

Opportunities in Adaptive Optics for NOAO

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1 Introduction

During the last decade, adaptive optics has gone through an extensive phase of energetic development for astronomy. The first phase of that development is now nearing completion, and has provided the technique of natural guide star adaptive optics. A number of adaptive optics systems, implementing very different scientific and engineering strategies, have been operational for several years. The scientific productivity is just now reaching a quantity and quality which permits an overview of the performance in a research context.

This is a reasonable time to review the opportunities which adaptive optics offers to NOAO for augmentation of existing or planned telescope facilities. This document will review the status and achievements of adaptive optics for astronomy, and suggest possible courses for Kitt Peak and Cerro Tololo, leaving the issue of adaptive optics in solar studies for review by NOAO staff actively engaged in this area.

2 The Investment in Adaptive Optics

To some extent the development costs of adaptive optics for astronomy has been shared between the astronomy and military communities, though due to the very different objectives this overlap has been considerably less than sometimes suggested. In the U.S., specifically, it has been possible to prepare a reasonably accurate accounting of spending specifically for adaptive optics in astronomy. The total spent or committed for the interval 1990-1999 is approximately \$35M dollars. The breakdown by source is shown in Table 1.

Table 1: Identified U.S. Spending on Adaptive Optics for Astronomy 1990-1997 plus Known Future Commitments.

| Organization | Spending |
|-----------------------------|--------------|
| National Science Foundation | \$12,300,000 |
| Department of Defense | 10,500,000 |
| NASA | 2,700,000 |
| Private and State | 9,650,000 |

To a considerable extent the spending figures are fairly realistic estimates of actual costs, including personnel, with the possible exception of the salaries of some scientist participants. Perhaps not coincidentally, this total is close to the the spending level recommended for adaptive optics in the 1990's by the Astronomy and Astrophysics Survey Committee (NRC, 1991). A histogram of this spending with time shows a steady increase from 1990 to 1997, now perhaps leveling off.

For an estimate of activity in Europe, the participation of more than 50 persons from the ESO community in a recent summer school on laser beacon systems¹, as well as the number of independent groups working on adaptive optics systems, lasers or laser beacons, suggests that current spending in excess of several \$M per year is likely.

These numbers testify to a remarkable level of support, reflecting the great confidence and salesmanship of the developers, and the eagerness of major observatories to augment their facilities with the expected benefits of adaptive optics. There is also, perhaps, the fear of being left behind by a development which by its very nature is expected to change the rules of the game. With such expectations, the first question to ask is - does adaptive optics work?

3 Does Adaptive Optics Work

The very good news is that natural guide star adaptive optics works well, and the performance and limitations are described fairly accurately by models. The most current available information for two highly successful natural guide star systems is collected in Table 2. In this table, the Bright Star Strehl

¹Laser Guide Star Adaptive Optics for Astronomy, Cargese (France), October 1997

Table 2: Demonstrated performance of operational natural guide star adaptive optics systems. BVRI data are from the Mt. Wilson system (Shelton, private communication), and JHK are from the CFHT PUEO system (PUEO WEB homepage).

| | B | V | R | I | J | H | K |
|--------------------|------|------|------|------|------|------|------|
| Bright Star Strehl | 0.02 | 0.07 | 0.15 | 0.30 | 0.27 | 0.41 | 0.56 |
| R mag (50% loss) | 10.0 | | | | 14.3 | 15.0 | 15.7 |
| Offset (50% loss) | | | | | 20" | 30" | 40" |

gives the on-axis Strehl achieved in median conditions for a bright wavefront reference star. (The higher Strehl at I than J may seem unexpected, but is probably due to differences in the design optimization or estimate of median conditions for the two systems.)

The actual Strehl observed will be reduced for fainter reference stars, and for off-axis angle away from the reference star, and these reductions must be multiplied together when both apply. The 50% reduction values for these parameters are also given in Table 2.

To the extent that the table entries differ from model expectations, it is in a favorable direction. First, the limiting magnitudes are a little brighter than expected with foreseeable detector developments, so there is some room for improvement. Second, the size of the corrected infrared field of view is significantly larger than most predictions, indicating that models were conservative and actual capability is greater in this regard than expected. Improving measurements of the turbulence profiles over observatories will probably bring models and performance into agreement.

