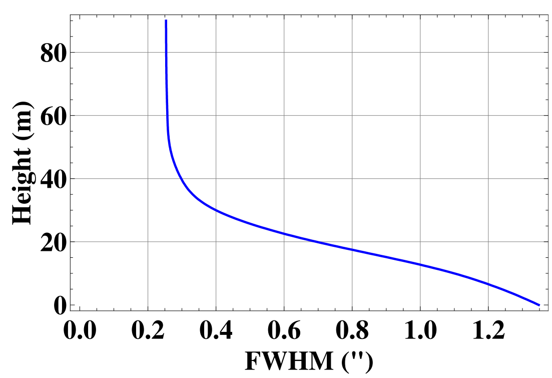

Figure 1. Seeing as a function of height, derived from the C_N^2 balloon data of Trinquet *et al.* (2008).

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layer. The layer has variable thickness as the wind rises and falls, with a median height of ~33m (Trinquet *et al*. 2008).

The median wintertime free seeing above this surface layer is $\theta_0 \approx 0.25''$ (Lawrence *et al*. 2004, Trinquet *et al*. 2008a). For a significant fraction of the time (~20%), the boundary layer drops below 8.5m (Trinquet *et al*. 2008b). The best recorded wintertime seeing is ~ 0.1" (Lawrence *et al*. 2004, Trinquet *et al*. 2008b). The median seeing as a function of height, calculated directly from the Trinquet *et al.* (2008a) balloon microthermal data, is shown in Figure 1. At a height of 33m, the median seeing is 0.38". This means that the residual contribution from the surface layer above that height, is comparable with the free seeing. The Trinquet median profile is used throughout the rest of this paper, as the more detailed (and more pessimistic) data.

The temperature variation with height is shown in Figure 2(a). It shows a strong, but decreasing, gradient with height.

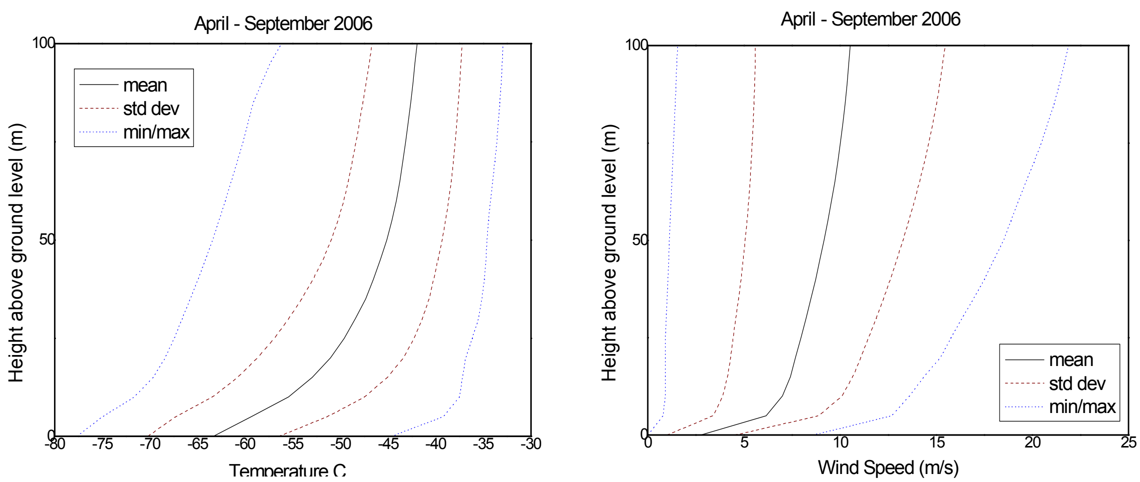


Figure 2. (a) Winter temperature versus height and (b) winter wind speed versus height. Based on PRNA 2006 balloon data.

The temperature gradient is important in determining dome and telescope seeing, while the temperature itself determines the thermal background from the telescope. The median wintertime temperature at a height of 30m is -48.5°C, with a gradient of 0.15°C/m; the annual range, over which the telescope must operate, is -65C to -25C, with gradient in the range 0-0.5°C/m.

