`IMAKA: Imaging from Mauna KeA with an atmosphere corrected 1 square degree optical imager

Olivier Lai[a], Mark Chun[b], Jean Charles Cuillandre[a], Ray Carlberg[c], Harvey Richer[d], David Andersen[f], John Pazder[f], John Tonry[k], René Doyon[g], Simon Thibault[j], Jim Dunlop[d], Chris Pritchet[e], Jean Pierre Véran[f], Christ Ftaclas [b], Peter Onaka[k], Klaus W. Hodapp[b], Robert A. McLaren[k], Emmanuel Bertin[h], Yannick Mellier[h], Pierre Astier[i], Reynald Pain[i].

[a] Canada France Hawaii Telescope, Kamuela, HI 96743, USA.
[b] Insitute for Astronomy, University of Hawaii, Hilo, HI 96743, USA.
[c] University of Toronto, Ontario M5S 3H4, Canada.
[d] University of British Columbia, Vancouver, BC V6T 1Z1, Canada.
[e] University of Victoria, Victoria, BC V8P 1A1, Canada.
[f] Hertzberg Institute for Astrophysics, Victoria, BC V9E 2E7, Canada.
[g] Groupe d'Astrophysique, Univerité de Montréal, QC H3C 3J7, Canada
[h] Institut d'Astrophysique de Paris, Paris 75014, France.
[i] IN2P3, Paris Cedex 05, 75252, France
[j] Immervision, Montréal, QC H3A 2A5, Canada
[k] Insitute for Astronomy, University of Hawaii, Manoa, HI 96822, USA.

ABSTRACT

The goal of this project is to achieve exquisite image quality over the largest possible field of view, with a goal of a FWHM of not more than 0.3" over a square degree field in the optical domain. The narrow PSF will allow detection of fainter sources in reasonable exposure times. The characteristics of the turbulence of Mauna Kea, a very thin ground layer with excellent free seeing allows very wide fields to be corrected by GLAO and would make such an instrument unique. The Ground Layer AO module uses a deformable mirror conjugated to the telescope pupil. Coupled with a high order WFS, it corrects the turbulence common to the entire field. Over such large fields the probability of finding sufficiently numerous and bright natural guide sources is high, but a constellation of laser beacons could be considered to ensure homogeneous and uniform image quality.

The free atmosphere seeing then limits the image quality (50% best conditions: 0.2" to 0.4"). This can be further improved by an OTCCD camera, which can correct local image motion on isokinetic scales from residual high altitude tip-tilt. The advantages of the OTCCD are not limited to improving the image quality: a Panstarrs1 clone covers one square degree with 0.1" sampling, in perfect accordance with the scientific requirements. The fast read time (6 seconds for 1.4 Gpixels) also leads to an improvement of the dynamic range of the images. Finally, the guiding capabilities of the OTCCD will provide the overall (local and global) tip-tilt signal.

1. Introduction

The goal of this project is to achieve exquisite image quality over the largest possible field of view. CFHT's location at the best-known image quality site in the world offers the prospect of taking advantage of the superb high altitude seeing in the 0.2-0.3" range by implementing a GLAO system.

SLODAR (Wilson, 2002 [14]) and LOLAS (Avila & Chun, 2004 [2]) measurements (Gemini GLAO site testing study) carried out by Chun et al. (2008 [4]) indicate that the prevalent ground layer is very thin (Figure 1). In ~18 months of SLODAR data the scale height of the turbulence near the ground is 23 meters and 90-95% of the profiles the strong turbulence is localized within the first resolution element of SLODAR (average resolution of 67m). 6 months of LOLAS data with an average altitude resolution of 22m shows that the turbulence closest to the ground consists of several layers but again localized within the first tens of meters. Both the SLODAR and LOLAS profiles show a distinct lack of turbulence above this thin layer up to the maximum altitude scanned (SLODAR: ~550m and LOLAS ~800m). This result should be compared a similar study at a continental site (Mt. Graham) by Egner and Masciadri (2007 [6]) that finds that the ground-layer is significant up to several hundred meters. The thin ground-layer at Mauna Kea is ideal for GLAO and would enable very large fields to be effectively limited by the free atmosphere turbulence.

Adaptive Optics Systems, edited by Norbert Hubin, Claire E. Max, Peter L. Wizinowich,
Proc. of SPIE Vol. 7015, 70154H, (2008)
0277-786X/08/$18 · doi: 10.1117/12.790114

The image quality can then further be improved by correcting the next dominant term in image degradation, the high altitude tip-tilt. This can be achieved with an Orthogonal Transfer CCD (Tonry et al., 1997 [13]), such as the one used in the PanStarrs project (Burke et al., 2006 [3]).

This project is unique amongst the instrumental landscape; competing wide field imagers will be discussed in the next section, but they will all be seeing limited (apart from PanStarrs, Kaiser, 2004 [8], and ODI, Jacoby et al., 2002 [7]). With regards to improving the image quality improvement, the scale of the corrected field of view is much larger than other proposed GLAO systems; for example, the Gemini proposal offers a 7'x7' field of view, while the ESO Hawk-I instrument will provide 7.5'x7.5' in the near infrared. `IMAKA makes use of the WFOV capabilities of CFHT and the fact that the measured ground layer on Mauna Kea is very thin, thus enabling very wide fields to be corrected. The concept of the "gray zone", first introduced by Tokovinin (2004 [12]) is useful to understand why correction over such large fields is possible on a site such as Mauna Kea. The gray zone is the range in altitude at which the atmospheric compensation becomes partial due to the mismatch of the deformable mirror conjugation and the turbulence. Below the gray zone, all the atmospheric turbulence is corrected and the isoplanatic field is effectively very large; $H_{min} = d/(2\theta_0)$ where d is the inter-actuator spacing and θ_0 is the corrected field. Above the gray zone, the turbulence in the different directions is basically decorrelated and there is no correction; $H_{max} \sim \lambda/(\beta\theta_0)$, with λ being the wavelength and β is the resolution reached by GLAO. If θ_0 is 30' (radius), β, as a goal is 0.3" and λ is 700nm, then H_{max} is roughly 60m. If $d \sim$ 0.4m, then $H_{min} \sim$ 23m. It is important that the DM is within H_{min} of the pupil, and this will be important if `IMAKA were to use an adaptive secondary mirror. LOLAS high resolution measurement of the vertical turbulence profile indicate that most of the turbulence is within 70m of the ground, so within the gray zone of the proposed system.