Laser beacon adaptive optics systems are at least 5 years behind natural guide star systems. Tests so far show that both Rayleigh and sodium beacon systems can probably be built to function as conceived. They have apparently yet to record long exposure images which could not have been achieved with natural guide star systems. The goal to image faint fields, using reasonably faint reference stars, still requires solution of numerous thorny problems.

Table 3: The number of adaptive optics facilities in the world astronomy community.

| Description/status | Number |
|---|--------|
| Natural guide star systems in operation | 8 |
| Natural guide star systems nearing completion | 4 |
| Natural guide star systems in advanced planning | 5 |
| Laser beacon systems in operation | 3 |
| Laser beacon systems nearing completion | 5 |
| Laser beacon systems in advanced planning | 2 |

4 Where are the Adaptive Optics Systems

The large expenditures on adaptive optics have in fact led to a large number of systems on telescopes at many different sites. Any list is rapidly obsolete, so just some statistics will suffice here. These are shown in Table 4.

The particularly remarkable number is the total of 11 operational adaptive optics systems. Most astronomers would not guess such a large number. There are several clear reasons for this. Only five have produced science publications, and of those only two are heavily utilized for astronomy. The number of publications prior to 1997 is fairly modest. Many of the publications tend to be outside the mainstream of astronomy, which currently emphasizes dark sky and multi-object observational programs.

5 What Will Adaptive Optics Do for Astronomy?

Perhaps it seems a little late to be asking this question. Actually, the expectations for adaptive optics have been immoderate in some cases, and some clarification is still needed. The basic answer is that adaptive optics will improve the angular resolution of our telescopes. There are a number of potential derivative gains, especially in sensitivity, but these must be examined with special care.

The angular resolution gain is relatively straight-forward in the infrared, where even simple shift-and-add imaging has shown great power to achieve high angular resolution with medium to large telescopes. In the infrared partial adaptive correction produces the well-known core-halo image, with

the core approximating an Airy function (including diffraction rings), and for Strehl ratios similar to those in Table 2, angular resolution to or very near the diffraction limit is immediate.

The terminology used to describe adaptive optics performance should be clarified here. As soon as a narrow Airy core is achieved, the angular resolution is effectively diffraction-limited, in the sense that the width of the Airy core (to the first zero) is $2.44 \frac{\lambda}{D}$. This is true even if the Strehl is low – an Airy core can be obtained with Strehl of 0.1-0.2 (even myopic HST achieved diffraction limited resolution. This is the kind of diffraction limit that high resolution imaging attains. However, in optics, the term diffraction-limited is by convention reserved to describe an image quality with Strehl of about 0.8 – a far more stringent criterion, and virtually never achieved with adaptive optics.

The obvious domain in which improved angular resolution will accrue benefits in increased information content is direct imaging, including imaging spectroscopic techniques such as long-slit and integral field spectroscopy. Improved resolution will produce an information gain which can be of great importance for observations of sources which have angular structure between the seeing limit and the diffraction limit – a range of a few to about 20X depending on wavelength. Not coincidentally, many sources in this angular size range are relatively bright, and hence are possible candidates for natural guide star adaptive optics.

6 Sensitivity and Speed of Observations with Adaptive Optics

In certain circumstances adaptive optics may improve sensitivity or speed of general astronomical observations. However, it is necessary to be fairly specific about the circumstances. Adaptive optics may fail to give a sensitivity gain due to details of the image correction process, or due to the nature of the measurement.

6.1 Raw Sensitivity

While relatively low Strehl ratios can give high angular resolution (thanks to the formation of the narrow image core), most improvements in sensitivity require overall concentration of flux. This concentration allows a higher ratio of signal to background (which may be sky or telescope emission, depending

on wavelength). The ideal sensitivity gain should be on the order of the ratio of seeing-limited FWHM to Airy width. This can be of order 10X. But including realistic Strehl ratios, transmissions of adaptive optics systems, and where appropriate emissivity, more realistic expected gains may be in the vicinity of 2-3X.

This subject appears to be a sensitive one, so let's take a closer look at an example. Consider an 8 meter telescope at an excellent site, where the natural seeing is 0.5 arcsec at 0.5 μ m. In Table 4, consider first just the IR bands JHKK'. The table shows, as a function of wavelength, the expected seeing limited FWHM (using scaling from Kolmogorov turbulence) and the diffraction-limited resolution, $1.22\lambda/D$. There are entries for both K and K' filters. The center wavelengths differ by little, but the K' filter cuts off on the long wavelength side to reject the thermal background, while the K filter includes thermal background which limits sensitivity.