The temperature is about as variable with time as at temperate sites. There are extreme warming events, but these are always associated with cloud cover. The largest temperature gradients when observing are ~0.5°C/hour (Travouillon *et al*. 2008). Figure 3 shows the blackbody and sky emission as a function of wavelength, at Dome C and Mauna Kea. The sky and telescope backgrounds are reduced at Dome C by factors of 10-100, due to the extreme cold. However, the *relative* contributions of telescope and sky emission are comparable, throughout the thermal IR; hence cold-stopping is as important at Dome C as at temperate sites.

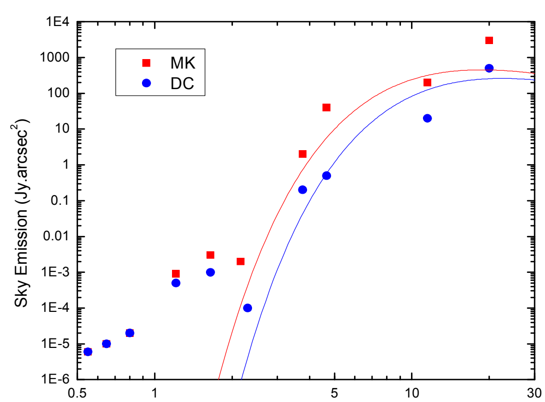


Figure 3. Sky and telescope (assumed 5% emissivity) emission, as a function of wavelength, at Dome C (assumed 227K) and Mauna Kea (273K). Sky data taken from Burton *et al.* 2005.

The wind speed also increases strongly with height, and again the gradient decreases with height. The wind speed versus height is shown in Figure 2(b). At 30m, the median wind speed is 7m/s, with a maximum of less than 20m/s.

The absolute wintertime humidity at Dome C is extremely low, ~$0.1g/m^3$. However, based on the frost-point experiment GIVRE (Durand 2008) and also on theoretical considerations, the relative humidity is usually ~150% with respect to frost. Vaisalla balloon HUMICAP data showing subsaturated humidity at 10-50m is now believed to be caused by a combination of detector saturation and time delay in its response. Diamond dust (airborne ice crystals spontaneously condensing around aerosol particles) is ubiquitous, and all exposed surfaces suffer severe frosting even when kept at ambient temperature. This is exacerbated by radiative losses to the sky, which cools unheated surfaces as much as 2°C below ambient.

3 DESIGN OVERVIEW

The 2.4m size of PILOT is determined by commercially available designs, by the availability of ion-beam mirror polishing, by the limits for passive mirror support, and by the limits for useful gains from fast guiding. PILOT will be a Ritchey-Chrétien design, with twin Nasmyth foci. For wide-field work, the pixel scale is matched to the median free seeing. However, provision is made for sampling diffraction-limited images at all wavelengths longer than 500nm.

The telescope will be installed on a ~30m tower, above most of the turbulent surface layer. It will be in a thermally and humidity-controlled enclosure. It will allow 24 hour remote operation with minimal human intervention.

The secondary mirror will be on a hexapod mount, and will have a fast (~30Hz) tip-tilt capability. Tip-tilt is essential for compensating for wind-shake and residual surface layer turbulence. Defocus and decentering coma caused by telescope thermal deformation or sag will be corrected by the hexapod. The primary is intended to be passively supported, though it is possible that we will allow active astigmatism compensation, since this is by far the dominant mode for deformation.

The optical design has evolved during the study; a Gregorian design was originally preferred, because of the conjugacy of the secondary with residual surface layer turbulence just above the telescope. However, in practice the gain from this is very small, because the isokinetic angle for correction of residual boundary layer turbulence is in any case larger than the field of view. A Gregorian design incurs large penalties in telescope length, cost and field of view.

Narcissus mirrors were originally envisaged for infrared use (as per Gillingham 2002), but the current design is (a) much warmer that there assumed (because it is now at 30m elevation), and (b) now intended to be a general-purpose telescope. These considerations lead us to a design with a cold stop within each of the infrared instruments. Optical use requires a baffle on the top end, of diameter 1/3 the primary, to prevent skylight reaching the detector directly; this baffle will have to be deployable so than it can be stowed away for infrared use.

