Pueo Nui: an upgrade for Pueo

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1 Rationale

Pueo is currently the most scientifically productive adaptive optics (AO) system. If we look to refereed astronomical journals, and consider the scientific publications based on AO observations, we find that more and more of these publications are based on Pueo results. In 1998, 36% of them were made with Pueo. In 1999, 10 out of 20 came from Pueo that is 50%. This remarkable achievement is due to the ability of Pueo to work with faint guide stars (up to at least mag 15), an ability shared only by Hokupa’a, the UH visitor instrument and only other currently operational curvature AO system.

However, Pueo has only 19 actuators which compensate the equivalent of 8 Zernike modes. For comparison, the next two most scientifically productive systems compensate the equivalent of 14 modes (Adonis) and 19 modes (Hokupa’a). Because of its moderate compensation capability, the use of Pueo is limited to the near infrared. By comparison, when operated on the CFHT, a 36-actuator system such as Hokupa’a produces the largest image improvement in the I band ($\approx 0.9 \mu m$). Upgrading Pueo to 36-actuators would extend its capability toward shorter wavelengths well into the range of CCD detectors.

Another desirable characteristics of an AO system is its ability to use extended objects as guide sources. Currently, the field-of-view of the wavefront sensor in Pueo is limited to 3 arcseconds. This is a serious limitation. For instance, Pueo has problems guiding on Neptune and cannot guide on Uranus. It has also problems guiding on some non-stellar sources such as galaxy cores or small planetary nebulae. Artifacts are likely to appear when it is not guiding properly. A drawback of a larger field of view is the increase of the sky background contribution when guiding on a faint source. However,
this drawback can easily be overcome by using an iris as a field stop. The iris could automatically close down to a preset value once the loop is closed.

Finally an AO system should produce a clean point spread function (PSF). Fig. 1 shows a deep image of a binary star recorded with Pueo. It reveals a pattern in the PSF wings with a six-fold symmetry. Such patterns are detrimental to the detection of faint companions. They are thought to be produced by the deformable mirror. Since Pueo was built, important advances have been made in the fabrication of bimorph mirrors. As demonstrated with Hokupa’a, such patterns can now be avoided. An upgrade of Pueo (hereafter called Pueo Nui) would also benefit from these advances.

2 Could Pueo Nui be competitive?

Since Pueo came in operation in 1996, larger telescopes have been equipped with AO systems. These are the 5-m Palomar telescope and one of the 10-m Keck telescopes. Last June, the 8-m Gemini North telescope produced its first images with Hokupa’a. The second 10-m Keck telescope, and the Japanese 8-m Subaru telescope will also be soon equipped with AO. The four European 8-m VLTs will quickly follow. Could Pueo Nui be competitive in front of such instruments?

Surprisingly it could. This is because of a fundamental limitation of AO. The larger the telescope, the more modes an AO system must correct. To produce the same image quality at the same wavelength, the number of compensated modes must grow as the square of the telescope diameter. For instance to produce the same image quality as Hokupa’a on the CFHT, the Keck AO system would have to compensate 150 Zernike modes. Currently, it is one of the most powerful AO system ever built. However, it compensates only the equivalent of 35 to 40 modes, which falls short by a factor of almost 4. Because the technology does not exist, it is unlikely that a more powerful AO system will be built in a near future.

The consequence is that AO systems on large telescopes are bound to operate at long wavelengths, in the near-thermal infrared (H and K bands). At these wavelengths, they will outperform Pueo Nui because they will produce sharper images and/or use fainter guide sources. At shorter wavelengths, they will not perform as well. In the visible, they will not substantially improve CCD images. If the same systems were installed on the CFHT, they would perform only slightly better than the current Pueo system in the
near-thermal infrared, but they would considerably extend the capability of Pueo toward shorter wavelengths all the way down to the visible (at least for bright sources). In this region, they would produce images with an angular resolution comparable to that achieved on much larger telescopes in the near thermal infrared. They would therefore produce an information very complementary to that obtained on large telescopes, which can only be obtained with a smaller telescope like the CFHT. This is a very important reason to upgrade Pueo. Equipped with a 36-actuator Pueo Nui system, the CFHT would be the only ground-based telescope able to compete seriously with the Hubble Space Telescope (HST), assuming that the cryo-cooled NICMOS camera works as expected starting in 2001. Advantages of Peo Nui will be a smaller pixel size (35 mas versus 43 mas for HST/NICMOS), a larger field of view (36” x 36” versus 11” x 11” for HST/NICMOS), the flexibility to use any type of filter, and the availability of observing time.

Another reason to upgrade Pueo has to do with the optical quality of the CFHT. An important application of AO is the study of the circumstellar environment. Using the central bright star as a guide source, one looks for faint companions (possibly brown dwarfs or large gaseous planets), or circumstellar dust (disks or dust shells) in the near environment. In this case light scattered from the central star is the main limitation, and the optical quality of the telescope becomes essential. Another example is the detection of Neptune’s dark satellites and the arcs on the Adams ring (Nature, vol. 400, p. 731) which was made possible by the CFHT high optical quality. Only the lowest aberrations are compensated by AO. Small scale defects in the wave front remain uncompensated and scatter light at larger distances were one wants to observe (typically of the order of one arcsecond). Light scattered by the atmosphere is quickly smoothed in a long exposure, but light scattered by the telescope produce speckles which are often unstable and very difficult to calibrate out. Fig. 2 shows an example of PSF produced in the H band by Hokupa’a on the CFHT. To date, no other AO-equipped telescope has yet produced such a clean PSF. This is because all the larger telescopes have a lower optical quality than the CFHT. Discontinuities between the Keck segments is an important source of scattered light. The primary mirror figure is a limitation for the Palomar 5-m telescope, and may also be a limitation for Subaru. The light weight secondary mirror of Gemini is its main limitation. If it were equipped with a high order AO system, the CFHT would remain the best telescope to detect faint stellar companions.