For ideal, lossless adaptive optics, and ignoring a small factor depending on the detailed image shapes, the ratio these numbers should give the relative sensitivity (we have implicitly squared the ratio to get the number of photons, and then taken the square root to get the background photon noise). This ideal gain in sensitivity is shown.

The next column gives an entry for the bright star Strehl ratio from Table 2 are shown. Of course, the bright star case will normally not apply. Increased raw sensitivity will be scarcely required for study of stars so bright. The interest in improved sensitivity will generally involve faint reference stars at the maximum useful angular distance. A survey of the published science confirms that most of the interesting sources are near the limit, and adaptive optics is employed at well below the bright star limit. Let's suppose that the reference star brightness and distance impose a Strehl reduction of 0.5 (as described in Table 2. This factor is shown as Strehl Reduction.

Next, a transmission value for the adaptive optics system must be factored in. Here, a value of 0.8 is used, reflecting the specification of the Gemini north adaptive optics system (Mountain, 1997). Of course this is significantly better than achieved in most existing systems.

If the observation is in the thermal infrared (approximately 2.4 μ m and beyond), there is also a loss due to emissivity. Assume that the emissivity of the adaptive optics system is given by 1.0 minus the transmission. If the specification for the telescope emissivity is 0.04, the emissivity after the adaptive optics will have increased by a factor 5.8, for an increase in background noise of 2.4X. This loss must also be included in the thermal infrared.

vide increased spatial resolution, observations will obviously be slower due to the lower photon flux per spatial resolution element. For a particularly interesting case of observations of high *Z* galaxies, sure to be an important topic of research in the next decade, the relative gain with adaptive optics will depend in detail on the requirement for observation of integrated fluxes of galactic scale sources (which are resolved with seeing limited observations), or of more compact proto-galaxies or sub-galactic condensations, which are much smaller than the seeing limit.

7 The Isoplanatic Patch

Though defined precisely, the term “isoplanatic angle” or “isoplanatic patch” is most often used loosely to describe the size of the corrected field of view achievable with adaptive optics. The etymology suggests that the PSF might be approximately uniform over the isoplanatic angle, but this is not correct. The Strehl can vary by $2\times$ between the on-axis position and an off-axis distance equal to the isoplanatic angle. Furthermore, the definition of isoplanatic angle does not map directly to Strehl loss.

There is some good news, however. The isoplanatic angle is found to be somewhat larger than expected. This seems to be due at least partly to actual turbulence profiles more benign than expected.

There is an interesting relationship between telescope aperture size and isoplanatic angle. This was described analytically by Fried (1982) but was widely overlooked for some time, since the formal analysis was complex and the infinite aperture approximation seemed well suited to certain cases discussed early on. The folly of this error can be readily appreciated by noticing that sub- 7λ apertures are diffraction limited and the isoplanatic angle for them is effectively unlimited. Between very small and very large apertures, there is an interesting range in which telescope apertures of order 1-3 meters, operating in the infrared, should have an isoplanatic angle of several arcminutes.

8 What about Photometry?

The utility of imagery is greatly increased if accurate surface brightnesses and other photometric quantities can be extracted. Depending on scientific objectives, accuracy of 1-10% may be needed. This accuracy range is fairly standard in conventional observations. In adaptive optics enhanced

Table 4: Estimating the gain in raw sensitivity with adaptive optics

| | V | I | H | K [*] | K |
|--------------------|-------|-------|-------|----------------|-------|
| Seeing (arcsec) | 0.50 | 0.44 | 0.40 | 0.37 | 0.37 |
| $1.22\lambda/D$ | 0.016 | 0.028 | 0.050 | 0.069 | 0.069 |
| Ideal gain | 31 | 16 | 8 | 5 | 5 |
| Bright Star Strehl | 0.07 | 0.30 | 0.41 | 0.56 | 0.56 |
| Strehl reduction | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Transmission | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |
| Emissivity factor | 1.00 | 1.00 | 1.00 | 1.00 | 0.41 |
| Net gain | 0.8 | 1.9 | 1.3 | 1.1 | 0.5 |

The sensitivity gains achieved will probably be in the vicinity of those shown as Net Gain in Table 4. Gains much more than $2\times$ greater are rather unlikely. This (partly empirical) calculation suggests that small sensitivity gains may be possible in the near infrared near $1\ \mu\text{m}$. Laser beacons will not greatly change this prediction – the laser beacon Strehl will generally be lower than the bright star Strehl, and a Strehl reduction factor will usually be needed to account for the magnitude and distance of the tilt reference star. Adaptive secondaries will not much change this result – the assumed system transmission is already very high.

