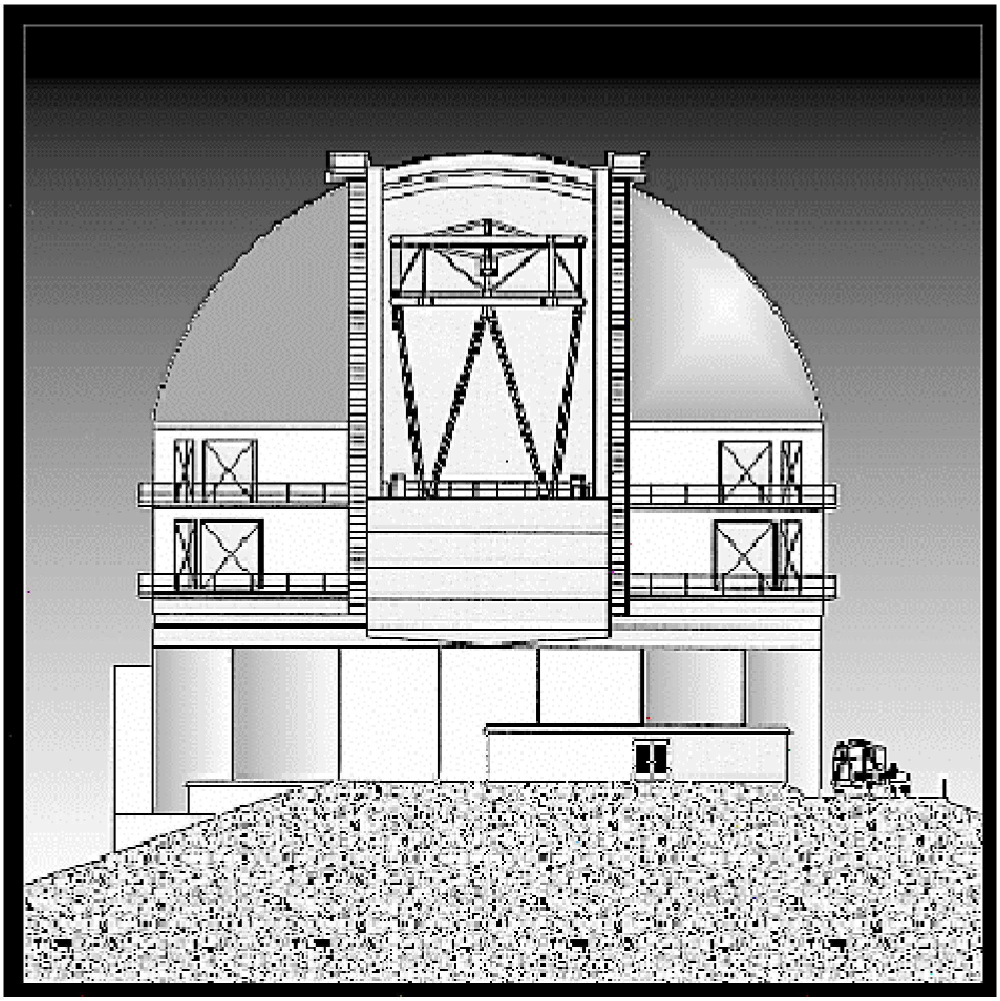
GEMINI
8-M Telescopes
Project

RPT-I-G0056

Adaptive Optics for the Gemini Telescopes: A Recommendation



M.J. Northcott, F.Roddier (Institute for Astronomy, University of Hawaii)
F. Rigaut (CFHT Waimea Hawaii)

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GEMINI PROJECT OFFICE 950 N. Cherry Ave. Tucson, Arizona 85719
Phone: (520) 318-8545 Fax: (520) 318-8590

1 Introduction.

The purpose of this document is to argue that for their initial AO implementation the Gemini telescopes should aim for a simple and robust system, rather than for leading edge system. Since a curvature based AO system combines excellent robustness with mechanical and operational simplicity, we believe that such a system would be a good choice for the first generation Gemini AO system.

In our view it would be wise to generate a broad base of enthusiasm for AO amongst the astronomical community by providing a simple general purpose system with modest capability but high availability and usability. The existence of such a system at the beginning of the Gemini commissioning should create a positive attitude to AO which will facilitate the upgrade to a more capable system. Conversely, if Gemini were to pursue the development a higher risk but higher capability system from the outset, there is a very real possibility that operational and performance difficulties with commensurate low availability would ensure that AO remains a minority interest in the astronomical community.