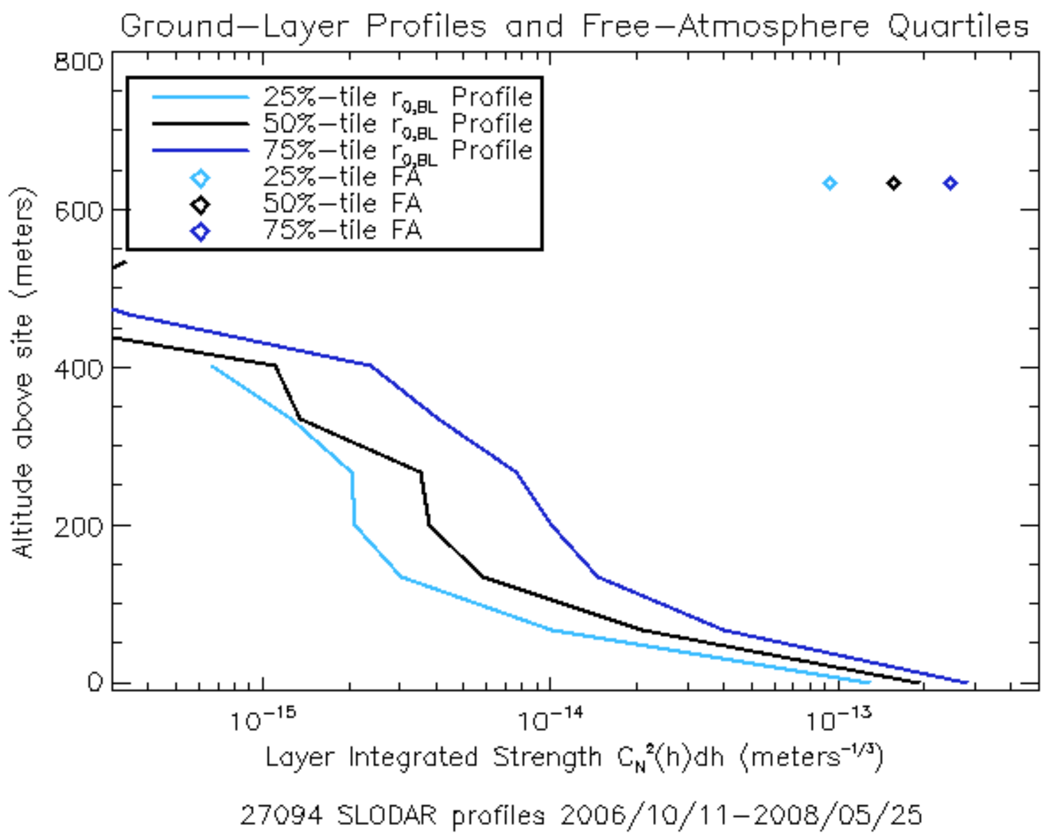

Figure 1: Gemini study of vertical turbulence profile. High resolution (LOLAS) measurements show that most of the turbulence is within 70meters of the ground. Data from Gemini GLAO site testing study carried out by Chun et al. (2008 [4]).

`IMAKA is an acronym (Imaging from Mauna KeA), but it also means look-out, scenic viewpoint or observation point. This is appropriate as we use a characteristic of the site (thin ground layer) to view the sky in a special way.

2. Scientific capabilities and astrophysical sample cases

Providing not more than 0.3" over a full square degree field in the optical domain will allow to be effectively competitive with ground based and space instrumental projects at the 2012-2013 horizon. The narrow PSF will allow detecting fainter sources in reasonable exposure times, and with a resolution that will eliminate many systematic errors. It would effectively turn the CFHT as we know it today with MegaCam into an equivalent ~8m telescope when considering point source detection and be comparable, from an étendue point of view to competing projects such as PS4, Hyper-SuprimeCam or LSST. But it is the angular resolution that makes this project stand out. The characteristics of the turbulence of Mauna Kea, a very thin ground layer that allows very wide fields to be corrected by GLAO, may be unique. Taking advantage of this would enable a powerful and unrivaled instrument capable of high angular resolution wide-field surveys!

GLAO will provide images about 1 magnitude deeper per unit observing time than natural seeing, reduce confusion noise in crowded fields, and open up new science opportunities for "barely resolved" objects. Combined with a field of view of about 1 degree CFHT will have a uniquely competitive capability.

2.1. The Solar System

The steep luminosity function of the Kuiper Belt means that probing to lower flux levels will rapidly increase our statistical knowledge of its dynamical structure. Moreover, pushing past the m~27 rollover in the apparent magnitude distribution probes the ~30km size objects that are at the root of the formation and collisional evolution of the Kuiper Belt. For the giant planets, like Jupiter, a GLAO system would allow detection of many more moons, probing capture theories that constrain how the giant planets acquired their molecular-rich envelopes.

2.2. Extrasolar Planets

Planet transits are a potentially powerful discovery tool and a powerful probe of the properties of systems discovered via radial velocity techniques. The ideal instrument needs exceptional PSF stability, exceptional astrometric stability, exceptional calibration stability and the ability to work well in the dense star fields that allow these properties to be fully exploited to search for milli-magnitude brightness variations. There are estimated to be about 1 in 10,000 planetary systems that lead to 1% or deeper eclipses. Jupiter eclipsing our Sun is very close to 1% and the fainter M stars offer the prospect of detecting large terrestrial planets. CFHT-GLAO should allow detection of 0.2-0.3% eclipses over a large field.

2.3. Stellar Astrophysics

Stellar astrophysics benefits enormously from a smaller PSF and a wider field of view. The concentrated PSF of a GLAO is particularly important to allow deeper measurements with minimal confusion noise in the crowded fields of star clusters. A sharper PSF also allows for better centroiding of the stellar image yielding improved proper motion measurements, which help in isolating pure cluster samples or in the search for exotic stellar objects in the field. Proper motion surveys with GLAO on CFHT will produce cluster CMDs devoid of field stars, which will be used to age the system, explore the mass function to the limits of hydrogen burning, and yield samples of white dwarfs, which will feed larger telescope spectroscopic studies. Ancient white dwarfs, the only observable remnant of the high mass end of the pop II mass function, will also be located answering whether they are the MACHOs and providing an independent age estimate of the Galactic halo.

2.4. Galaxy Formation and Evolution

Galaxy formation and black hole growth is only just getting underway around redshift six and the universe is just becoming ionized again. Further progress requires studies of much larger areas of sky imaged with 0.2-0.3" resolution at the ~27 magnitude depth that JWST and 30m telescopes will routinely probe. The redder optical bands are crucial in this work as the photometric band "drop-out" technique is used to screen for the rare objects in the redshift ranges of interest. Also at redder wavelengths, 0.3" resolution will allow to perform a morphological galaxy survey up to redshift z~1 on very large scales and confront the predictions of galaxy evolution models from the forthcoming generation of cosmological simulations.