6.2 Multiobject Observations

A powerful observational technique in observational astronomy is the simultaneous study of large numbers of sources spread over an extended field. Wide field imaging and multi-object spectroscopy can easily cover fields $100\times$ larger in solid angle than an adaptively corrected field, and this gives a gain in speed which far exceeds any promised by adaptive optics. Of course adaptive optics can be critical in the specific case of a confusion limited field, as witnessed by recent exciting observational results, but no concept currently on the drawing board will compete with wide-field instruments currently in operation.

For sources which are extended to near the seeing width or larger, there would in general be no sensitivity gain with adaptive optics, either in imaging or spectroscopy. This should be clear. In the case of both imaging and integral field spectroscopy, where the goal of adaptive optics will be to pro-

9 Other Gains with Adaptive Optics

A widely suggested application of adaptive optics is in support of coronagraphic observations, in order to detect faint sources near a bright point source. The benefit is three-fold. First, it concentrates the point source flux in a small area where it can be blocked with a small mask. This allows longer integrations without saturation. The second gain is the reduction of illumination in the halo of the bright point source. This gain is much more difficult to obtain, as the halo brightness is roughly proportional to $1/S$, where S is the Strehl ratio. Typical achieved Strehls of 0.5 only produce a gain of order 2X in this sense. The third gain is of course the concentration of flux if the "faint" sources are unresolved. Referring to the discussion of point sources earlier, this gain is likely to be only a factor of a few.

All of these gains together are impressive but much less than the dynamic range differences that one wishes to defeat to detect host galaxies around quasars or planets around stars. Such programs may require exotic special-purpose facilities. For the NASA interferometry augmentation of the Keck telescopes, expected to directly detect the indirectly discovered "hot Jupiters", the single Keck telescope adaptive optics is required to provide Strehl ratios of about 0.98 at 10 microns. Angel (1995) has proposed adaptive correction with a 10,000 element deformable mirror, in order to achieve high Strehl and detect extra-solar planets by a single aperture imaging technique.

Another interesting opportunity is the combination of adaptive optics with speckle imaging. Speckle is based on post processing of short exposure images. This may seem retrograde with adaptive optics, but a possible circumstance with laser beacons is the capability to correct higher order aberrations, but not tilt. Speckle could be an interesting option. Recent results from Lick (Max, 1997) show that adaptive optics and speckle can work effectively together.

A frequently mentioned potential benefit of adaptive optics is the achievement of high spectral resolution with a small spectrograph. This is possible because high resolution astronomical spectrographs for large telescopes are slit limited - the slit size required to collect a large fraction of the source flux limits the spectral resolution. With a small adaptively corrected image, the slit could be reduced in size and the resolution increased. This is a very attractive concept. It is most interesting for very high spectral resolution, which will generally be possible for relatively bright sources, which can be useful as reference stars for the adaptive optics wavefront sensor. Of

observations, questions arise because the point spread function may be more difficult to determine. If the Strehl ratio can vary by $2\times$ within the "corrected" field of view, as noted above, we might expect problems in extracting precise photometric information.

The adaptive optics corrected PSF is expected to vary over the field of view, in a rather complex way which is difficult to predict even in principle. The "on-axis" PSF, that is toward the reference star or beacon, depends on many of the parameters that determine adaptive optics performance, including reference star magnitude, natural seeing and wind velocity in turbulent layers. The variation of the PSF with off-axis angle depends on the distribution of turbulence with altitude and the velocity of turbulent layers, in addition to angular decorrelation of the aberration which, ideally, can be estimated from a general Kolmogorov turbulence model subject to determination of the parameters which characterize it - seeing, and outer scale.

There are few published adaptive optics observations with accompanying analysis of the photometric properties, and some of the following comments are anecdotal in nature.

It appears that a field richly populated with point sources provides enough internal information to determine the variation of the PSF over the field, using techniques developed to deal with HST images.

