PUEO NUI: a feasible AND fast upgrade of the CFHT adaptive optics system for high dynamic range imaging.

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ABSTRACT

Rethinking the efficient use of 4m-class telescopes in the dawning era of larger facilities is a timely but challenging debate. The extensive use of PUEO for imaging (and now spectroscopy) has kept CFHT at the forefront of scientific research with adaptive optics since its commissioning in 1996. Even though larger facilities are now starting to think about ways of implementing high order AO systems, we believe the medium size of the CFHT and the excellent quality of our site on Mauna Kea is a perfect combination to reach the highest performances with a high order AO system.

The fields of application of high order adaptive optics are exciting: They include extremely high contrast imaging and coronography in the near-infrared and diffraction-limited imaging in the optical, with the corresponding gain in angular resolution. Specific science examples are described in an adjacent paper (Ménard et al, these proceedings [4839-133]), and planned instrumentation in the form of four quadrant coronagraph\textsuperscript{1} or existing dual (or triple) wavelength imagers (such as TRIDENT\textsuperscript{2}) would benefit tremendously from >90% Strehl ratios in the K band.

Simulations of a high order (104 electrodes) curvature system have been performed and produce the required performance and are presented in an adjacent paper (Lai & Craven-Bartle, [4860-28]). Technologically, the system is quite simple and re-uses most of the opto-mechanics of the existing PUEO. Deformable mirrors and real time computers are well within existing (and commercially available) specifications. An innovative solution of using a dedicated low read noise CCD camera (specifically for curvature systems) overcomes the potential cost drawbacks of using avalanche photo-diodes (APDs). This detector is described in detail in an adjacent paper (Cuillandre et al, these proceedings [4839-31]).

Keywords: adaptive optics, high dynamic range, curvature wavefront sensing

1. INTRODUCTION

With adaptive optics systems starting to produce spectacular results on 8 meter telescopes, the role of the 4 meter class telescopes has to be re-evaluated. The advantage of using an 8 meter telescope is obvious as the resolution at the diffraction limit is inversely proportional to the telescope’s diameter. However, the amount of turbulence (in other words the number of speckles, proportional to $(D/r_0)^2$) to correct is proportional to $D^2$. It follows that the number of actuators required to achieve a given level of performance also has to increase with the same proportion. This can easily be understood when one considers that, to a first approximation, the inter-actuator spacing has to remain constant with respect to $r_0$ for a given level of performance.

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1.1. Comparison to 8 meter telescopes

In the case of conventional adaptive optics, systems on 4 meter telescopes usually have between 20 and 60 degrees of freedom. In theory, the step to 8 meter telescopes would require \( \approx 200 \) actuators for the same level of performance. In practice, however, it is not a trivial task, and most AO systems on very large telescopes have to overcome difficulties such as increased noise propagation and sensitivity to alignment, as well as mirror seeing and vibrations related to the complexity of such large instruments. Nonetheless, spectacular results are starting to appear from such systems, as amply demonstrated elsewhere in this conference. The fact that such systems usually fall short of their expected performance can usually be explained by the fact that they are still in their infancy and pushing the limits of what can be achieved. However, François Roddier\(^3\) defined an AO system’s efficiency as the ratio of the effective number of corrected "modes" to the actual number of actuators. Applying this efficiency criterion to real AO systems empirically shows that systems with a large number of degrees of freedom tend to have unduly low efficiencies. If this is indeed a real trend, the road to high dynamic range systems on large telescopes may prove harder than originally envisaged.

The new field of high dynamic range imaging requires very high Strehl ratios to obtain stable PSFs with a large fraction of coherent energy, that can be removed or cancelled with the use of techniques such as deconvolution, phase\(^1\) or Lyot coronagraphy or multi-channel imagers.\(^2\) Large telescopes have an intrinsic \( D^2 \) advantage in detectivity over smaller ones (as shown in figure 1), due to the smaller and therefore higher peak of the PSF with respect to the diffraction halo. This implies that at equal Strehl ratio, very large telescopes do indeed have a detectivity advantage. However, this is only true in the photon noise limit. It turns out that even on small telescopes with low (\( \approx 70\% \)) Strehl ratios, the fundamental detection limit is never photon noise but speckle noise.\(^4, 5\) And the number of residual speckles can only get worse on larger telescopes!