At lower redshift, we will be able to reconstruct the star formation histories of nearby galaxies using multi-band photometry of their resolved stellar populations. In a complex population hosting a mix of chemical abundances and ages, an accurate star formation history can be reconstructed from photometry reaching Mi = -4, which for CFHT GLAO will reach out to the Virgo Cluster.

2.5. Cosmology

Establishing a limit on the redshift variation of the dark energy "equation of state" parameter, w, with redshift is of great interest to fundamental physics. CFHT can be an important player given smaller images and better red response which will allow supernova measurements to probe the distance "crossover" around redshift 1.2. To extend lensing measurements to both higher redshifts and smaller scales means working with source plane samples with higher sky densities and higher redshift, which in turn means galaxies that are fainter and smaller than can be grasped with natural seeing. Even with JWST and 30m class telescopes it will be a huge challenge to work in the nano-Jansky (mAB ~ 31 mag) range. Strong lensing can, through magnification, raise the brightness into a much more accessible regime. To a good approximation both the numbers of lensed galaxies and the maximum magnification are inversely proportional to the angular resolution - meaning that GLAO will allow factor of 3 to 4 improvements.

3. Instrumental concept

An optical feasibility study is currently underway to explore the various possibilities. The constraints common to all are that there needs to be a deformable mirror that needs to be as close as possible to the pupil. There also needs to be a wavefront sensor with a mechanism to pick up the light of the brightest stars in the field. The camera needs the proper plate scale to adequately sample the improved PSF over a degree field of view; this will require $36\,000^2$pixels. Various locations have been considered and it appears that Prime or Cassegrain focuses are the most promising. Prime focus provides access to the widest field and the size of the optical elements required to re-image the pupil benefit from the F/3.8 input beam. Although the main difficulties for a Prime focus solution are the weight, moment and volume constraints, this option remains on the table at the level of the feasibility study. The most likely solution though, is a Cassegrain system. In this context, there are two distinct concepts: an Adaptive Secondary Mirror or a full Cassegrain AO relay. Specifics of each are described in the next sections.

3.1. Adaptive Secondary Mirror

An adaptive secondary mirror makes for a very simple optical design, and is extremely favorable in terms of throughput. The camera is placed at the direct focus after a wide field corrector, which can also serve as a focal adapter to obtain the proper plate scale on the detector. The cost of such mirrors is high and the conjugation is not ideal, since in a Cassegrain design the secondary mirror is usually conjugated to negative altitudes. The CFHT secondary mirror is located 8.6 meters above the primary, and is conjugated to -23.3m, just within H_{min}. It is also 1.5m in diameter; although this is smaller than the LBT adaptive secondary mirrors, such large mirrors are difficult to manufacture.

In this configuration, there would be no intermediate focal plane to redirect the light from the brightest stars to the wavefront sensor. While pick off mirrors on articulated arms would be able to select the light required for wavefront sensing ahead of the focus, a dichroic solution is also conceivable, wherein a beam-splitter directs the visible light to the science camera and the infrared is sent to the wavefront sensor. Measuring the wavefront at longer wavelengths than the science beam is usually detrimental to the quality of the correction, because for a given wavefront, the strength of the signal in waves or cycles is decreased. However, in a GLAO system, since each wavefront sensor is not null driven and the dominant error is the free (uncorrected) atmosphere, the signal is always large with respect to the dynamic range of the sensor. The promise of low noise, fast readout infrared arrays (e.g. Teledyne quoted $5e^-$ at 900Hz) is encouraging for such a solution.

Full simulations of infrared wavefront sensing for correction in the visible domain are underway and will be part of the final feasibility study. The Groupe d'Astrophysique de l'Université de Montréal has initiated a study into ASM and `IMAKA may be an ideal application for this development (Doyon, *private communication*).

We note in passing that an ASM would benefit every single instrument proposed in the current call for ideas for the CFHT 2012+ instrumentation plan: the SPIROU near-IR spectro-polarimeter (Donati et al., 2006 [5]) and the FIRST high dynamic range imager (Perrin et al., 2006 [10]) could use an on-axis wavefront sensor for conventional AO correction, while the SITELLE wide-field imaging FTS could use the GLAO mode of `IMAKA. Especially in the case of near-IR fiber-fed spectro-polarimetry, an AO module using an ASM would greatly increase the sensitivity of any proposed instrument!

3.2. Cassegrain Module

In the case of a full Cassegrain module, the optical system of the instrument will consist of a wide field corrector, an optical AO relay, wavefront sensing optics, and the camera optics. Just as for the ASM case, the wide field corrector must correct for the field aberrations in the telescope optics. The AO relay will form a pupil image for the deformable mirror and an output intermediate focus for picking off the light to the wavefront sensors. The camera optics will relay the AO output focus to the back focal plane.

3.2.1. AO relay

The intermediate field of view at the output of the AO relay will be used to pick off the light for wavefront sensing, presumably with small mirrors on articulated arms, or possibly with steerable micro-mirrors. The disadvantage of articulated pick-up mirrors is that some field is lost under the footprint of the arm. The larger the number of guide stars, the greater the complexity and footprint.

The micro-mirror solution is technologically more risky; as such devices have not yet been used, but would offer an elegant solution to directing only some parts of the field (those with bright stars) in the direction of the wavefront sensor(s). These beams would then be redirected via pupil steering mirrors, possibly on gimbal mounts, to the detector of the wavefront sensor(s). Here, the trade-off of how much field is lost is to be balanced by the number of segments on the micro-mirror. The fill factor of the segmented micro-mirror is an important parameter as the amount of diffracted light depends on it with direct proportionality; and even though there is a pupil plane, which can be used to mask off the diffracted light, this ultimately reduces the sensitivity of the instrument.

3.2.2. Deformable mirror

The signal of the wavefront sensor is sent through a reconstructor and the optimal correction is applied to the deformable mirror, which will be conjugated to the telescope pupil (or very close to it). The geometry of the deformable mirror may pose a challenge as the large field, small pupil and limited space may require fairly large angle on the deformable mirror, which may mean that, on top of the non-isotropy of the influence function on the DM, the opposite edges of the pupil may not be conjugated to the same altitude. Ways to mitigate this effect could be a reverse telescope arrangement (using a hole in a parabolic mirror to match the central obscuration) or an Ebert-Fastie design.

The current prescription is for a 100mm pupil on the deformable mirror, as such mirrors are available commercially. It is possible to obtain smaller mirrors, but much larger than 100mm is difficult. The stroke of the DM does not have to be very large as the system is only supposed to correct for a fraction of the turbulence.