2 Results from operating AO systems.

One of the prime difficulties of designing a user AO system is predicting the likely performance of the various systems. This difficulty arises because the field of AO is very young, particularly if one is thinking in terms of building user instruments. This means that one must rely almost completely upon the results of computer simulations to predict AO performance. The main difficulty then, is in deciding how well the computer models will apply to real systems. Unfortunately the availability of only a small number of engineering prototypes makes this extrapolation problematical. Data from those systems which do exist tend to indicate that a fair degree of caution is needed in order to extrapolate the computer modeling results.

In terms of direct applicability to the Gemini AO system there are probably only four working AO systems of relevance, these are the SOR, COME-ON, Lick, and UH AO systems. We have included only results which are based upon closed loop exposures of 10s or longer, since shorter exposures may bias results to a large degree. We have therefore not included the results from Lick (1], since their published performance results are based upon 1 second closed loop exposures. A summary of the results published by these three systems is given in Table 1.

The characterization of AO performance from measured results is extremely difficult, see Appendix A, so the errors in Table 1 must necessarily be large, there is also some added uncertainty in deriving the system efficiencies from the published data. However even with these uncertainties, Table 1 tends to indicate that higher order systems are not performing as well as should be expected. With the exception of SOR II, all of the systems appear to be giving approximately the same level of absolute correction of 9-10 Zernikes. Since higher order systems are in general more sensitive to all sources of error this should not be surprising.

Some of the short-fall in performance may certainly be blamed upon lack of correction bandwidth, but this does not appear to account for all of the discrepancy. Note that detector noise is not an issue for these results, which were all obtained on bright natural guide stars. It is probable that developers of each system are continuing to fix problems which detract from system performance. However it is difficult at this point to predict how rapidly these systems can be improved.

System	Reference	N_{free}	D/r_o	Eff.	N_z	BW	Static	Remarks
Come-on	OSA 92 [2]	19	6.8	45%	9	50	0.2 µm cor	
Come-on	OSA 92 [2]	19	6.8	30%	6	50	0.2 µm uncor	
Come-on+	SPIE 94 [3]	52	6.8	17%	10	50	?	
SOR GenI	JOSA 11 4[]	149	9.4	5%	9	65	?	NGS
SOR GenII	JOSA 11 [4]	241	8.3	8%	21	130	?	NGS
UH	SPIE 94 [5]	13	4.3	70%	9.5	> 100	0.15 µm cor	
UH	SPIE 94 [5]	13	4.3	44%	6	> 100	0.15 µm uncor	

Table 1: *Estimated system efficiencies for various real AO systems, derived from published performance figures. The N_{free} column indicates the number of actuators or degrees of freedom in the AO system. D/r_o indicates the seeing conditions under which the measurements were made. An estimate of the equivalent number of Zernikes corrected by the system is shown in column Nz, and the estimated system bandwidth (3dB closed loop) in the "BW" column. The "Eff" column contains the estimated system efficiency, defined as the number of corrected Karhunen Loève divided by N_{free}. Finally the column "Static" indicates, if known how much of a static aberration was found in the imaging system, and if it was uncorrected or corrected.*

2.1 Low order versus high order.

While the theoretical reasons for preferring high order AO correction are well understood, table 1 would tend to indicate that we may not in practice be able to realize the full potential of a high order systems. In contrast we note that the lower order systems, particularly the UH curvature system are giving results which are much closer the those predicted by theory. We note that the 13 to 19 element systems on a 4m telescope, translate to around 50 to 75 elements on a 8m telescope.

We see no obvious reason why high order AO systems with high efficiency cannot be built, but note that no such system has yet been demonstrated. It follows therefore, that if a relatively high order AO system is chosen for Gemini first light, it would to some extent be an experimental system, and might suffer a considerable performance shortfall. Given the better relative performance of lower order systems, particularly the curvature systems it would be possible to design a first light AO instrument for Gemini with very low associated risk, capable of delivering close to its theoretical performance.