The way that high order systems affects the PSF in the focal plane is illustrated in figure 1. A comparison of two different AO systems (a low order one with an inter-actuator distance \( l_{act_1} \), and a high order one, with \( l_{act_2} < l_{act_1} \)) on a telescope of a given diameter \( D \) is shown on the top row. The left diagram shows that the Strehl produced by the high order system, \( S_2 \) is greater than \( S_1 \). Because the energy (the integral) of both PSFs must be the same, the (incoherent) energy is transferred from the seeing halo into the (coherent) core. A plateau appears on the PSF at the level of the PSF at \( \lambda / l_{act_1,2} \), which means that spatial scales smaller than \( l_{act} \) are not corrected. The simulation on the right uses a simple PSF model\(^6\) for PUEO (thin black line) and PUEO NUI (thick grey line), while the uncorrected PSF is shown for comparison (thick black line). The strong ringing of the monochromatic PSF somewhat hides the plateau, although it can be seen in the dark rings. At distances greater than \( \lambda / l_{act_1,2} \) from the core, the corrected PSF follows the uncorrected PSF and the AO system provides no gain in dynamic range with respect to the seeing limited case (on unresolved objects, because any underlying point-like companion will be sharpened).

The middle row illustrates the effect of different telescopes (having diameters \( D_2 > D_1 \)) with the same inter-actuator distance, that is, to a first approximation, providing the same level of correction, the same residual error and hence the same Strehl ratio. Note that the gain with the larger telescope \( (D_2) \) is not with respect to the seeing/diffraction halo, but due to the peak of an unresolved object \( S_2 \) which is \( (D_2/D_1)^2 \) higher than \( S_1 \) for the same inter-actuator distance \( l_{act} \). The diagram on the left illustrates that the level of the plateau is fixed with respect to the halo and that the plateau is the same for both telescopes. The gain occurs in the range \( \lambda / D_1 < r < \lambda / D_2 \) and with respect to the peak of the PSF. The simulation on the right compares PUEO (thin black line) with an equivalent system on an 8 meter telescope (thick grey line), with the seeing limited PSF (thick black line) shown for comparison.

The bottom row illustrates the gain of going to PUEO NUI when compared to existing AO systems on 8 meter telescope (left) and compared to high dynamic range on 8 meter telescopes (right). The comparison of PUEO NUI (thin black line) with existing AO systems on 8 meter telescopes (thick grey line) shows that the gain in detectivity will be mostly in the range \( \lambda / l_{act_1} < r < \lambda / l_{act_2} \), or between 0.2 and 1.\(^6\) However, in that range, the simulations show that the \( D^2 \) advantage will be negated by the level of the PSF plateau, which will be lower than the uncorrected PSF on the larger telescope. When high dynamic range systems will be available on 8 meter telescopes, the comparison shown on the right shows that, again, the gain only occurs in the range \( \lambda / D_1 < r < \lambda / D_2 \) and with respect to the peak of the PSF.
Same telescope, different inter-actuator distance
1: Low order system
2: High order system

Different telescopes (D1<D2), same inter-actuator distance (Lact).

\[ \frac{S_2}{S_1} = \left( \frac{D_2}{D_1} \right)^2 \]

Figure 1. High dynamic range PSF schematics and examples. See text for explanation.
1.2. Advantage of 4 meter telescope

The number of residual speckles after adaptive correction at a given Strehl ratio (or at a residual phase error or to a first approximation at a given inter-actuator spacing) will be proportional to $D^2$. In the case of high dynamic range imaging, we have seen that a larger telescope is at an advantage (figure 1, middle and bottom rows, right), but this is only true in the case of the photon noise limit. In reality, most systems are (and will be) limited by speckle noise. Furthermore, the $D^2$ advantage of larger telescopes is only valid for equal Strehl ratios (as shown on figure 1, bottom row, left), which means that a high dynamic range system on a 4 meter telescope will compare favorably in terms of detectivity in the halo to a conventional AO system on an 8 meter telescope with Strehl ratios almost twice as high.