3.3. Wavefront sensor

Whether in the full Cassegrain configuration or with the Adaptive Secondary Mirror, the wavefront sensor can integrate one of two concepts: either each guide star has its own detector, which allows for greater flexibility for the reconstruction (for example weighted averaging, tomographic reconstruction). Or, the light from each guide star is brought to a single wavefront sensor and the averaging of the wavefront is done optically before detection. The former provides more flexibility at the expense of cost and noise, while the second may be limiting in terms of reconstruction, but is both cheap and optimal with regards to noise; although we note in passing that a ground layer AO system is not as sensitive to read or photon noise as a high performance on-axis AO system.

3.4. Laser Guide Stars

In its first stage, `IMAKA is thought of as a natural guide stars system, although it is possible to envisage laser guide stars as a path to upgrade. Indeed, Raleigh guide stars are ideally suited for ground layer AO and can be much cheaper than sodium tuned lasers. However, for initial budget and complexity reasons, and because the probability of finding asterism with guide stars brighter than magnitude 12 in a degree is quite high, it seems reasonable to first concentrate on a NGS design, even though this requires movable parts to send the light of these stars to the WFS. However, if an elegant solution were available for a fixed constellation (e.g. pierced mirrors), it might be worthwhile to consider an LGS solution.

3.5. OT-CCD camera

The Orthogonal Transfer CCD (Tonry et al, 1997 [13]) provides the last step in the `IMAKA design. As will be shown in section 4, the GLAO correction is still shy of the 0.2"~0.3" image quality goal. Once the turbulence common to the entire field (i.e. the ground layer) has been removed, the next dominant term in the contribution to image degradation is the high altitude tip-tilt. This is spatially decorrelated, so it needs to be sampled across the field of view. The OT-CCD uses some of its chips to measure the local tip-tilt, and applies a correction by shifting charges in the two orthogonal directions (rows and columns) of the plane of the CCD. Besides having an ideal plate scale to cover 1 degree field of view with 0.1" sampling, a clone of the PanStarrs camera (Burke et al, 2006 [3]), the very fast read time (6 seconds for 1.4Gpix) leads to an improvement in the achievable dynamic range. If `IMAKA were to use laser guide stars (see next section), then the OT-CCD would also provide the overall (as well as the local) tip-tilt.

4. Simulations, estimated performance

Initial simulations have been performed with three independent packages to assess the level of performance. Two of these are Monte Carlo simulations, while the third is an analytical PSF model. They all confirm the level of performance of GLAO. Details of the system architecture have not yet been studied. Stitching together two independent Monte-Carlo simulations has allowed estimating the combined correction of GLAO with the OT-CCD, although it is our goal to simulate the entire system end-to-end. Sky coverage computations and semi-analytical processing of the site testing data complement the performance analysis.

4.1. Sky coverage

The sky coverage was determined by estimating the probability of finding at least *n* stars brighter than magnitude *m*:

$$P(m,>n) = 1 - \sum_{i=1}^{n} \mu(m)^i \frac{e^{-\mu(m)}}{i!}$$

where $\mu(m)$ is the mean star density of magnitude *m* from the Besançon model of star counts for a field of view of 1 degree (r=30'). Results are shown on Figure 2. There is a 50% probability of finding 6 stars of magnitude 11 or brighter within a square degree at the North galactic pole. If the wavefront sensing can be done on 12th magnitude stars, the sky coverage is effectively 100% if 6 stars are sufficient for efficient averaging of the turbulence.

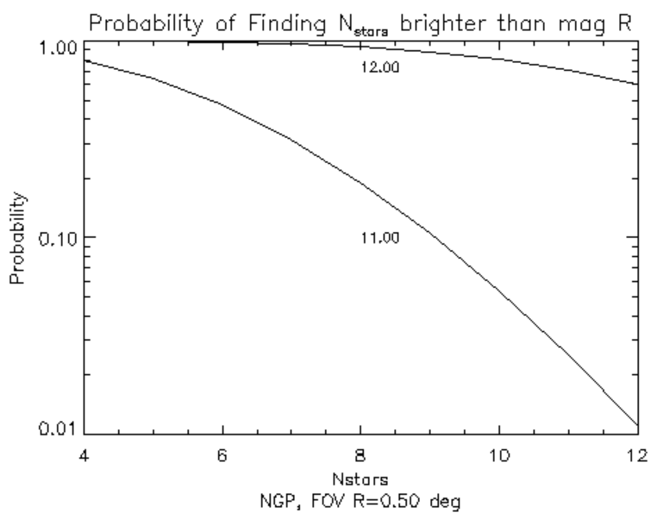

Figure 2: Estimated number of guide stars available for wavefront sensing at North Galactic pole. The probability of finding 8 stars brighter than magntiude 12 within a degree is high enough to ensure very high sky coverage.

4.2. PAOLA

PAOLA (Jolissaint & Véran, 2002 [8]) is an analytical PSF modeling tool based on Rigaut et al (1998 [11]). This software is ideal for scanning large range of parameters (such as altitude conjugation, number of actuators or guide stars) but does not treat noise (at least for the ground layer case) in a very intuitive way. Preliminary results of PAOLA with 7 guide stars are shown in Figure 3. These results show that if the ground layer is prevalent, a GLAO system is capable of significantly improving the image quality over a large field, and very smoothly at that. The exact conjugation of the deformable mirror is not critical in this case. What is not shown in this figure is that the most important parameter in these simulations is the input vertical turbulence profile; although this is understandable, it dominates the performance much more than the number of degrees of freedom or even the number of guide stars.

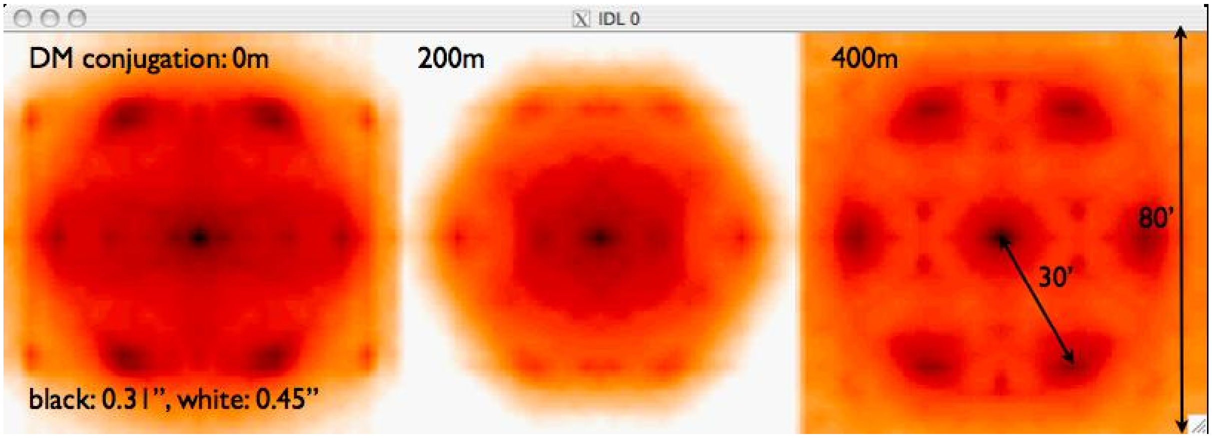

Figure 3: PAOLA simulations of a 7 guide star constellation as a function of altitude conjugation of the deformable mirror. The color scale shows the major axis FWHM.