Imaging with no included point source provides a special challenge. Measuring the PSF in a separate observation of a reference star requires extreme care to ensure that the PSF is as similar as possible: for example, minimum elapsed time, staying at the same zenith distance and at the same reference star magnitude. It may be possible to monitor seeing related parameters to confirm stability of conditions, or to select similar data sets under varying conditions. Recent work by Veran et al (1997) have determined PSF's from the recorded residual errors determined by the wavefront sensor - but only for relatively bright reference stars.

A common requirement for study of binary stars will be precision relative photometry of two point sources in the visible, for stars which are separated by a significant fraction of the isoplanatic angle, but with PSF's which overlap. This may be a particularly difficult case, since it implicitly requires some information about the variation of the PSF with minimal internal diagnostic information.

course, any efficiency loss must be much smaller than the slit losses which it eliminates, if the strategy is to be effective – thus far this has not been the case.

The adaptively improved image size is a useful element of design flexibility, but it is only one of a number of factors facilitating high resolution spectroscopy, including new sites with higher quality seeing, tilt correction, immersion gratings, mosaic gratings, and slitless interference spectroscopy. Also, in the infrared, diffraction and grating resolution limits become important and the slit size is less significant.

Adaptive optics aided slit reduction is likely to be most important for resolutions much greater than 100,000. The only demonstration of the concept is a visible echelle (Woolf et al, 1995). This echelle is currently installed at Mt. Wilson with a fiber feed to the visible adaptive optics system at the 100 inch telescope. It is interesting to note that the Keck NIRSPEC infrared spectrometer, which is designed to be used with adaptive optics, will not exploit the narrow slit for higher spectral resolution – this option was judged too expensive.

10 How Adaptive Optics will Make the Rich Richer

Since reaching the sky background limit, astronomers have only gained sensitivity roughly as the aperture diameter of their telescopes rather than as the aperture area. Adaptive optics attacks that barrier in two respects. Since the resolution with adaptive optics improves with the diameter, the areal resolution improves with the square of the diameter, and the image information content in some sense probably increases in similar proportion. Second, if perfect Strehl and 100% throughput could be achieved, then due to the combined benefits of increased light gathering power and suppression of background, the sensitivity of a measurement would gain with the square of the aperture diameter. Though this kind of gain has not been demonstrated yet, it stands as a goal for the future. Although this discussion is highly idealized, it seems that large telescopes will potentially gain more from adaptive optics than small telescopes.

At a good seeing site (large r_0) the wavefront sensor subapertures will be large, hence the photon rate per subaperture will be high. The large r_0 will also result in a longer atmospheric time constant, hence a longer integration time on the wavefront sensor detector. So a good seeing site will be able to employ adaptive optics with much fainter reference stars than a poor seeing

site.

In laser beacon adaptive optics, it is still necessary to have a natural star reference for tilt and focus. The full telescope aperture can be used for these measurements. Thus a large telescope can use fainter tilt and focus reference stars than a small telescope.

In sum, the largest telescopes at the best sites will profit most from adaptive optics. The inevitable size-site pecking order in astronomy will be exaggerated as adaptive optics is implemented, especially if it is preferentially implemented on the large telescopes at good sites, as appears to be the case thus far.

11 How much is Adaptive Optics Used

The two adaptive optics systems available to a wide user community on a competitive, peer reviewed basis, are ADONIS at the ESO 3.6m, and PUEO at the CFHT. In 1997, PUEO is scheduled about 24% of the time, and in the year 1996 Adonis was scheduled a surprisingly similar 27% of the time. A 1/4th share is a huge fraction for a 4m class telescope serving a large community, and it highlights a strong user interest and a high level of supportiveness on the part of the Telescope Allocation Committees. This level of usage clearly can not continue for long without a very strong return of published science.

12 What Does Natural Guide Star Adaptive Optics Offer Astronomers?

The answer is improved angular resolution, of course, but actually quite a bit more. The additional benefits are less obvious, but in fact much more generally applicable.

12.1 Correction of Static Aberrations

Virtually no telescopes are fabricated to sufficient optical quality to take full advantage of an excellent site. Even those few which meet very high specifications in the lab rarely deliver the same performance for nightly use. Since the optical aberrations are usually dominated by low order errors, a low order correction can go a long way to remove those aberrations.