Of course high dynamic range AO systems on large telescopes (for example the CfAO's eXao$^7,8$ system or ESO's Planet Finder$^9$) will reduce this advantage but will require up to $10^4$ actuators. Such systems rely on new technologies and are some years away from producing astrophysical results. They will also be complex systems, with a very targeted range of scientific applications. As we show in section 4, the PUEO NUI upgrade does not require new technologies, would be reliable and cheap and could be rapid in its implementation. This means that it would concentrate on the astrophysical exploitation and results rather than the technology required to obtain these results. However, the experience gained with such a system would certainly benefit the second generation high dynamic range systems for 8 meter telescopes.

1.2.1. Scintillation

Because PUEO NUI is a curvature system, its subapertures would be larger than a Shack Hartman system providing the same level of correction. They would be approximately 30 cm across compared to 10 cm subapertures for equivalent performance with a Shack Hartman. Scintillation becomes important$^{10}$ when the height of the turbulent layer, $h$ is less than $\rho^2/\lambda$, where $\rho$ is the scale of the turbulence one is trying to correct (in our case our subaperture size) and $\lambda$ is the wavelength. Assuming a turbulent layer 6km above the telescope for the Mauna Kea site, and a wavefront sensing wavelength of 700nm, the scale at which scintillation errors start to become the dominant source of error on the wavefront measurement, $\rho$ is $\approx 6$cm. Scintillation has been studied as a source of degradation of image quality on high order AO systems$^{11,12}$, and as a first approximation, it produces a halo with a FWHM on the order of $\lambda/\rho$. The solutions to overcome its effects appear complex and cumbersome. Fortunately, in the case of PUEO NUI, $l_{act} \gg \rho$ and we do not have to be too concerned about the effects of scintillation on the image quality. However, this effect will have to be further studied and resolved when $l_{act} \approx \rho$.

1.3. Laser guide star

Another advantage of building a high dynamic range AO system on a smaller telescope is that it could make more effective use of a Laser Guide Star (LGS) to increase the realm of scientific application considerably. There are two reasons for this, both related to the purely geometrical aspect of LGS. The first is related to the fact that the spot elongation will be much smaller on a 4 meter than an 8 meter telescope. Furthermore, with the large CFHT secondary mirror, there would almost certainly be enough room for a launch telescope in the center of the pupil, further decreasing the spot elongation. At least this large central obscuration, which is detrimental to high dynamic range imaging, would serve a useful purpose: providing the perfect location for the launch telescope! The second reason why a Laser Guide Star would be more effective on a smaller telescope is, of course, the cone effect: Let us define the subaperture decorrelation altitude as the altitude at which the subapertures at the edge of the pupil have shifted by one full subaperture between the cone of the laser and the cylinder of the object at infinity (see figure 2). This geometrical altitude is by no means profoundly significant but approximately indicates up to which height above the telescope the full aperture can be corrected by the system.

The degradation of the PSF due to the cone effect in the hypothetical case of a perfect correction on the common area (between the cone and the cylinder) would be a fairly sharp increase of the phase structure function at the largest spatial scales (low spatial frequencies), leading to an increase in the FWHM, a smoothing of the corrected halo, and of course a lowering of the Strehl ratio. Because the high spatial frequencies (small spatial scales) are still fairly well corrected (there is a large fraction of the pupil, close to the center where the
decorrelation is very small), the flat plateau of the corrected PSF remains. An empirical model demonstrates this effect in figure 2. In reality, two other effects may alter this simple explanation fairly drastically: the first is that most telescopes have large central obstructions which will lead to a decrease of the correction of the high spatial frequencies, as most of the very well corrected small spatial scales would occur in the center of the pupil. The second is that the cone effect would affect some modes more than others (e.g. spherical aberration would be less well measured than say, tip or tilt) and would also increase the amount of aliasing present in the system (coma in the cylinder would be seen as tip in the cone). It is very difficult to say exactly what the effect will be without detailed simulations, because the low spatial frequencies are also the ones that have the largest isoplanatic angles, i.e. the largest spatial correlations in the atmosphere. It is therefore necessary to perform these simulations to correctly assess the impact of the cone effect on a high dynamic range system.

