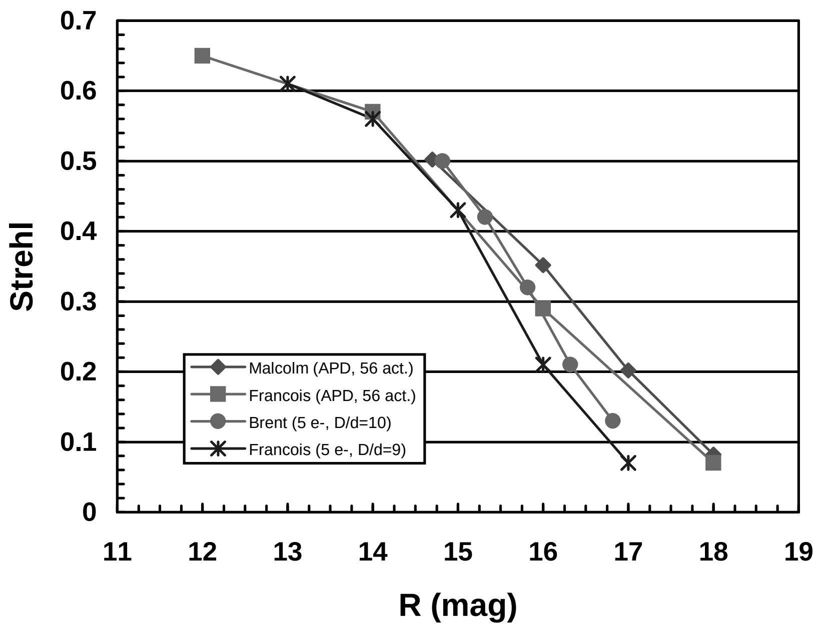
Comparison of Adaptive Optics Technologies for Gemini



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SUMMARY REPORT FOR A COMPARISON OF ADAPTIVE OPTICS TECHNOLOGIES ON GEMINI

Brent Ellerbroek - "Adaptive Optics Magnitude Limits for Gemini with a Shack-Hartmann Wavefront Sensor and a Zonal Deformable Mirror"
Malcolm Northcott - "Adaptive Optics Simulations"
Francois Rigaut - "Gemini Adaptive Optics System Simulations"
Doug Simons - Summary Report

OVERVIEW

Gemini is entering a key phase of the design process for its adaptive optics unit with the selection of a wavefront sensor technology. Since there are a number of technologies that might be used, selecting one that delivers the necessary scientific performance must first be done through models. Accordingly the IGPO organized a theoretical comparison of curvature WFS's (hereafter CWFS) and Shack-Hartmann WFS's (hereafter S-HWFS) on Gemini as the first step in the selection process for the WFS used in the Gemini AO module. Accordingly, three individuals were approached to develop models. Brent Ellerbroek (Starfire Optical Range) and Francois Rigaut (CFHT) agreed to assess the performance of a stack actuated mirror (SAM) + S-HWFS system. Brent has considerable expertise in both theoretical modeling and practical use of S-HWFS's at SOR while Francois worked on the COME-ON S-HWFS AO system as part of his doctoral thesis and has also developed analysis software for such devices. Malcolm Northcott (IfA) and Francois agreed to model CWFS's on Gemini. In this case, Malcolm has extensive practical and theoretical experience with the curvature system developed by the Roddier group at University of Hawaii, while Francois has extensively modeled the performance of the CFHT AO system, which is based on a curvature sensor.

From the outset of the modeling process it was decided to constrain designs to those already demonstrated as functional in the field. The combination of a SAM and S-HWFS has been in use at the Starfire Optical Range for several years. More recently the combination of a bimorph deformable mirror and a CWFS has been demonstrated quite successfully by the Roddier group through astronomical observations at CFHT and UKIRT. CFHT has selected this technology for their Adaptive Optics Bonnette, PUEO, and Subaru is considering it for their facility AO system. Though considerable expertise has been developed in both of these WFS arenas, it has been difficult to confidently identify which one offers the best performance when used with an 8 m telescope from models developed to date. The following series of reports describes the results of Gemini AO models. The primary purpose for this summary report is provide background information for this study and simplify comparing the results of all of the models by overlaying plots of predicted strehl as a function of guide star brightness. Please refer to the individual reports for detailed explanations of the models. Note that, for reference, the latest version of the Gemini adaptive optics science requirements is listed in Appendix A of this summary report.