A natural guide star adaptive optics system can and must be designed to reduce fixed aberrations. Hopefully the aberrations will be relatively independent of, or systematically dependent on, zenith distance, in which case an offset matrix for the deformable mirror can be determined with high signal to noise on a bright star, and the fixed correction will then be applied even if no wavefront reference star is available. More commonly, the aberrations will vary with telescope pointing. But if the aberrations vary slowly with time (the case for any credible telescope), then a relatively faint reference star can be used to provide a low bandwidth but continuously updated correction.

Slow correction of this kind is conventionally called active correction rather than adaptive. However, use of a deformable mirror other than the primary is a non-standard means of achieving this active correction. Apparently it has only been implemented as a secondary feature of adaptive optics. However, the active correction is potentially valid for a wide field of view, and adaptive optics has always been implemented for a narrow field of view appropriate to the small adaptively corrected field.

It is currently unclear to what extent the use of active/adaptive optics can be a cure-all for telescopes with marginal optical quality. The NASA IRTF² at Mauna Kea may soon provide an interesting test case. The telescope has been plagued with poor image quality. Now, after considerable expense, the dome related turbulence has been greatly reduced, only to reveal important pointing dependent telescope aberrations. Fixes to the telescope will be expensive and are not imminent. The first generation curvature sensing adaptive optics system (from Roddier's group at UH) will be implemented at the IRTF, to support an imager and spectrograph. Though it will offer adaptive correction when sufficiently bright reference stars are available, it will also offer active correction of telescope aberrations.

The most modern telescopes include an active mirror support and active secondary alignment adjustment which is expected to reduce telescope aberrations to a low level. Whether or not an adaptive optics stage will provide further improvement is a technical question of time constants, gains, and systematic errors. Normally, a continuously updated closed loop correction can be expected to provide a better aberration reduction than a static lookup table correction.

²Infrared Telescope Facility

12.2 Painless Focus

A very significant benefit of adaptive optics is providing good, unambiguous focus with zero overhead. Observers know that achieving focus without adaptive optics can be very frustrating. When focus involves real-time interaction, the $1/f$ power spectrum of focus variation is a serious problem. In integrating systems, readout and analysis time can be significant. For programs involving observations through multiple filters, the focusing time can be increased by a corresponding factor. Most telescopes have focus variations, and often there is no unambiguous indicator of when refocusing is required. Even in a telescope with focus stabilized by an athermal optical mechanical structure, pooling of cool air in the primary mirror can cause unexpected focus variations.

In a closed-loop active or adaptive system, the focus is fixed automatically in a few time constants. This is a major factor in the report that at the CFHT PUEO system, imagery with adaptive optics involves less overhead than normal direct imaging.

Focus as a side benefit of adaptive optics offers a significant enhancement of quality and throughput of data, and it is available in either active or adaptive mode. The major tradeoff for general use is any loss of flux due to added optical surfaces.

12.3 Tilt Correction

Tilt correction without higher order correction is already interesting. In the infrared, it can provide improved much images, particularly for moderate aperture telescopes where D/r_0 can be on the order of a few. In the visible, the gain due to correction of atmospheric tilt should be small, but correction of telescope drive errors and wind shake can be significant, and of course apply to a large field. A surprising number of the most modern telescopes have been plagued with image quality limiting vibrations due to mechanical resonances in the vicinity of 20 Hz. While proper mechanical solutions are preferred, adaptive tilt correction can also reduce the amplitude of such image motion. Nevertheless, the number of telescopes implementing tilt correction alone is relatively small. There are at least two reasons for this. The optimum place to do tilt correction is at the secondary mirror, and such an installation can be quite expensive, and tilt correction may serve primarily to provide a better view of a telescope PSF badly aberrated at a scale just smaller than the seeing limit. Fixing this profile by brute force can

involve replacing mirror supports, repolishing secondaries, and installation of active alignment capability, all at high cost.

Correction of atmospheric tilt is effective over a wider field (sometimes called the isokinetic angle) than is higher order correction. In the case of tilt correction for a field of view greater than the isokinetic angle, however, the measurement of tilt is not entirely trivial. The tilt as commonly measured with a quadrant detector or a centroiding algorithm includes contributions from higher order terms (comatic aberrations). The tilt for which the field of view is optimized is the true or Zernike tilt, which can be more accurately measured with a wavefront sensor. Just distinguishing the tilt from the first order coma is the most valuable gain. Thus an adaptive optics system may give better tilt correction than a tilt only system, simply due to the wavefront sensor.