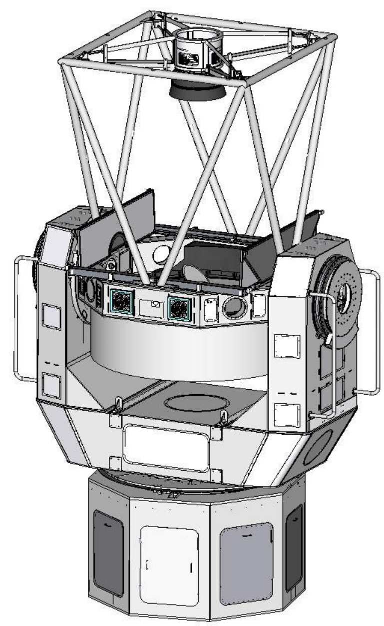


Figure 4. EOS telescope design

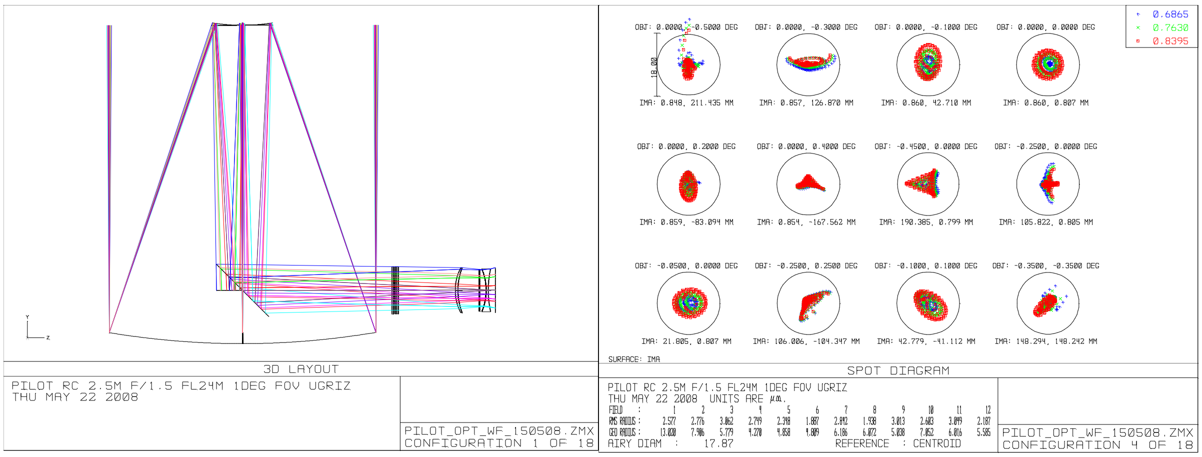
Guiding will be controlled from within each instrument. The reasons for this are (a) the requirement for multiple guide stars (to average out guide star image motions caused by high level turbulence uncorrelated across the field), making deployable probes very complicated, (b) the desire to minimise mechanisms, (c) the requirement for these probes to have their own corrector optics, or to be inside the instrument dewars.

In general, the design for PILOT is deliberately conservative wherever possible - the aim is to provide a feasible solution to the problems of observing from Antarctica.

4 OPTICAL DESIGN

The telescope design is very close to a classic Ritchey-Chrétien. The primary speed of f/1.5 is the speed that our optical consultants (REOSC) advised for minimising overall telescope difficulty and cost. The overall speed of f/10 is determined by the requirement to Nyquist sample the anticipated median seeing in the NIR with Hawaii-2RG detectors and 18µm pixels, and gives an image scale of 8.55"/mm. The secondary size (563mm for 1° field) is as preferred by optimisation, and allows for convenient back focus (1.1m from the edge of the primary) with the Nasmyth layout. The pupil is on the primary

A slight departure from exact Ritchey-Chrétien geometry allows for improved wide-field image quality, when combined with a pair of corrector lenses. It still allows diffraction-limited imaging on-axis, by a small (50µm) refocus between M1 and M2. Figure 5 shows the layout and image quality for *i*-band (800nm) use over a 1° field, with two silica correctors and an ADC.



Figures 5. (a) Optical layout and (b) image quality in wide-field optical (800nm) use over a 1° field, with ADC, filter and two silica corrector lenses.

The large field of view of the optical camera increases the diameter of M2 by 7.5% over the NIR requirements. This causes a very small, and acceptable, degradation of the diffraction-limited energy concentration, as shown in Figure 6. However, the requirement for a large baffle on M2 in optical use would cause unacceptable loss of Strehl, so this baffle must be stowed when the telescope is in infrared use.