GUIDELINES FOR MODEL DEVELOPMENT

In order to establish a fair performance comparison a number of “ground rules” were adopted between Rene Racine, Glen Herriot, the IGPO, and the modelers. These rules are as follows:

- Brent & Francois model SAM + S-HWFS
- Malcolm & Francois model Bimorph + CWFS
- Make designs practical in terms of implementation - do not construct designs based upon "future/poorly defined" technology
- Each person selects optimal WFS/DM geometries, creates optimal reconstructors, and selects simple/realistic servo models, based upon the practical constraints of APDs and CCDs
- Use natural guide stars, on-axis, with the telescope pointed at zenith
- Use r_0 = 0.25 m at 0.55 µm (median Mauna Kea conditions)
- Sky brightness = 20.3 mag/arcsec^2 (dark sky, Mauna Kea, zenith)
- 0 mag star at R yields 8.2×10^{11} photons/sec for Gemini entrance pupil
- Adopt a total system throughput at R along the WFS path of 50%
- WFS’s operate at a single wavelength of 0.7 µm (expect a small performance change if monochromatic models are extrapolated to broad band performance)
- For CCD detectors, read noise = 5 e^- and the maximum read-rate is 1 Mpix/sec
- For APD detectors, read noise = 0 e^- and 0 latency
- Phase sheets involve a single turbulence layer with a wind speed of 20 m/s
- Identical phase screen files were used by all modelers
- Telescope pupil is 7.9 m OD and 1.2 m ID

These guide lines were judged to allow the participants in the modeling adequate freedom to explore parameter space while emphasizing that this is not a purely academic exercise, i.e., all models must be capable of being built without radical advances in current technology. Implicit with the ground rules is the decision that the modelers, not the design reviewers, are best suited to determine what is practical to build. Having Francois run independent models for both the SAM + S-HWFS and bimorph + CWFS is obviously useful for cross checking the results of the other two modelers. The issue of off-axis performance was deliberately not explored in an effort to keep the amount of free parameters down to a manageable number (all models were run on-axis). Likewise a relatively simple single phase screen was used though there are clearly instances on Mauna Kea where more than one turbulence layer effects the natural seeing. In order to make sure that all models used the exact same set of phase screens, code supplied by Brent was run by Malcolm and distributed via ftp to all of the modelers.

S-H COMPARISON

The results of the S-HWFS models are summarized in Figure 1. The most readily compared models are the D/d=10 version by Brent and the D/d=9 version by Francois. Brent's strehl of 0.5 at R=14.8 mag is a simulation result while his other results are analytical estimates adjusted by 0.44 mag, as determined by comparing analytical and simulation strehls at R = 14.8 mag. Francois' D/d=9 model using 2x2 pixels per subpupil is plotted to match the parameters used by Brent. Overall there is fairly good agreement between these independently constructed S-HWFS models, lending confidence to the predicted performance. Also plotted is a D/d=5 model that Brent created to demonstrate the level of improved performance possible for faint stars if larger subpupils are adopted (the D/d = 5 model offers higher strehl for R > 16.5 mag). Of course reducing the resolution of the lenslet array reduces the strehl attainable for relatively bright stars, but in practice it might be possible to switch between two lenslet arrays, depending on the brightness of the guide stars available in the AO acquisition field.