If the field of view is greater than the isokinetic angle, there is no guarantee that the tilt from a single star (on-axis or not) is the best estimate of tilt over the full field. Multiple reference stars could be used to give a better estimate for the mean tilt value, or to apply different tilt corrections to subfields of the full field. Neither of these uses of multiple reference stars has been reported. There is a close analog, however, in the NSO use of correlation tracking in solar observations (November, 1986).

12.4 Resolution Improvement Near Sufficiently Bright Stars

High angular resolution is seen now as only one of a number of benefits from adaptive optics, and not the most generally applicable. Achievement of resolution to near the diffraction limit will be available to a degree limited ultimately by the brightness of nearby reference stars.

13 Why Not Higher Order Correction?

A common definition of “diffraction limited” is an image Strehl ratio of about 0.8. This is beyond the limit of what is currently achieved even in the near-infrared with a bright reference star, and achieving such performance for faint sources is really not foreseeable.

Consider the common modal control used in many adaptive optics systems, in which the wavefront error is decomposed into its Zernike components. A low order correction corresponds to correcting the tilt, focus, astigmatism, etc. These low order modes include most of the aberration. Correcting them gives the most aberration reduction per mode. For higher

and higher modes, the improvement per mode decreases steadily. But this is only part of the problem. In order to determine lighter order Zernike components of the the wavefront error, it is necessary to use smaller subapertures in the wavefront analyzer. The number of available photons per subaperture per time constant is on order d^{-3} , where d is the subaperture diameter. This includes a factor of d^{-2} for the collecting area, and d^{-1} for the time constant, which must be on the order of v/d , where v is the wind velocity in the turbulent layer). This combination of factors vigorously closes the window on very high order correction.

A fully successful laser beacon would not lead immediately to higher order correction, since the cone effect would limit the correction to a level lower than achievable with bright natural guide stars.

14 Laser Beacons

If the laser beacon brightness is assumed to be large, the wavefront measurement and correction can be extended to higher orders, improving the correction at all wavelengths. However, the lowest order aberrations, tilt and focus, must still be determined from a stellar reference source. Since most of the aberration power is in tilt and focus, even small errors in correcting them can be extremely deleterious, especially in the visible. Also, all beacon systems will leave some turbulence unmeasured (due to the cone effect³), with the result that the best achieved Strehls with laser beacons will actually be lower than the best achieved Strehls with natural reference stars.

The motivation for laser beacons is to extend the adaptive optics functionality to the vicinity of fainter reference stars, albeit at somewhat reduced performance.

Rayleigh beacons are formed by scattering of a bright laser beam. In order to obtain reasonable scattering at an altitude of 10-20 kilometers, a relatively high power at UV wavelength is chosen. Low altitude scattering is rejected by temporal range gating. These choices have many ancillary impacts. Among the benefits, the required lasers are relatively cheap. The hazard of the laser light at the telescope is significant, but once launched (at reduced brightness) the hazard is small, and minimal aircraft and satellite coordination is required.

³Often called *angular anisoplanatism* in the literature.

15 Partial Adaptive Correction

Although astronomers initially hoped that adaptive optics would completely compensate for atmospheric turbulence, the reality of bright limiting magnitudes for complete correction led quickly to an interest in partial correction. (Partial correction is not entirely synonymous with low order correction, since at longer wavelengths low order correction may be sufficient to achieve high image quality.)

There has been some uncertainty, and even misunderstanding, of what image quality would be achieved with partial compensation. An early, schematic theory predicted that a partially compensated image would consist of a diffraction limited image core, plus a halo at least as large as the seeing width and possibly larger. Such a core is certainly observed when the Strehl ratio is of order 0.1-0.2 or greater. In fact, such images may have a near-diffraction limited FWHM. This can lead to misunderstandings, since observers unfamiliar with adaptive optics may tend to associate the small FWHM with a small encircled energy criterion - but in this case the two image quality measures are decoupled.

At sufficiently low Strehl, the core is missing or not prominent. Experience is showing that image quality improvement is often obtained at visible and even blue wavelengths. The nature of the improvement is reflected by significant FWHM reductions. Lacking a narrow image core, the FWHM can legitimately be compared to the natural seeing FWHM. Gains of 2-3 \times have been demonstrated at Mauna Kea on the CFHT. Image improvement is achieved over a much larger field of view than expected for the classical isoplanatic angle. This is not surprising, since the low order aberration modes corrected have a larger correlation angle than the high order modes considered in the formal definition of isoplanatism.