A design and costing for the reflective optics is currently underway by REOSC. This includes the minimum thickness, support requirements, and achievable optical quality.

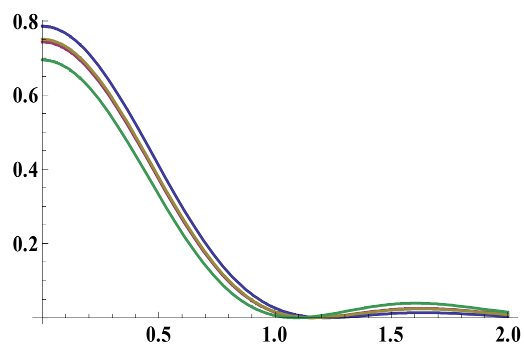


Figure 6. Diffraction-limited PSF for (in order of descending Strehl) unobscured aperture, M2 for 15' field, M2 for 1° field, M2 and baffle for 1° field. Units are dimensionless (intensity distribution versus radius in units of λ/D)

5 TELESCOPE DESIGN

A design for the telescope is being undertaken by Electro-Optical Systems (EOS). The design is based on their 2.4m Alt-Az Rocky Planet Finder telescope for the Lick Observatory, modified to meet the requirements of low temperature use. The other principal design change is the Nasmyth layout (vs Cassegrain) and large field of view, necessitating oversize Nasmyth bearings. The telescope design allows for active ventilation inside the yoke structure, and this is required to maintain thermal equilibrium, to within 0.25°C, with the air within the dome. The telescope tube and top-end structure is thin and light enough (~1 tonne) not to require active cooling.

6 TOWER

The tower design (Hammerschlag *et al*. 2006) is extremely stiff to twisting and bending, giving a fundamental frequency of ~3Hz and an expected windshake of <0.2" (Lanford *et al*. 2006). Our own analysis, and also that done for Gemini (McGonegal 1996), suggest that this will be reduced by factors of several, by the fast tip-tilt secondary.

The tower does not need to lift the telescope entirely above the boundary layer (which, from Figure 1, would imply a height greater than 50m). What is needed is that any residual surface layer turbulence above the telescope be correctable, via the tip-tilt system, down to a level much smaller than the free seeing. For the Trinquet *et al.* profiles, this is met for a telescope height of 33m.

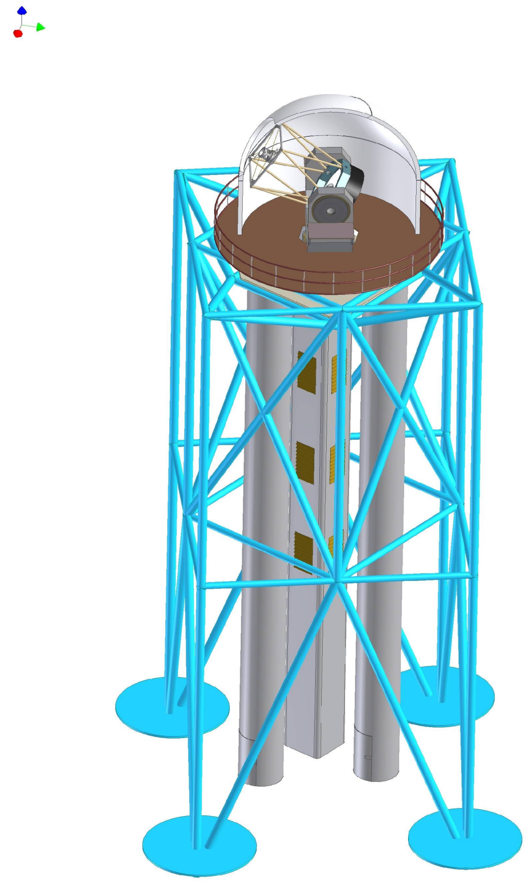


Figure 7. PILOT telescope, enclosure and tower.