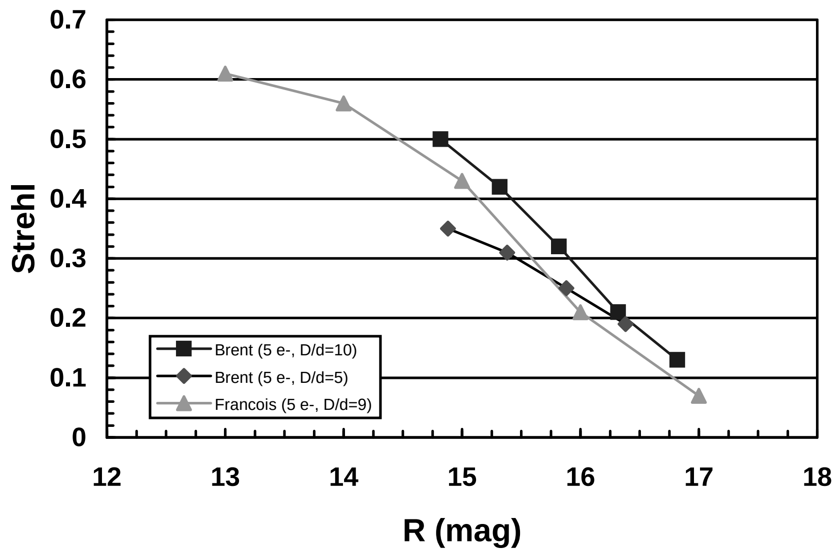

Figure 1 - Results of the Shack-Hartmann model comparisons are plotted. For comparable numbers of subpupils, the predicted performances of Brent's and Francois' models are quite close.

CURVATURE COMPARISON

Figure 2 shows a comparison of curvature models for various numbers of actuators. Typically higher order systems provide significantly better correction for brighter stars but for bimorph mirrors ranging in size from 80 to 37 (i.e., the size range covered in the models) it appears that all provide comparable strehl performance as guide stars grow faint. It should

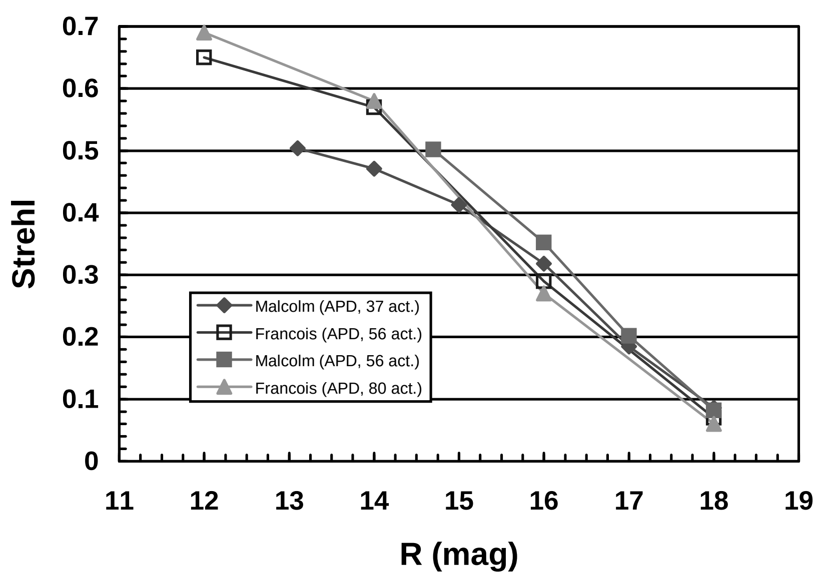

Figure 2 - Comparisons of all the curvature models are presented. All of the models yield comparable performance for stars fainter than R ~ 17 mag.

be noted that there was a slight difference in the interpretation of the ground rules between CWFS modelers. Specifically, Malcolm weighted more heavily the ground rule specifying that models must be practical in terms of fabrication and he felt that a 37 actuator design would be a natural extension of the system already in use by the UH group, hence spent much of his optimization effort working on relatively lower order designs. In contrast Francois optimized higher order. To be clear, both curvature modelers felt that designs with as many as ~80 actuators are feasible to build with current technology. Also note that both Francois and Malcolm felt that using a CCD on a curvature sensor with 5 e^- noise would degrade performance by 1-2 magnitudes over APD based designs, hence they did not seriously pursue these designs after making simple predictions and concluding the performance was clearly not going to be competitive with APD models.

COMPARISON OF CURVATURE AND S-H MODELS

Figure 3 shows a comparison of what I have termed "mid performance" models. The models plotted represent designs that have good overlap in terms of numbers of actuators and should be readily feasible to manufacture based upon current technology. It is clear that for the designs plotted the CWFS outperforms the S-HWFS for faint stars. This advantage is somewhat mitigated if a S-HWFS design is used that offers at least two lenslet arrays, one with perhaps D/d ~ 5 to offer better faint star performance (see Figure 1). Malcolm stresses in his report that, given the limited sky coverage offered by any of these models that faint star performance is important in the practical use of AO systems. It should be noted that for relatively bright guide stars (R ~ 15 mag) a noisy S-HWFS is competitive with all of the CWFS models, despite the fact that they rely on 0 read noise detectors.