![Diagram](image)

**Figure 2.** Left: The cone effect is less critical on a small telescope and with larger subapertures, because the subaperture decorrelation altitude H is higher and a larger vertical fraction of the atmosphere is corrected by the AO system. Middle: The full line represents the MTF of a full pupil telescope, and the thick (black) line the MTF of the atmosphere. The dashed line is the MTF of a PUEO NUI like system with a 90% Strehl ratio, while the thick grey line is a basic model of subaperture decorrelation. Right: Effect on the PSF; as can be seen the reduction of the high frequencies in the MTF reduces the Strehl ratio, smoothes the PSF’s airy rings and increases the FWHM as well as the average level in the region of interest (0.2” < r < 1.0”).

Referring to figure 2, it is easy to compute the subaperture decorrelation altitude. It is given by:

\[
H_d = \frac{l_{a,ct} \times H_{sodium}}{D}
\]

(1)

The decorrelation altitude is therefore higher for smaller telescopes and larger subapertures. A numerical example illustrates that on an 8 meter telescope (using a Shack-Hartman,\textsuperscript{7-9} which implies subapertures on the order of 10 cm), the correction of the outer ring will be good up to approximately 1.1km above the telescope, assuming a sodium layer altitude of 90km. With PUEO NUI, the subapertures are 30cm across, and the decorrelation altitude becomes 7.5km above the telescope. On a site such as Mauna Kea, this actually would be higher than the tropopause. It should be noted that the decorrelation altitude of PUEO NUI is even higher than those of planned or existing systems on 8 meter apertures with 50cm subapertures.

There are two comments concerning this simple calculation. The first one is that the subaperture decorrelation altitude is not necessarily a completely meaningful parameter when comparing a curvature with a Shack-Hartman system. It could indeed be argued that the larger subapertures of a curvature system are also more decorrelated than the smaller subapertures of a Shack–Hartman system, thereby making the true decorrelation altitude of a curvature system somewhat lower. This will need to be demonstrated in further simulations (see Lai & Craven–Bartle, \textit{A4860-28}). The second point is the fact that the limiting magnitude to achieve such a high dynamic range (see figure 6) will require a laser much more powerful than what is currently available.
However, due to the very strong effort currently going into solid state lasers for the needs of multi-conjugate adaptive optics, a laser that would fulfill our requirements may become available within the next five years.

2. SIMULATIONS

Simulations performed to investigate the behavior of curvature adaptive optics with high numbers of degrees of freedom\textsuperscript{13} were the starting point for the proposed PUEO NUI upgrade. The code used was François Rigaut’s IDL \texttt{simul.pro} code. The concept that motivated the simulations was the fact that the outer sub-apertures have different scaling laws (due to aliasing) than the inner ones.\textsuperscript{14} The natural suggestion was to increase the number of edge sub-aperture/electrodes. However, because the radial edge derivative is a null measurement, its signal to noise ratio decreases as the signal decreases, which means that in closed loop the number of photons detected on the outer ring of subapertures (and hence the SNR of the modes strongly dependent on those) is very low. This prompted the opposite approach of decreasing the number of subapertures in the outer ring to increase the area of each and reduce the number of system modes that were highly dependent on the outer ring and therefore very noisy in closed loop.

2.1. Parameters and conditions used

As a validation test of our simulation protocol, we modeled the current PUEO configuration and compared to real AOB observations, with the same environmental parameters used in the PUEO NUI simulations ($r_0(0.5\mu m)=12$ cm, same wind speed, etc.). The simulations produced a Strehl ratio of 43\% in K-band. Referring to Fig. 5 of Rigaut et al. (1998)\textsuperscript{15}, this is very similar to the performance delivered by PUEO in these conditions. This is shown on figure 3.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{Left: Confirmation that the simulation parameters (atmosphere, wind speed, etc) reproduce experimental data for PUEO-19. Right: subaperture/electrode configuration for PUEO-NUI with 104 electrodes.}
\end{figure}

In all the simulations, the following telescope and atmospheric parameters were used. The telescope is a 3.6 meter telescope with a large central obstruction (42.1\%), such as CFHT at F/8. Also, a realistic $D/r_0$ was used, as opposed to the so-called Mauna Kea median seeing. $D/r_0$ was set to 20 at 700nm. This is equivalent to 12 cm in the V-band, or to an 0.8\" seeing. The turbulence was split into two dominant layers, one at high altitude, 10km, having a speed of 25 m/s, and a second at ground level and moving at 10 m/s.