7 ENCLOSURE

Two other major challenges at Dome C are (a) the enormous vertical temperature gradient, (~1°C/m at surface level and ~0.15°C/m even at 30m) and (b) the supersaturated humidity. Both theoretical considerations and the results of site testing (Durand 2008) indicate that the relative humidity (with respect to ice) is usually ~150%, or equivalently, that the frost point is ~ 3.5°C above ambient. Warming the telescope components above their frost point would cause unacceptable mirror, telescope and dome seeing (e.g. Wilson 1999). Hence we propose to flush the dome with subsaturated air, matched in temperature to the external air at the dome aperture. At these temperatures, the saturated moisture content of air halves for each 5°C temperature drop; so the obvious source for dry air is from lower down the tower, using the waste heat from the instrumentation to warm it to the required temperature. Extensive CFD modelling (by LEAP Australia) has been done to determine the air-flow required to prevent ingress of outside air into the dome, and to determine the

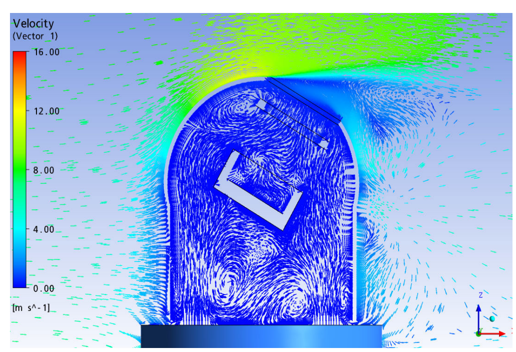


Figure 8. Wind vectors for the proposed dome-flushing scheme, showing a clean interface between internal and external airflows.

resulting dome seeing. We find that flows of a few m^3/s, and heat loads of 10-20kW, are required. This requirement may be reduced by use of an air curtain at the dome aperture (this is work in progress), but is in any case well matched to the waste heat generated by the large optical and infrared imaging cameras proposed for the telescope.

A second advantage of this scheme is excellent dome seeing, since the temperatures are carefully matched, and the external airflow suffers minimum disruption. Our specification is 35nm rms wavefront error, and this looks achievable.

The dome is currently specified as a calotte-style fibre-glass structure. It will be insulated, both to prevent heat loss to the sky via radiation, and to allow warming of the telescope, to ~-5°C, for maintenance. The nominal external diameter is 8m.

8 MIRRORS

The primary mirror will be a Zerodur (or equivalent) meniscus, of thickness 100-150mm. Aluminium offers no significant structural advantage, while silicon carbide and carbon-fibre reinforced polymer are not available in the required sizes. To make a Zerodur mirror that passively tracks ambient temperature with an acceptable temperature differential (<0.25°C, Wilson 1999) requires a thickness no greater than 50mm. We were unable to design a light-weighted primary with this thickness, which still allowed passive support. We have therefore adopted a simple mirror-flushing scheme (as implemented on the AAT) in which air is blown across the top and lower mirror surfaces at a several m/s (Figure 9). This has the combined advantages of greatly speeding up the thermal equalisation rate of the mirror, and flushing away any turbulent cells before they form, hence making larger temperature differentials acceptable and further decreasing the equalization time. Figure 10 is derived from the fomula for mirror seeing of Zago (1995). It shows that mirror temperature differentials ~1°C give acceptable mirror seeing for ~6m/s flushing. At this temperature differential and flushing rate, we are able to track the expected 0.5°C/hr temperature variations.

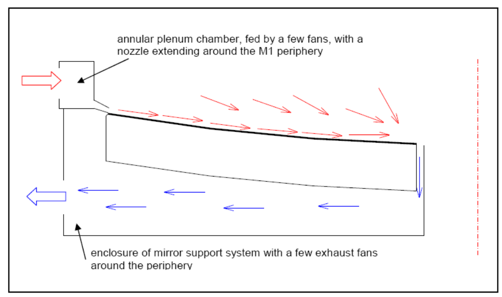


Figure 9. Proposed flushing mechanism for the primary mirror.

The low operating temperature and the required optical performance of the telescope places very great demands on the homogeneity of the mirror material. Using the data supplied by Schott, we estimate that the mirror will likely go out of shape between manufacture and use, at a level greater than our specification. However, a simple warping harness allows for periodic correction during commissioning and thereafter, and the subsequent thermal deformations should be acceptable over the range of temperatures in normal use.