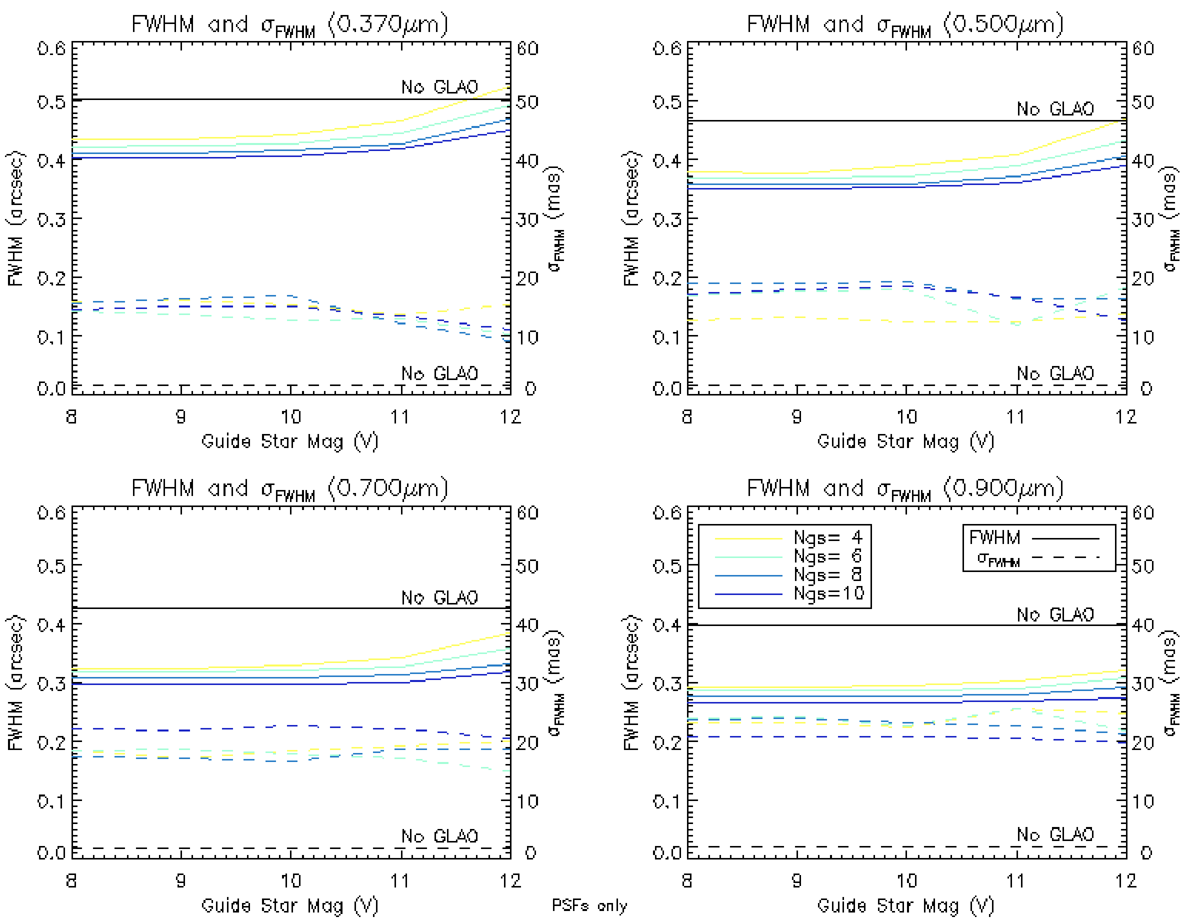

Figure 4: IDL simul GLAO performance for various guide stars in 0.5" seeing. 10x10SH with 3e- read noise.

4.3. IDL `simul.pro`

`Simul.pro` is a Monte Carlo code originally written by F.Rigaut, although the version used here has been modified by M. Chun to be able to simulate Ground Layer AO. The curves shown in Figure 4 were obtained for various guide star constellations using a 10x10 Shack-Hartman system in 0.5" seeing at different wavelengths (the dotted line shows the FWHM variation across 36 locations in the field). The read noise was 3e$^-$. Performance starts to degrade at magnitude 12, which provides good sky coverage as shown in section 4.1. These curves were obtained at constant gain, and with the loop gain is optimized (Figure 5), the GLAO system can maintain its performance down to magnitude 13 or 14.

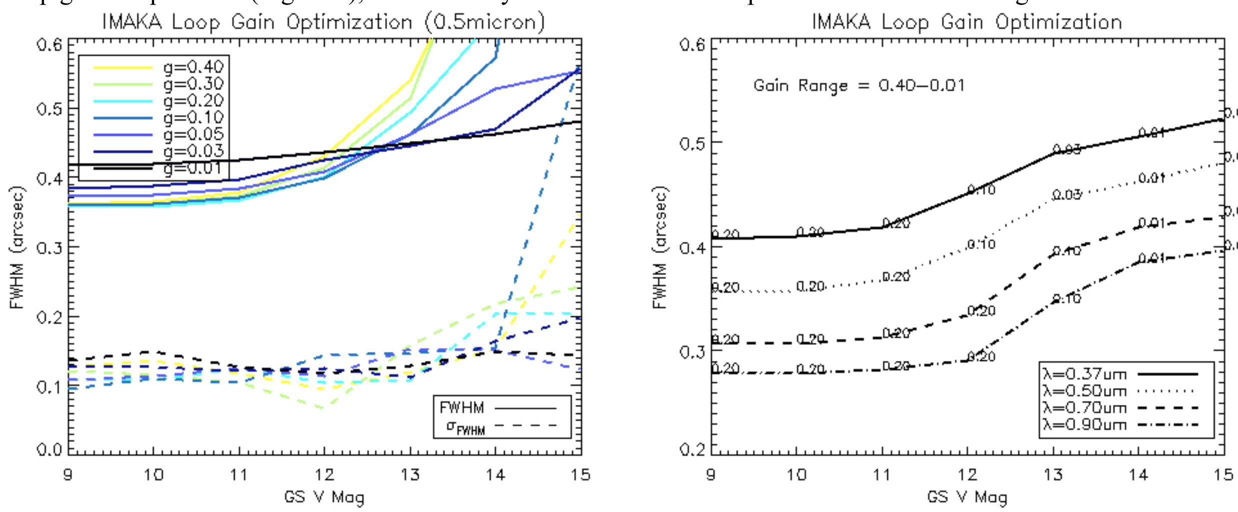

Figure 5: IDL simul GLAO loop gain optimization, showing that performance can be maintained down to magnitude 13.