Different systems were tried, but with a design goal of a Strehl ratio > 90\% in K band, a 104 element system running at 2kHz was selected (see Lai & Craven-Bartle, AS4800-28). The subaperture configuration is 8, 16, 24, 32, and 24 electrodes per ring, from the inside out, as shown on figure 3.
Figure 4. The table shows the performance of an upgraded PUEO with 104 degrees of freedom at 2kHz under 0.86" seeing. The figure shows the PSFs obtained in simulations. The top row shows the perfect theoretical PSFs of the CFHT in the K-, I-, R- and V- bands. The bottom row shows the simulated PSFs in the corresponding bands with Strehl ratios of 0.92, 0.58, 0.43 and 0.21 respectively. These values correspond to the performance of the 104-electrode configuration. All figures are plotted with a logarithmic stretch.

2.2. Results

As a reminder, the results of the simulations of the PUEO NUI system are given in figure 4, illustrating the high level of performance. An advantage of systems with high Strehl ratios, that is often overlooked, is the exquisite PSF stability they provide. For an average Strehl ratio of 43% in K, the Strehl fluctuations of the current PUEO are ±14% (i.e., the instantaneous Strehl ratio varies between 20% and 60%). The 104-element system described above, at 92% Strehl ratio, sees its PSF vary by only ±2%. In case of good seeing, when the Strehl increases to 96%, these variations decrease further, to only ±1.5% (See Fig. 5). This means that PSF calibration, so critical for coronography, for deconvolution and for PSF subtraction, will actually become not only possible, but accurate!

Figure 5. The Stability of Strehl ratios. The lower curve shows the instantaneous Strehl ratio during a 4-second simulation of the current PUEO under nominal conditions. The upper curve shows the stability of a 104-element upgraded PUEO under the same conditions, but for 2 seconds only, due to heavier CPU requirements for the more complex system.

Figure 6. Comparison of Strehl for PUEO-19 with PUEO NUI as a function of magnitude. The faint end of the curves match as expected from theoretical arguments. See text for explanation.
2.2.1. Limiting and maximum performance Magnitudes

On first approximation, an upgraded PUEO system using modal control would maintain the level of performances on faint targets. It would however provide a significant gain when using a bright guide star (R<12). Fig.6 presents a comparison of the K-band Strehl ratio delivered by the current and by an upgraded PUEO as a function of guide star brightness. The faint end of the curves match as expected from theoretical arguments. The 104 system’s performance keeps increasing until about magnitude 8 where maximum performance is achieved. However, the simulated PUEO-19 curve is shifted by 1.5 magnitudes with respect to reality (the simulations are overly optimistic with respect to the actual throughput of PUEO) and so one may expect that the true maximum performance magnitude of PUEO NUI will be closer to 7. However, a better lenslet array and the Fly-Eyes detector may help to reach the simulated performance.

The key issue to remember is that an upgraded PUEO would not degrade the current capabilities of PUEO. For similar performances, similar sky coverage will be achieved. Performance would only keep increasing on stars brighter than R=12. The sky coverage in that case must be lower! But there are a number of targeted problems that can be addressed whose solutions have long been awaited for.

3. SCIENCE CASES

A compelling science case is emerging. Many fields of high dynamic range astronomy have already been started by PUEO, from solar system physics to Galactic astronomy. An upgraded PUEO would give CFHT a resolution at 600μm that would rival Keck’s, Gemini’s, and VLTI’s at 2μm. Observations in the optical will benefit from lower sky background and higher quantum efficiency, lower read-noise detectors than in the near-infrared. But in the near-infrared, the new PUEO would successfully challenge HST / NICMOS. It would produce images with better angular resolution and comparable Strehl ratios (actually better at K). The NICMOS cameras NIC1 and NIC2, have a field-of-view of only 11" and 19.2" respectively, with NIC2 being undersampled. KIR’s corrected field-of-view behind PUEO is larger by a significant amount.

Here, we present an rapid overview of some of the scientific potential of PUEO NUI. For a more detailed review of the possibilities, see the adjacent paper: Ménard et al, these proceedings [4839-132].