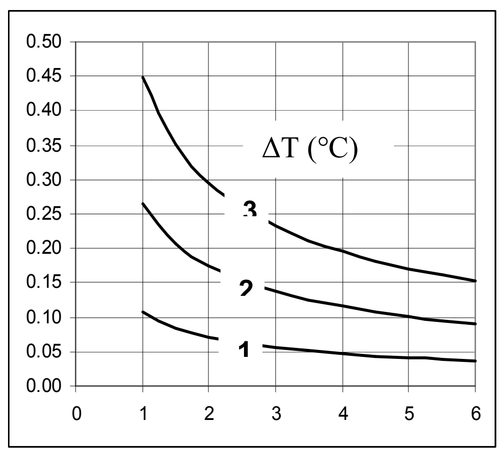


Figure 10. d_{80} (arcsec) versus air velocity (m/s) for three values of mirror temperature differential.

The secondary is required to have a tip-tilt capability for fast guiding, with a throw of about 1" at no less than 30Hz. The accelerations involved are small (<< 1*g*), so there is no apparent requirement for special materials. We expect to use Zerodur, lightweighted to reduce overall top-end mass.

The coatings will be protected silver, throughout. The detailed design is not yet determined, but will be such as to give a design life of 10+ years in the pristine conditions of Antarctica; no recoating plant is envisaged.

9 ERROR BUDGET

The imaging specifications for PILOT are that it should be capable of taking diffraction-limited images over small fields at 1 μm in the best conditions; and that the imaging over wide fields, longwards of 0.4μm, in normal conditions should be limited by the median free (tip-tilt-corrected) seeing and/or diffraction, rather than by imperfections in the telescope itself. These are formalised by demanding that the contribution, in quadrature, of the entire system (aberrations, optical imperfections, mirror/telescope/dome seeing, guiding, wind-shake) to the idealized, diffraction-and-seeing limited image quality, should be not greater than d_{80}=0.2" at 1μm in the best conditions, or d_{80}=0.3" for $\lambda > 0.5\mu m$ in median conditions. This complicates the error budget, because of the mixture of wavelengths, and of diffraction-limited and geometric regimes. However, in practice the toughest specification is for wide-field optical imaging, so we set the error budget there. Even at this wavelength, the effects of diffraction must be included. The preliminary error budget is shown in Table 1; each entry is the allowable contribution, in quadrature and including the effects of diffraction, to the total image quality.

Contribution	***V*, WF**	***Y*, NF**
ZEMAX optical aberrations	75	75
Surface error M1+M2+M3	175	100
ΔCTE of M1+M2+M3	50	50
Sag	75	0
Misalignment	50	50
Flexure	50	0
Defocus	50	50
Camera optics	75	50
Mirror seeing	75	50
Telescope seeing	75	50
Dome seeing	75	50
Windshake	75	50
Guiding	50	50
Total	**285**	**195**
Budget	**300**	**200**

Table 1. PILOT wavefront error budget, for d_{80} in milliarcsecs, for wide-field use at 500nm (*V*-band) and narrow-field use at 1μm (*Y*-band).

10 IMAGE QUALITY

As well as correcting for windshake, the tip-tilt secondary gives significant adaptive optical improvement, especially in the NIR. We have modelled the C_N^2 profiles determined by Trinquet *et al*. (2008), and we find that residual surface layer turbulence just above the telescope is largely cleaned up by this, across the entire field-of-view, and of course better at longer wavelengths. This partly compensates for the increasing diffraction limit at longer wavelengths, so the overall image quality is rather constant. For the expected median natural seeing of 0.38" FWHM at 500nm, the expected delivered image is close to 0.3" for 0.7-2.5μm (Figure 11).

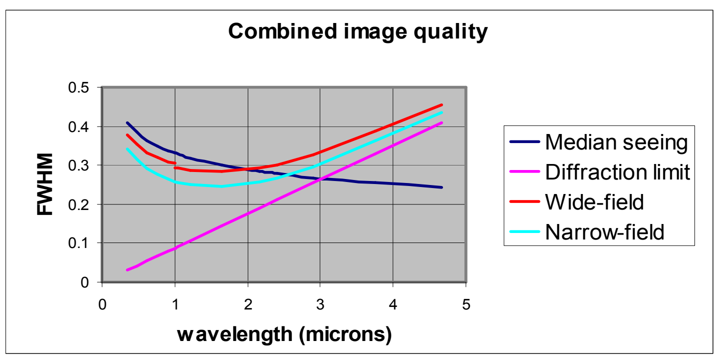


Figure 11. Anticipated median image quality for PILOT, as a function of wavelength, and including contributions from tip-tilt-corrected seeing, diffraction, and telescope.