4.4. YAO package

YAO is a yorick Monte Carlo simulation package developed by F. Rigaut based on the `simul.pro` code. To verify the consistency between the `simul.pro` and YAO codes, performance was estimated using the same set of parameters as those used in section 4.3 and were found to agree well (figures 4 and 6). The YAO code was then used to see if there was any gain to be had in increasing the number of subapertures (from 10x10 to 20x20) and it was found that the performance is in fact not improved by going to a higher order even in the bright guide star case. This means that in a 10x10 system, the fitting error is already smaller than the free atmosphere residual. The effect of detector noise was also simulated and it was found that decreasing the read noise from 3e$^-$ to 0.5e$^-$ significantly improves the performance, all the way down to magnitude 14 (in these simulations, the gain was kept constant and not optimized; of course if the read noise is negligible, the photon noise is averaged in the loop, so it is not as critical to optimize the loop gain).

Finally the combined effect of the GLAO module and the OT-CCD was simulated, and results are shown in Figure 7. This result was obtained in two steps: first the GLAO module was simulated. The final FWHM was then set as the starting point for an OTCCD (i.e. tip-tilt only) simulation, where the vertical turbulence profile took into account that the ground layer had been corrected. The OTCCD correction was computed on axis (i.e. in the direction of the tip-tilt guide star) and 10' away (> isokinetic patch size, presumably).

A few points are worth mentioning: in the direction of a tip-tilt star, the GLAO-only and OTCCD-only performance are comparable, although the OTCCD image quality decreases as the distance to the tip-tilt star increases (while it remains constant for GLAO). However, by combining the two techniques, it is possible to reach 0.2" to 0.3" as afar as 10' from a tip-tilt star.

Ideally in the long run, the entire system will be simulated in a single step instead of manipulating the turbulence profile at each step. The simulations will also be used to study the performance as a function of the number and position (asterims) of the guide stars, the wavelength of wavefront sensing, the number of sub-apertures and actuators on the DM. Potentially different architectures could provide superior performance for a given number of photons, but as curvature and pyramid schemes depend on the improvement of the wavefront over the entire pupil to improve the signal strength with respect to noise, the gain may be limited in the partial correction regime. The tolerance to altitude conjugation will also need to be examined especially for an ASM. The performance will not only be defined by the average FWHM but also its variation across the field (e.g. the dotted lines in figures 4, 5 & 6). Much of this work is in progress and will be part of the final feasibility study.

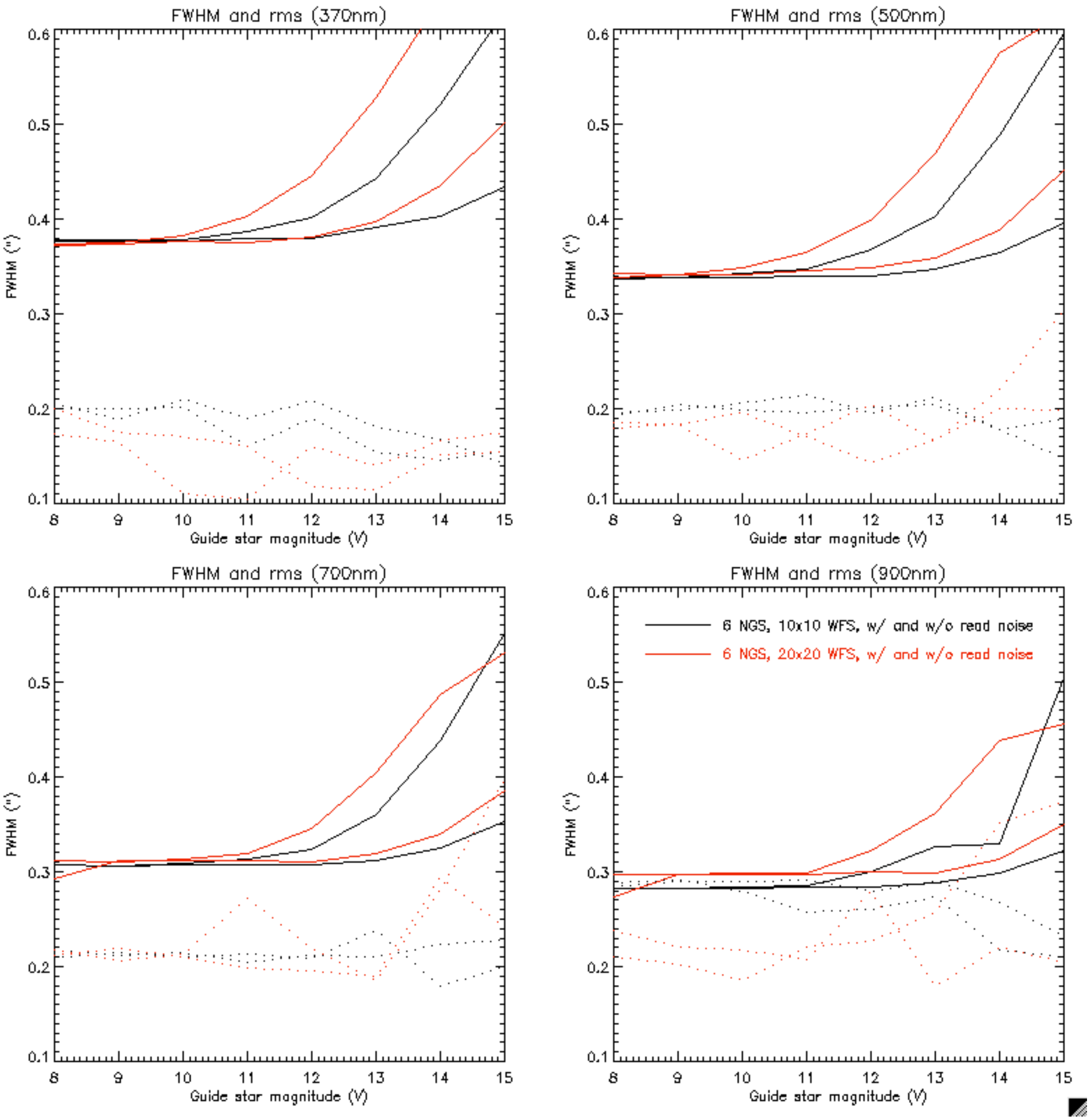

Figure 6: Yorick GLAO simulations showing the same results as Figure 4, but comparing 10x10 (black) with 20x20 (red) SH and 3e$^-$ (top curves) and 0.5e$^-$ (bottom curves) read noise.