3.1. Solar system

3.1.1. Asteroids

There are several distinct dynamical populations of asteroids, each of which has likely had a different collisional history and likely may have different compositions and structures. Study using adaptive optics has focused so far on the main belt asteroids.16–20 But there are other populations, the near-Earth asteroids (NEA) (of particular interest in learning about the hazards they pose to Earth and how to mitigate it), the Trojans (at the Lagrangian points of Jupiter), the Trans-Neptunian objects (TNO) or the Kuiper Belt objects (KBO). The problem is that these other populations are both faint and will have small primary/secondary angular separations. However, as recently demonstrated21, there are many occurrences of KBOs passing sufficiently close to bright guide stars to make such observations possible on a nightly basis.

A new AO system such as proposed here would make a tremendous difference in the search for asteroid satellites, as both higher resolution and high dynamic range are the main goals of this upgrade. Many bodies in the Asteroid Main Belt could be resolved by CFHT. The linear resolution , for an asteroid at 1AU, is about 30km at K and 10km at R. The largest Asteroids are already resolved by PUEO (e.g. 216 Kleopatra19). Better resolution would allow to resolve a larger sample and better constrain their morphological parameters, namely their shape, spin, and mineralogical features at the surface. Indeed, a very stable PSF would allow to detect very weak and localized changes in their surface albedo. Near-Earth Asteroids (NEAs) could also be resolved and studied with resolutions better than 100m for the closer ones, also allowing the same studies. Solving these issues is important to understand the formation of these bodies, their dynamical history, and the history and evolution of our solar system.
3.1.2. Planets and their satellites

The higher image quality will permit the detection and study of fainter satellites of the main planets. PUEO in K-band was able to detect Puck and Portia, two faint (V ~ 21) satellites of Uranus\textsuperscript{22}. Also, planetary atmospheric features are observable from the ground on Neptune\textsuperscript{23-25}. Better images and more monitoring would permit to detect and better define the orbital parameters of many of these faint satellites. Finer details in the atmosphere of Titan, the volcanoes on Io, the structure of rings and arcs, the clouds on Neptune and Uranus but also on smaller satellites, never studied before for lack of resolution, could be detected and monitored by an upgraded PUEO.

3.2. The mass-luminosity relation of low-mass stars and brown dwarfs

The IMF, the mass distribution of stars, is a fundamental indicator of the content of our Galaxy. A good knowledge of this distribution is mandatory if one hopes to understand star formation on galactic scales. The IMF is fairly well known for solar-like or more massive stars\textsuperscript{26}. However, the lower main-sequence and the substellar part of this distribution remain poorly known, both observationally and theoretically. Unfortunately, that’s where most of the stars/bodies are found, at least in young open clusters like the Pleiades\textsuperscript{27}.

The best way to accurately estimate the mass of a star is to resolve the orbits in binary systems, knowing both the radial velocity and the visual orbital parameters. Spectacular advances have been made in recent years, partly based on work with PUEO, and masses can now be estimated to an accuracy of ~0.5-1% for the best cases\textsuperscript{28,29}. But the road to a full characterization of the mass-luminosity relation, down to planetary sized bodies, is still long.

An upgraded PUEO would allow to find fainter objects closer to the bright star because of improved contrast and finer PSF. Low-mass objects are intrinsically very red and observations in the optical are not optimal, but the gain in resolution would allow to follow the orbits of closer systems at critical points in their orbits, hence increase the size of the sample. There are more than 1000 nearby bright stars that need to be looked at!

3.3. The evolution and dissipation of accretion disks

3.3.1. Gas and dust disks around Pre-main sequence stars

Our understanding of the planet formation process will benefit from better observations of accretion disks around young stars as they evolve toward the main sequence.

HST observations of HD 141569 give a perfect example of what can be expected from the gain in resolution by going to shorter wavelengths. Coronographic images of the disk surrounding the Herbig Ae star HD 141569 were obtained at 1.6 µm with HST/NICMOS\textsuperscript{30} in 1999 and at 0.7 microns with HST/STIS\textsuperscript{31} in 2001. The NIR image shows the presence of the dust disk around the star, and clear suggestions of asymmetry. However, the scattering cross section of the dust located the disk is almost 10 times larger at 700nm than it is at 2.2 microns. This fact, coupled to a diffraction-limited PSF that is 10 times finer (in surface) allows us to probe the dust disk of HD 141569 with unprecedented details in the visible domain. An upgraded PUEO on the CFHT would provide a gain of another factor of 2 in resolution, without the dramatic PSF artefacts seen in the HST images.