The performance of the telescope is reasonably robust to variations in the residual surface layer turbulence. In Figure 12, we show the modeled wide field performance for the Trinquet profile, with and without its surface layer component. Although the raw seeing varies enormously, the tip-tilt-corrected performance varies much less, especially in the NIR.

The gains in seeing, isokinetic angle and coherence time over existing sites collectively mean that, in terms of suitable guide stars per isokinetic patch, Dome C enjoys a 20-fold advantage over, e.g., Mauna Kea. This means that there are enough guide stars at *r* and *i*-bands, to map the entire atmospheric deflection field, at a level giving negligible anisokinetic error (Kaiser, Luppino and Tonry 2000). This means median image quality ~0.2" is in principal achievable over arbitrarily large fields, using tip-tilt correction for high-level turbulence via Orthogonal Transfer CCD's.

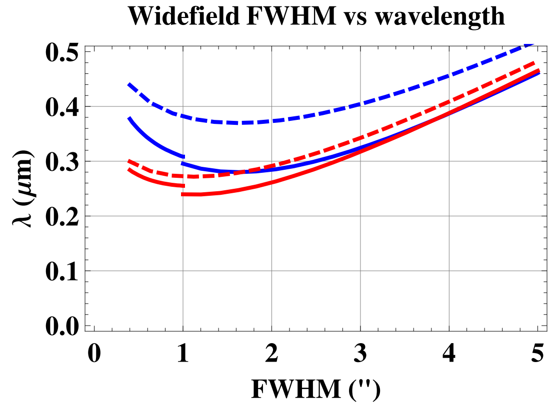


Figure 12. Raw (dashed) and tip-tilt-corrected (solid) diffraction+seeing for Trinquet *et al.* seeing profile (blue), or without its surface layer component (red). The break at 1μm is due to the smaller field size (and hence smaller anisokinetic error) of the NIR camera.

11 SENSITIVITY

The wide-field tip-tilt corrected image quality and backgrounds calculated above give optimally-extracted point source sensitivities as follows:

Band	λ Mm	Δλ/λ μm	image fwhm "	Sky Jy/□"	Sky AB/□"	PSS 1hr, 5σ
G	0.475	0.14	0.362	4E-06	22.42	27.61
R	0.62	0.14	0.340	1E-05	21.43	27.04
I	0.76	0.15	0.325	2E-05	20.68	26.64
Z	0.91	0.14	0.314	8E-05	19.17	25.79
Y	1.04	0.2	0.293	2E-04	18.18	25.48
J	1.21	0.26	0.286	5E-04	17.18	25.07
H	1.65	0.29	0.280	1E-03	16.43	24.61
Kd	2.40	0.23	0.296	1E-04	18.93	25.41
L	3.76	0.65	0.371	2E-01	10.68	21.32
M	4.66	0.24	0.435	5E-01	9.68	19.68

Table 2. Median image quality and point-source sensitivities

12 INSTRUMENT SUITE

The proposed first-generation instrument suite is subject of a companion paper (7014-166). Only a summary is provided here.

1. 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-4RG detectors (available ~2011) with 15μm pixels. The design includes two CaF2 corrector lenses and an Offner relay cold stop.

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 CCD's, or large format traditional CCD's such as the STA 10Kx10K detectors with 9μm pixels. The design includes two silica corrector lenses, one of which is aspheric.

3. High resolution, high speed optical camera for lucky imaging. Short exposure images will have a ~50% chance of being diffraction-limited at *i*-band in median conditions. The proposed camera is based on an E2V L3-Vision detector (which allows fast readout without read noise), with 1K x 1K, ~0.030" pixels.

4. Mid-infrared imaging spectrograph with Fabry-Perot filters. It is proposed that we have a double-beamed 7-40µm camera, with ~1"/pixel, allowing both spectroscopic and narrow band imaging. This camera could be used during the daytime.

13 CURRENT STATUS

The PILOT feasibility study will be completed in July 2008. Subject to continued funding, first light is anticipated for the end of 2012.

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