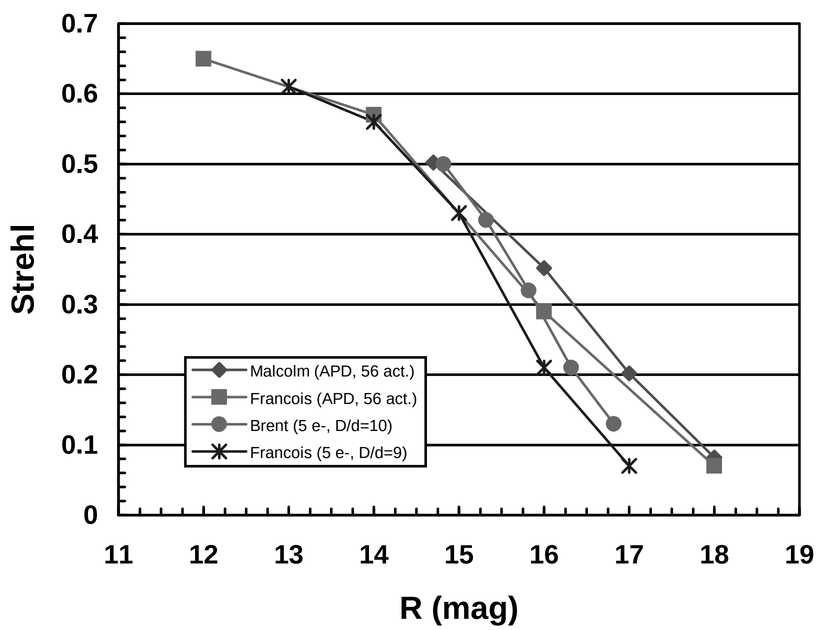

Figure 3 - A comparison of mid-performance models is shown. At a strehl of ~50% all models offer comparable performance. The curvature models yield better performance at fainter magnitudes.

Figure 4 shows the "high performance" models developed, with a noiseless D/d = 14 S-HWFS compared to a noiseless 80 actuator CWFS. Of course the ultra low noise (read noise < 1 e^-) CCDs required to make the modeled S-HWFS work are

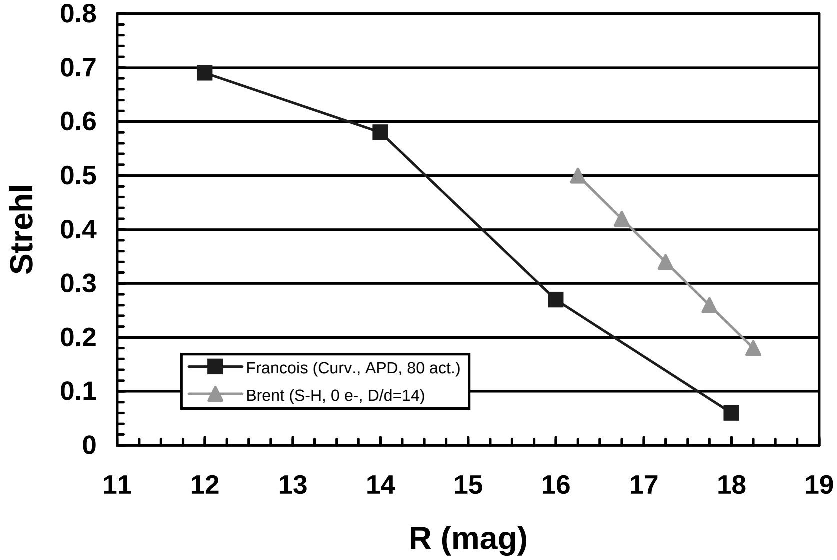

Figure 4 - A comparison of the "high performance" models is shown, which admittedly push technology. In this case, the S-HWFS clearly outperforms the CWFS if given identical (i.e., noiseless) detectors.

certainly years away, but if available the D/d = 14 S-HWFS design offers impressive performance even at faint magnitudes.

During the September 1994 meeting of the Gemini A&G/AOSWG it was decided that performance will be declared a "tie" if the S-H and curvature models yield the same limiting magnitude at the 50% strehl level to within 0.5 mag. If applied to the models shown in Figure 3 (i.e., the most easily constructed designs) it appears that a "tie" was reached. The gain in CWFS performance at fainter magnitudes is clear but this advantage is mitigated if a switchable 2 lenslet S-HWFS design is used, or lower noise detectors at some future date are used, hence it is not obvious even at faint levels that either technology offers a significant advantage in terms of "raw" performance on an 8 m telescope.