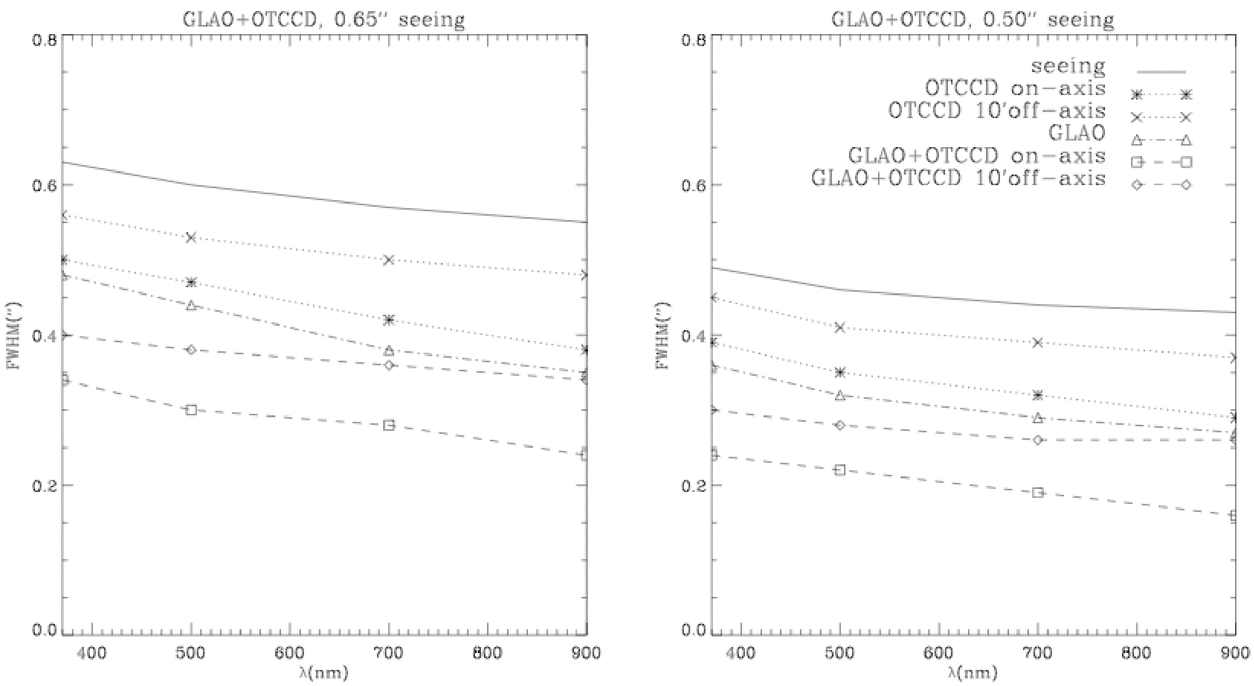

Figure 7: GLAO and OT-CCD performance as a function of wavelength. It can be seen that the OT-CCD in the direction of a guide star provides similar correction to a GLAO system, but it degrades as the distance from the tip-tilt star increases. However, the combined action of a GLAO and the OT-CCD allows us to reach <0.3" even at a distance of 10' from a tip-tilt star.

4.5. Semi-analytical computations

All the simulations above start from a median (0.65") or good (0.5") seeing estimate, but seeing is really a statistical quantity. Based on individual turbulence profiles, an estimate of the cumulative probability distribution of the seeing was computed by D. Andersen, based on the method exposed in Andersen at al. (2006 [1]): From more than 7000 vertical turbulence profiles (C_n^2) obtained early in the Gemini GLAO study, it was assumed that a perfect ground layer adaptive optics system would be able to remove all the turbulence below a certain altitude so the curves of Figure 8 show the integral of C_n^2 from 60 meters (dashed line) and 700 meters (thin line) respectively to the top of the troposphere. The bold line shows the integral of C_n^2 from the ground up.

The 50^{th} percentile of uncorrected seeing is 0.5" at R band and 0.75" in V band. As we saw in section 1, the gray zone for such a wide field is more likely on the order of 60 meters; the 50^{th} percentile of image quality achieved by an ideal GLAO system is 0.50" in V band and 0.33" in R band. However, we also see that GLAO only (that is, without the OTCCD capability) would provide 0.2" in R band and 0.3" in V band 10% of the time. Being able to correct for a 700-meter high gray zone would provide this level of performance 20% of the time.

5. Proposed experiment

To get *in situ* data of the ground layer but also the dome and telescope seeing, an atmospheric sensing experiment using the main beam of the telescope is being planned. Originally, the idea was to use a Hartmann mask that sits in the top ring with the MegaCam imager out of focus. This would have allowed obtaining snapshots of the wavefront at various locations on a 1-degree field. From this (by subtracting the average wavefront to each location), it would have been possible to deduce the performance of an ideal GLAO system. Unfortunately, the focus travel on MegaCam is not sufficient to separate the out-of-focus spots further than the FWHM due to the diffraction of the Hartmann mask holes. The possibility of implementing a g-SCIDAR experiment in our MOS instrument is now being studied instead.