3.4. The more speculative extrasolar planet detection

About 70 hot and massive (Jupiter-like) planets are now known to orbit solar-like stars. However, the search as only begun recently and there is no doubt that, as the time span increases and the sensitivity of the instruments improves, lighter Earth-like planets will be discovered around very nearby stars.

The planets known today are all orbiting their parent stars at distances less than a few AU. See for example fig. 7. This is no doubt a selection effect, a direct consequence of the increased detectability of massive and rapidly orbiting objects. Nevertheless, it is important to realize that these planets are located around relatively nearby stars and, in the most favorable cases, are separated visually by half an arcsecond or more from their parent star (e.g. Eps Eri b). Angular resolution is therefore not the limiting factor to ”resolve” the planet from the central star. It is the glare from the central star itself that drowns the signal of the planet and forbids its direct detection... so far!
Figure 7. Orbital plot of newly discovered Jupiter-like planets compared to the Sun-Earth system. The images shows that orbits larger than 1AU are often found. These could be easily resolved by CFHT if located at d < 10pc. In this volume, there are several hundreds of stars that can be looked at for planets with adaptive optics. Image courtesy of Stéphane Udry, Observatoire de Genève, Switzerland.

The interest of a higher order AO system to look for extrasolar planets lies in the progressive suppression of the unwanted seeing halo. Figure 8 shows radial cuts of PSFs in K and R bands. In the K-band, the increase in dynamic range provided by an upgrade PUEO is maximum for small separations. It is about a factor of 10 between 0.3″ and 0.7″. The more stable PSF of an upgraded PUEO (see Fig. 8) also means that coronographs can be used efficiently, further increasing the dynamic range achievable. In the R-band, the gain is about 1000 everywhere with respect to the current PUEO!

4. TECHNICAL IMPLEMENTATION

One of the reasons that makes PUEO NUI so compelling is because of the fact that the opto-mechanical bench can be re-used and much of the instrumentation already exists. This means that the upgrade can be relatively cheap, quick and completed with minimal risk. This system does not necessarily depend on new technology, but could also be used as a test bench for advanced subsystems such as new algorithms (e.g., predictors or compensators). Because the main goal of the upgrade is to produce astrophysical results, the reliability of the existing system should be maintained and the complexity kept to a minimum. This will be easily achieved as this system has fewer degrees of freedom than most AO systems on large telescopes.

The main difficulty, namely the price, delivery time and fragility of APDs as a detector will be avoided by using the new CCID-35 detector, known as the Fly-Eyes project.

4.1. Fly-Eyes

Ordinary CCDs are not well suited as detectors for curvature wavefront sensors. The reason is that the detector must be read out at each cycle of the membrane mirror, to obtain the flux from the intra- and extra-focal images separately. Because the read noise of a CCD increases with with the read speed, each measurement would be read noise limited and averaging many would not increase the Signal-to-Noise ratio on the curvature signal.

The principle of the new CCD for curvature wavefront sensing (CCID-35) is to store away the charge collected during the intra- and extra-focal periods on two distinct storage areas on the chip. This way, the storage areas can be read out only when a new curvature signal needs to be calculated. This chip shifts the intra- and extra-focal photoelectrons in each super pixel between the sensor area and the charge storage areas on either side of the sensor area. The CCD is then read out relatively slowly while the next integration can start on the chip. In this way, a read noise of two electrons RMS with a read-out delay of 250 μm can be achieved.
Simulations of the effect of such a detector in an AO system have been performed for ESO's MACAO system\textsuperscript{33}, and the loss in performance due to the read noise and read-out delay is found to be negligible. Note however that this comparison was done between APDs with a quantum efficiency of 80\% (the CCID-35 has a QE of \(-90\%\)), while the current APDs used on PUEO have a QE of 40\%. Therefore the new detector may actually improve the performance of the upgraded AO system at faint magnitudes!