3 System robustness.

Any AO system at an astronomical facility needs to be robust, by which we mean:

- Mechanical and electrical reliability: The system must be mechanically and electrically reliable, and need only a small amount of routine maintenance. Preferably the system would never fail in operation due to a mechanical or electrical fault.
- Operational robustness. The system should be able to cope with a wide range of seeing conditions and guide object morphologies. Since seeing can vary greatly during the course of a night, adapting to various seeing conditions should be as easy as possible.
- Ease of use. The system should present a simple user interface, easily controlled by a telescope operator, or even a visiting astronomer. Acquiring a guide object should be simple and fast. Once locked on an object the system should never lose lock.
- Good sky coverage. The first AO system should be usable for as many types of objects as possible, in order to acquaint as many astronomers as possible with the use of AO. This argues for a system which emphasizes faint guide star performance over ultimate high light level performance.

For general purpose an instrument which is going to be available during commissioning, these attributes are even more important. For a more specialized instrument, targeted at a smaller audience, some compromises in these requirements are obviously acceptable.

3.1 Mechanical and electrical reliability

In order to achieve mechanical and electrical reliability, a system should be designed to be as simple as possible. This means using off-the-shelf components where ever possible, and limiting the number of system degrees of freedom to the absolute minimum needed to meet specifications.

The curvature AO system meets these goals by maximizing system efficiency, and therefore minimizing the number of degrees of freedom needed. This in turn simplifies the control system sufficiently that it can be implemented with a small number of off-the-shelf single board computers. The curvature wavefront sensor is constructed from individual APD's which are easily replaced in case of failure. The bimorph mirror has a very simple structure with only a small number of electrical connections. At the UH we have had no bimorph mirror failures after the initial burn-in period of several hours of use (at full voltage). Bimorph mirrors can be constructed fairly inexpensively, so it is realistic to keep at least one spare mirror at the telescope. Finally the curvature AO system suffers a graceful loss in performance as one or more actuator channels are lost, since discontinuities occur only in the wavefront curvature.

3.2 Operational robustness.

Whilst AO cannot be expect to give excellent performance under all seeing conditions, the AO system should continue to give the best possible correction under a wide range of seeing conditions. It would also be advantageous if the AO system could sharpen images using extended guide sources.

Optimization of a curvature AO system design is to first order independent of the seeing parameter at which optimization is performed. The extra-focal distance used in a curvature AO wavefront sensor, is approximately inversely proportional to r_o. If this condition is fulfilled, the curvature signal level is first order independent of r_o, and can be maintained in the WFS linear region. Due to this r_o independence a curvature AO system can maintain approximately the same level of system efficiency independent of the seeing conditions.

In contrast, to optimize the SNR of a SH system for a given D/r_o, one must select the SH lenslet array to maximize the tilt signal for each sensor, whilst ensuring that adjacent sensors do not interfere with each other (causing non-linearity). This is a particularly delicate adjustment when using only 4 CCD pixels per SH sensor. Once this lenslet array is specified for a particular D/r_o, a decrease in r_o will increase the likelihood that adjacent detectors interfere, leading to a decline in compensation efficiency, and a loss in robustness. On the other hand, when the seeing improves, the full dynamic range of the SH sensor is not being used, which leads to a decrease in SNR, and thus a decrease in limiting magnitude relative to a curvature system.

By using a membrane mirror to switch between extra-focal planes in the curvature WFS, the system linearity region is easily tunable in real time. We have shown in the Laboratory that it is possible to change the extra-focal distance at bandwidths up to 100Hz, far in excess of that needed to follow atmospheric r_o variations.

3.2.1 Extended objects.

We have shown at the telescope that a curvature system can operate using extended sources as guide stars. Examples of objects used are Io (3"), Frosty Leo 1", and the center of M31 0.5". This also implies of course that a curvature system would have no difficulty working with a laser guide star, assumed to be about 1" in diameter. The size of the guide object for curvature sensing is limited either by the size of the field stop or the dynamic range of the detectors.