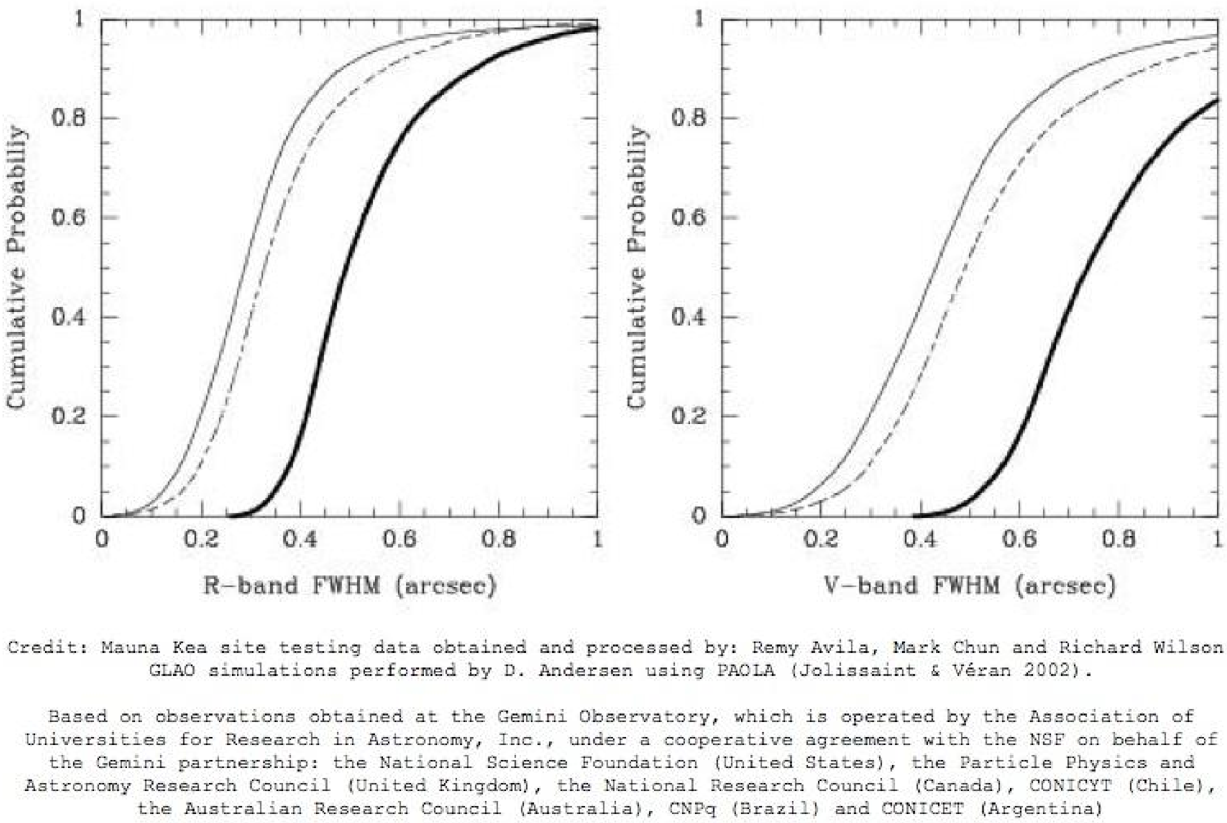

Figure 8: Cumulative seeing distribution of image quality at 700nm (left) and 500nm (right). The bold curve shows the integrated atmosphere, the dashed line is if the first 70 meters are perfectly corrected (i.e. removed from the turbulence profile) while the thin line shows the case of perfect correction of the first 600 meters of atmosphere.

6. Conclusion

`IMAKA is a very wide field ground layer AO system and camera proposed to CFHT in response to the call for ideas "CFHT Instrumentation for 2013 and beyond". It is in the feasibility study stage and answers to the following questions are currently being sought:

- What are the astrophysical applications that would uniquely benefit from improved seeing down to the 0.2"~03" level over an entire degree field-of-view and are they compelling enough to pursue such an ambitious instrument? Especially in light of the instrumental landscape at the 2012 horizon (wide field telescope such as Pan-Starrs, LSST, VISTA, HyperSuPrimeCam, "narrow" field GLAO (Gemini) and Hawk-I at ESO).
- What is the realistic level of performance that can be achieved with a GLAO system on a 4-meter telescope with such a wide field? By how much can this be improved by correcting local tilts? Answers are being sought through the use of simulations and will hopefully be confirmed by experiment.
- Is there an elegant solution to the optical design? An ASM is very attractive indeed but so far had not been considered due to cost and risk factors. However, a proposal by Université de Montréal to develop such mirrors may breathe new life in this idea. If the entire AO module is at the Cassegrain focus, is an optical design feasible and realistic?
- At this stage, there a strong preference for a natural guide star system. How will the light from various parts of the field be fed to the wavefront sensor (or sensors)? Despite added technological complexity of Rayleigh beacons, a

fixed constellation of guide stars would allow simple solutions (e.g. pierced mirror at the focal plane) to this problem.

- Can such a system be built within a reasonable cost envelope?

The deadline for the feasibility study is October 2008. Although ambitious, our strong team and collaborations makes us confident that we will be able to provide mostly positive answers to the above questions and that `IMAKA will turn out to be a unique, original and elegant niche scientific use of CFHT that will maintain its *raison d'être* well into the era of ELTs.

7. References

[1] Andersen, D., R., Stoesz, J., Morris, S., Lloyd-Hart, M., Crampton, D., Butterley, T., Ellerbroek, B., Jolissaint, L., Milton, N., M., Myers, R., Szeto, K., Tokovinin, A., Véran, J-P., Wilson, R., "Performance Modeling of a Wide-Field Ground-Layer Adaptive Optics System", PASP **118**, *1574* (2006).

[2] Avila R., Chun M.R., . "A method for high-resolution C_N^2 profiling in the first few hundred meters", Proc. SPIE **5490**, *742* (2004).

[3] Burke, B., E., Tonry, J., L., Cooper, M., J., Young, D., J., Loomis, A., H., Onaka, P., M., Luppino, G., A., "Development of the orthogonal-transfer array", Proc. SPIE **6068**, *173* (2006).

[4] Chun, M., R., Wilson, R., W., Avila, R., Butterley, T., Aviles, J-L., Weir, D., Benigni, S., "The Mauna Kea ground-layer site characterization campaign", Proc. SPIE 7015-163, *These Proceedings* (2008).

[5] Donati, J.-F., http://www.ast.obs-mip.fr/article.php3?id_article=637 (2006)

[6] Egner & Masciadri, "A G-SCIDAR for Ground-Layer Turbulence Measurements at High Vertical Resolution", PASP **119**, *1441* (2007)

[7] Jacoby, G., H., Tonry, J., L., Burke, B., E., Claver, C., F., Starr, B., M., Saha, A., Luppino, G., A., Harmer, C., F., W., "WIYN One Degree Imager (ODI)", Proc. SPIE **4836**, *217* (2002).

[8] Jolissaint, L., & Véran, J-P., "Fast computation and morphologic interpretation of the Adaptive optics point spread function", ESO Conference and Workshop Proceedings **58**, *201* (2002).

[9] Kaiser, N., "Pan-STARRS: a wide-field optical survey telescope array", Proc. SPIE **5489**, *11* (2004).

[10] Perrin, G., Lacour, S., Woillez, J., Thiébault, E., "High dynamic range imaging by pupil single-mode filtering and remapping", MNRAS **373**, *747* (2006).

[11] Rigaut, F., J., Véran, J-P., Lai, O., "Analytical model for Shack-Hartmann-based adaptive optics systems", Proc. SPIE **3353**, *1038* (1998).

[12] Tokovinin A., "Seeing Improvement with Ground-Layer Adaptive Optics", PASP **116**, *941* (2004).

[13] Tonry, J., L., Burke, B., L., Schechter, P., L., "The Orthogonal Transfer CCD", PASP **109**, *1154* (1997).

[14] Wilson R., "SLODAR: measuring optical turbulence altitude with a Shack-Hartmann wavefront sensor", MNRAS **337**, *103* (2002).