4.2. Deformable mirror

There is no major difficulty in building a 104 electrode bimorph mirror. The only constraint is that the size of the pupil and the amount of room available for the deformable mirror are imposed by the pre-existing optical set-up. The size of the pupil in PUEO is 46 mm and this implies that the only parameter that will be available to increase the stroke will be the thickness of the DM. This, in turn, may affect the lowest resonant frequencies, but preliminary discussions with potential manufacturers seem to indicate that this should not be a problem.

4.3. Real Time Computer

The upgrade of the RTC is under consideration. The requirements are not out of reach, but will require careful attention: a 104x104 matrix multiplication will need to be done at 2 kHz. This means the delay due to computation only will have to be shorter than 500\(\mu\)s. For comparison, Altair\textsuperscript{34} requires the latency for the 136x200 matrix multiplication to be less than 400 \(\mu\)s.

Unfortunately, the raw computing power may not be the only issue. The data transfer rate over the VME bus may be too slow with the current PUEO architecture. Both the Laboratoire d’Astrophysique de l’Observatoire de Grenoble in France and the Hertzberg Institute for Astronomy in Canada have expressed an interest in pursuing these technical issues.

4.4. Lenslet array

The lenslet array will most likely be a complex optical piece. Losses are likely to occur in this part of the optical path. The light has to be focused onto the core of multimode fibers so that the circular geometry of the wavefront sensor can be matched to the super pixels of the detector. The manufacture of the lenslet array itself may not be that problematic as the technique (developed by Laplacian Optics) of cutting lenses and gluing them together as a lenslet array should still be applicable to the 104 geometry. However, the accurate positioning of the fibers at the focus of the lenses may be the difficult part.

4.5. Upgrade plan

A plan for the upgrade has been devised with the goals of minimizing the amount of down time of the CFHT adaptive optics system, allowing the use of as many of the existing sub-system as possible, and reducing the risk factor.

- The first step will be the fabrication and testing of Fly-Eyes, for direct comparison with the APDs on the 19 element system.
- The upgrade of the Real Time Computer hardware of the final system can then be implemented.
- A laboratory set-up using the Fly-Eyes, the new lenslet array and deformable mirror and the real time computers could be tested at this stage.
- With PUEO off the telescope, the deformable mirror would be replaced, and the new lenslet array installed. The real time code would be tested in a controlled laboratory setting, as was done with PUEO 19.
- The telescope integration is the last step, but the user experience of PUEO-19 will be invaluable in speeding up and streamlining this process.

We expect that the down time of PUEO could be less than one year. Once PUEO NUI would be operational, the possibility of a Laser Guide Star for the CFHT should be seriously considered, as it would open the field of extra-galactic astrophysics to this high contrast instrument.
5. CONCLUSION

There are many benefits from a high order adaptive optics upgrade to CFHT’s PUEO.

- Deep diffraction-limited imaging in the optical would be possible with CFHT from the ground. PSF Stability and improved contrast in the near-infrared would rival larger telescopes on specific problems, including faint object detection, and possibly extrasolar planet if located around very nearby stars.
- The possibility to develop PUEO NUI on a very short time scale and with a low budget means that it would allow to reap the benefits of high dynamic range imaging well before larger telescopes that will face many years of technological development.
- Coronographic and nulling techniques\(^1,2\) require high and stable Strehl ratios to deliver their full rejection performances. CFHT would be the the best place on Earth where they could be exploited fully. PSF Engineering could also be attempted (i.e. produce a dark - destructive - region, where a faint companion is suspected).
- Experience with extremely high order AO will be acquired. Many of the complex control issues surrounding these advanced systems that we will master will necessarily be used later to efficiently design the instrumentation that will equip the extremely large telescopes currently under consideration.
- A Laser Guide Star may open up new science cases (exciting extra-galactic science around quasars would become possible) and would be an exclusive niche for a smaller telescope. The power requirements of such a laser are beyond our current technological reach but may be available in the near future, thanks to the development required for MCAO.
- Feed more signal into the fiber link to OHANA\(^3\) . CFHT would then provide flux to the interferometer at a level much more comparable to that of KECK or Gemini, reducing the loss of contrast due to unequal aperture sizes, and therefore improving the interferometer’s detection limit.

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REFERENCES