Item	Upper bound on cost	Lower bound on Cost	Probable cost
Bimorph	50	15	25
Amplifiers	60	20	30
APD's	240	60	180
Lenslet	50	15	25
Computer	50	to	25
Software	25	0	0
Spares	100	20	45
Misc	80	10	30
Total	655	150	360

Table 2: *Estimates cost for a 36 actuator curvature system, with High and Low bounds.*

3.3 Ease of Use.

It is easy to underestimate the importance of ease of use for an adaptive optics system. If for instance object acquisition is a difficult and time consuming task, many astronomers will choose to work without AO rather than risk losing their hard-won observation time attempting to obtain AO lock. Similarly if the system is unreliable, or looses lock to often, astronomers may chose not to risk using it. The controls to optimize AO performance need to be simple and easy to understand, since the system will mostly be used by people who have no interest in learning about the intricacies of AO.

Since at the UH we are forced to operate under astronomical observatory conditions, of small amounts of observing time at 6 month intervals, we have taken grate care to ensure that curvature AO has minimal setup time, and behaves robustly when locked. By using a large extra-focal distance in the WFS we can make the WFS linear over the entire field of view (defined by the WFS field stop), we can then run the ao system at low gain to acquire the object, progressively increasing the gain and WFS sensitivity as the object is centered on the WFS.

By continually tuning the WFS extra-focal distance in response to r,, changes, (can be done automatically) one can maintain a curvature WFS in its linear regime, and reduce the chances of loss of servo-lock.

3.4 Sky coverage.

For a general purpose AO system the overriding concern must be for sky coverage. In the absence of Laser guide stars, this mandates prioritizing faint guide star performance more highly than the ultimate bright guide star performance. By choosing to emphasize faint guide star performance one ensures that instruments designed to use AO are usable at reduced efficiency for a large proportion of objects. The alternative is to restrict instruments designed to use AO, to a much smaller set of targets, al-be-it at slightly higher performance.

The curvature AO system addresses the need to use faint guide stars by using an APD WFS, and thus eliminating CCD read noise from the system. The price paid for this, is a restriction to lower order systems, and hence a reduction in bright guide star performance.

4 Cost

If the system that is initially available on Gemini, is not the finally envisaged high order laser guide star system, how does it fit in with that final goal. There are basically two approaches here, the first is to design a system which is upgradeable to Laser guide stars, thus preserving some of the investment. The second approach is to make the initial system inexpensive enough that it can simply be retired when obsolete. The first approach is probably not tenable, given the rapid advance of technology, and the considerably more demanding requirements of a laser guide star system. Luckily the curvature system falls into the second category. We have included a rough cost estimates of a 36 actuator Curvature AO system, not including custom control software and assembly costs. The estimate assumes that the relay optics would be common to all systems.

5 Conclusion.

It appears from the simulations carried out for the Gemini AO working group, that when designed for a single r_o a SH system using a realistic WFS, performs similarly to an equivalent curvature system at moderate light levels. If a zero read noise WFS is used for the SH system, it will perform slightly better than the curvature system. However the relative performance of the curvature system is to first order independent of the seeing parameter, which means that as we move away from the design r_o the curvature system will probably out-perform even the zero read noise SH system.

Results from real AO systems seem to show that there is a discrepancy between the theoretical and actual performance of AO systems, which is particularly noticeable for higher order systems. Of all the results from real AO systems, the curvature results seem to be closest to the appropriate theoretical expectations.

The curvature system offers many practical benefits, such as increased reliability (due to reduced component count), excellent robustness, and ease of use.

We would recommend that the Gemini project consider a low order curvature based AO instrument as a first generation AO system. This system could later be upgraded to a higher order curvature or SH system. The low order curvature AO system would be inexpensive, robust, easy to use and widely applicable. We think it would be the best system to generate enthusiasm amongst astronomers for more capable, but more expensive and/or specialized AO systems.

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A Measuring AO performance at the Telescope.

Measuring AO performance at the telescope is extremely difficult. Even a relatively simple operation such as measuring a Strehl ratio is difficult, since it relies upon accurate background subtraction. One is apt to overestimate the Strehl due to under-estimating the total energy in the PSF. Unfortunately it turns out that most of the errors that can be made in measuring AO performance, lead one to over-estimate the quality of correction. In this appendix we list some of the problems which plague AO efficiency measurements.

A.1 Exposure time.