A third reason to upgrade Pueo is the availability of telescope time on
the CFHT. With the improved resolution provided by AO, more and more objects which showed no significant time evolution on a large scale are found to evolve with time and need to be monitored. Because of the competition for telescope time, this will be better done on smaller telescopes especially if they can achieve the same angular resolution as larger ones by observing at shorter wavelengths, that is if they are equipped with a sufficiently powerful AO system. An area where AO has been highly productive is the study of our own solar system. Fig. 3 shows an infrared image of Neptune obtained with Hokupa’a on the CFHT. Image quality is comparable if not better than that of Neptune’s HST images obtained in the same wavelength range, allowing the details of Neptune’s atmospheric activity to be monitored from the ground for the first time. Because ground-based monitoring is a very important complement to space missions, NASA has provided funding for a 36-actuator Hokupa’a-type system on the IRTF which has only a 3-m primary. Both Canadian and French planetary observers would highly benefit from an upgraded Pueo system on the CFHT.

3 Feasibility and cost

Rebuilding Pueo entirely would be costly and require considerable efforts. One should seek a solution which preserves Pueo’s main optical and mechanical components. Fortunately, such a solution exists. Given its size the deformable mirror of Pueo can easily be replaced by a mirror of the same size but with more electrodes printed on it. The technology is available at the Institute for Astronomy (IfA), where a custom made mirror could easily be fabricated according to specifications. Moreover, progress in mirror fabrication and mirror support would allow the IfA to deliver a mirror with a higher compensation efficiency and a better optical quality (avoiding artifacts such as shown in Fig. 1). Because of the small size of the lenslet array, upgrading the wave-front sensor may appear more difficult. However, a 36-element compact lenslet array of nearly the same size has been recently fabricated at the IfA for the IRTF AO system. Hence again, upgrading the current lenslet array to 36 lenslets is not a problem. Both the deformable mirror (with its associated high voltage amplifiers) and the lenslet array (with its optical fiber outputs) could be obtained either directly through an agreement with the IfA, or simply purchased through Laplacian Optics. The avalanche photodiodes (APDs) could be purchased directly from EGG or through Laplacian
Optics. Only software modifications would have to be made by the CFHT Corporation.

Regarding cost, one can only give an approximate estimate here. Based on the experience of the IfA AO group, one can estimate the cost of the above components in the $200 to 250 K range including the APDs but not the software upgrade. We believe that the low cost of this proposal makes it particularly attractive. It relies heavily on technology developments made at the IfA, and there is a unique chance to take opportunity of it. However, it is important to realize that this possibility may not last for ever. There is now a very good chance that Laplacian Optics will evolved toward a company more oriented toward commercial applications of adaptive optics (eye vision and optical communications), in which case the "know how" will no longer be available at the IfA.

4 Expected performance and applications

In the following we assume that Pueo has been upgraded to a 36-actuator system and we estimate its performance. It can be easily predicted from data recorded at the CFHT f/35 focus with the UH 36-actuator Hokupa‘a system, and is summarized in Fig. 4. The gain in Strehl ratio is particularly important at short wavelengths. Under median seeing conditions, it is by a factor 1.7 in the J band and by a factor 2.7 in the I band. Note that there is no degradation in the limiting magnitude as one would expect from a sensor purely limited by photon shot noise.

Regarding the potential applications of Pueo Nui, they will be best advocated by the current users of Pueo. We will give here only two examples. One is the application of Pueo Nui to planetary science. As noted above, the NASA IRTF is currently being equipped with a 36-actuator curvature AO system. This will give US astronomers a definite advantage over the CFHT planetary observers. Pueo Nui will easily outperform the ESO Adonis system and provide a competitive tool to the French planetary community. The benefits to planetary science are both an important increase in image contrast allowing the observer to detect finer details on the surface of asteroids and planetary satellites or finer structures in planetary atmospheres and rings, and the ability to observe these objects at shorter wavelengths. An example of planetary application is shown in Fig. 3.

The other example is the study of AGNs, quasars and starburst galax-
ies. Apart from improved correction on bright objects and at shorter wavelengths (which in itself would be sufficient to warrant such an upgrade), it is expected that the number of observable sources with substantial image quality improvement will also increase, even though the absolute limiting magnitude will not. This is illustrated on Fig. 5 which shows the number of AGNs as a function of their V magnitude. This curve is extracted from the Véron&Véron–Cetty catalogue, and even though details may vary, it gives a fair approximation. Super-imposed on this curve are Strehl ratio vs. magnitude plots for a 19 and a 36 elements system for the J band (at K band, we should obtain similar curves with higher absolute values of Strehl). The dashed horizontal line at a value of $\simeq 30\%$ approximately indicates the diffraction limit. It can therefore be seen that the number of extragalactic objects for which diffraction limited imaging becomes possible increases dramatically. Coupled with instruments such as OASIS and GRiF, this upgrade would become a very powerful and unique tool in the study of the close environment of AGNs and quasars.