Field Star Availability

Given the fact that reliable magnitude limits on the performance of AO systems on Gemini are now available, for the sake of completeness the issue of guide star availability should be mentioned. A modified version of Bahcall's "Export Code" was

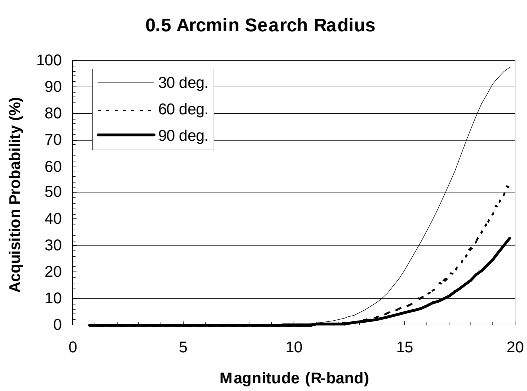

Figure 5 - The predicted probability that at least one guide star of a given magnitude will be in the central 1 arcmin AO field is plotted for three different Galactic latitudes.

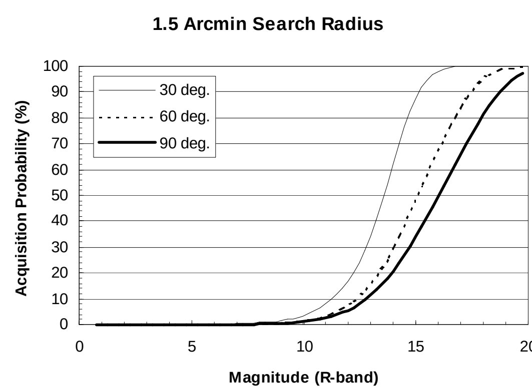

Figure 6 - The same as Figure 5 except a 1.5 arcmin search radius (i.e., the entire central science field) is used to compute field star acquisition probability.

used to predict field star densities at several Galactic latitudes. Figure 5 illustrates the probability that at least one guide star of a given R magnitude will be in a field of radius 30 arcsec, which given isoplanatic effects is probably applicable for sub-micron AO applications. Figure 6 illustrates field star acquisition probabilities for a 3 arcmin FOV and is more appropriate to H and K-band applications. Since the models were run at H this plot suggests that ~50% H-band strehls can be achieved using natural guide stars roughly half the time with Gemini.

ACKNOWLEDGMENTS

DS would like to extend his thanks and appreciation on behalf of the Gemini Telescopes Project to all of the individuals responsible for the models presented in this document. The sophistication of the models created for this study is a testament to the skill and expertise of Brent Ellerbroek, Malcolm Northcott, and Francois Rigaut. To date this arguably represents the most comprehensive set of AO models compiled in a single study for an 8 m class telescope, hence these results will no doubt be of value not only to Gemini but all other large telescope projects.

APPENDIX A

Gemini Science Requirements for the Adaptive Optics Unit

Requirements:

- Delivered Strehl Ratio >0.5 at 1.6 µm in median seeing conditions, with the intent of maximizing image concentration and sky coverage of a natural guide star system for $0.7 < \lambda$ (µm) < 5.0. This requirement is expected to deliver Strehls ~0.2 at 0.7 µm in 10th percentile conditions.

- The AO system should not increase the total emissivity by more than 15% for $2.2 < \lambda$ (µm) < 5.0 (i.e., a total telescope emissivity requirement of ≤19%).

- The throughput of the AO science path should be maximized in the band $0.5 < \lambda$ (µm) < 5.0 and should not be less than 50% at any wavelength in this band.

- The performance of the AO system as a function of zenith angle should degrade no faster than $S(Z) \propto S(0)^{\sec(Z)}$.

- The stability of the AO system should be sufficient to ensure that delivered Strehl ratios be limited only by atmospheric effects for up to a one hour integration.

Goals:

- The total AO emissivity should be less than 10% without ADC's in the band $2.2 < \lambda$ (µm) < 5.0.

- The order of correction should be selectable with the goal that performance of the lower order corrections should not be compromised.

- Laser Beacons: The natural guide star AO system should be designed in such a way that it can be upgraded to a laser guide star system with a priority to increase the system's sky coverage at the above performance levels.