In computer simulations where atmospheric statistics are rigorously stationary, a 1 second data-set will give reasonable statistical accuracy on the expected Strehl. However with real atmospheric data, a 1 second exposure may be totally inadequate. We find at MKO, even with 30 second exposures, the Strehl ratios vary on the order of 10% or more. With 1 second exposures, the variability is closer to a factor of 2. Since one always tends to pick the better images as representing the correctly operating AO system, performance estimates using short exposure images, tend to quite badly over-estimate performance.

A.2 Averaging Strehl Ratios.

As illustrated in Figure 1, the average of short exposure Strehl, is not the Strehl of the long exposure image. In fact the average of Short exposure Strehls always over-estimates the long exposure Strehl. This is because the operation implicitly corrects any residual tilt error (and some higher order residuals). As illustrated by Figure 1, the discrepancy can be quite large. For real measurements where short time scale atmospheric stationarity is not guaranteed the discrepancy can be even more dramatic.

The basic problem here, is that the instantaneous Strehl is always measured by comparing the brightest image pixel with the total PSF power. The correct way to do the computation would be to use value of the central pixel to determine the Strehl. Obviously for a real system, determining which pixel is the central pixel, presents its own difficulties.

Since no real object tracker works by centering up the brightest pixel, there would still be a discrepancy between these two measurements, even with "perfect" tilt correction based on a real sensor, for example a quad cell.

A.3 Telescope Aberrations.

Static telescope aberrations, or slow tracking error/wind shake, tend to be easily corrected by AO, but lead one to over-estimate the FWHM of the seeing profile. This again leads to over-estimation of system performance. Characterizing the telescope aberrations is very difficult, especially since they tend to vary with sky position.

There is however a rather simple procedure for correcting for the telescope static aberrations. That is when taking long exposure uncorrected images, an average drive vector (for say the last 30 seconds of AO operation) should be applied the adaptive mirror. This drive vector will correct telescope static aberrations. At the UH we have implemented procedure as an automatic part of our control system. When seeing is good, the apparent improvement in performance that is obtained by not correcting the telescope for the reference images can be dramatic. In fact it is rather easy to obtain performance measurements which are substantially better than theoretically possible by failing to take this into account.

It is much more difficult to deal with telescope tracking errors. The method we use at the UH is to close the tip-tilt AO loop at very low bandwidth (a few tenths of a Hz) when taking long exposure reference images. Even with this precaution one has to be particularly careful to avoid

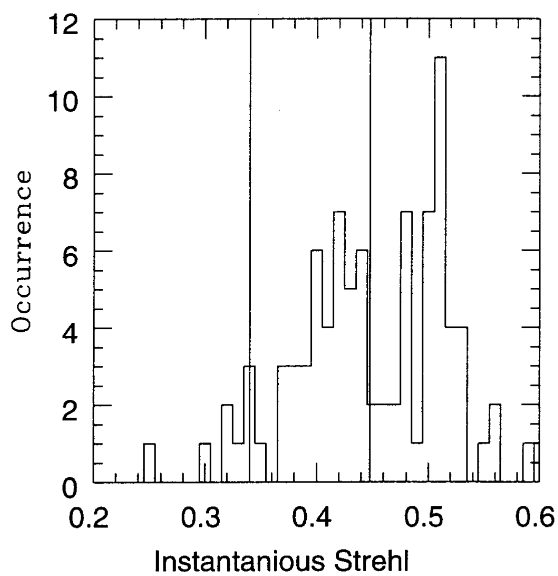

Figure 1: *Comparison of short exposure Strehl, to long exposure Strehl, for a simulation of a 56 actuator curvature system with a 106th magnitude guide star. The left vertical line is the Strehl of the mean image, the right vertical line is the mean of the Strehl of the short exposure images. This simulation was carried out using Breni's atmospheric simulation, with rigorously stationary statistics. We used the same atmospheric conditions as used in the Gemini AO evaluation (r_o = 25cm at 0.55μ m, 20m/s wind, 7.9m aperture).*

excessive wind-shake when measuring AO performance.

A.4 Imaging train aberrations.

Aberrations in the AO imaging train, is one of the few problems that can reduce the apparent performance of an AO system. This is particularly a problem when systems must be used with existing astronomical instruments, which are usually not constructed to the optical tolerance required by AO corrected imaging. Measurement and correction for these effects is quite difficult, which is why we include both the corrected and uncorrected Strehls in table 1, we think the performance is close to the corrected value, but it can be no worse than the uncorrected value.