16 Science results from Adaptive Optics

While adaptive optics has been in regular use at several facilities for at least five years, scientific productivity has not been very evident. The problem of the early years can be illustrated by a remark from an adaptive optics guru in the aerospace industry, who admitted that wavefront sensing was limited to V=5 stars at that time, but after all, "there are lots of fifth magnitude stars to study". (The problem, of course, is that a factor of 10-30 \times improvement in angular resolution contributes little to the study of V=5 stars - a topic

The only Rayleigh beacon system that has been operated for science is at the U.S. Air Force Starfire facility. Utilized with a 1.5 meter telescope, this system maintained a small guest observer program for several years under an NSF sponsored plan, though recently this activity has been terminated. The scientific utility has been limited due to the R&D priorities of the facility, to the moderate aperture and mediocre natural site seeing, and to a number of problems which hinder long integrations. In spite of these limitations, scientific papers have been published based on data from the Starfire system. It is not clear, however, that these science programs could not have been accomplished with a natural reference star system.

The laser beacon adaptive optics community has, for the most part, rejected the Rayleigh beacon on the basis that the sodium beacon obviously suffers less from the cone effect. Only one program to implement a Rayleigh laser beacon system for astronomy is under way - the ISIS⁴ project at Mt. Wilson (Thompson, 1994).

Sodium beacons are formed by scattering of a sodium wavelength beam at high altitude, approximately 90 kilometers. The higher altitude decreases the error due to unmeasured turbulence (reduced cone effect). The sodium wavelength has some disadvantages. The lasers are not readily available and are still relatively expensive. The sodium wavelength penetrates aircraft and satellite windows and coordination with the FAA and the Air Force Space Command is required.

As the sodium beacon systems have been developed, it has become clear that there are complications which were initially overlooked or underestimated. The continuously varying distance to the sodium layer is a significant complication. The non-circular, and changing, beacon image shape (due to the finite thickness of the sodium layer) results in serious difficulties in estimation of wavefront error. It is safe to say that these and other problems have not been fully resolved.

Several groups have formed sodium wavelength spots in the sodium layer. Two groups have achieved limited function of adaptive optics systems with sodium beacon wavefront reference. Neither, as of this writing, has released results of any scientific program, or any images that appear to be scientifically useful.

⁴University of Illinois Seeing Improvement System

Table 5: The number of science papers published or in press at major, refereed astronomy journals – as of December, 1997.

| Year | Number |
|------|--------|
| 1993 | 3 |
| 1994 | 2 |
| 1995 | 5 |
| 1996 | 8 |
| 1997 | 25 |

which is in itself a small subfield of astronomy.)

There have also been natural difficulties with mastery of the hardware, the observing technique, and data analysis issues. There has been an initial mismatch between the actual technical capability which adaptive optics provided and the major research themes of the astronomy community.

The current limits (especially with respect to reference star magnitude, field of view and image quality achieved) still constrain greatly the options, but astronomers have begun to master the capabilities offered and to match them to interesting scientific opportunities. The evidence for the success of this effort is illustrated in Table 5, which shows the number of adaptive optics science papers published or in press at major refereed astronomy journals (science, here, means papers which present actual analysis and interpretation of data, rather than an illustration of achieved instrumental performance). Of course some of these observations are merely in the nature of proof of feasibility, and some are focused on one or a few particularly well suited sources, and may not be indicative of future programs, but this is far less true than it was just one year ago.

Considerably more insight into the science programs can be gained from the distribution of these papers according to science topic. This is shown in Table 6. Studies of young stars and of solar system objects stand out as the areas where most adaptive optics observing activity is concentrated. In both cases the scientific objectives commonly require study of relatively bright sources, compact but with important image detail just finer than the seeing limit. From a review of the published papers, it is clear that these science programs profit specifically from the angular resolution gain of adaptive optics, and scarcely if at all from any improvement in raw sensitivity.

Table 6: The distribution of adaptive optics science publications according to science topic, based on papers published or in press at major, refereed astronomy journals during the interval 1990–1997.

| Science Topic | Number |
|-----------------------------------|--------|
| Young Stars and Vicinity | 14 |
| Solar System | 11 |
| Extragalactic and Galactic Center | 7 |
| Binary Stars | 4 |
| Star Clusters | 4 |
| Compact Nebulae | 3 |

17 A Closer Look at Adaptive Optics Science

It is not possible to do justice to 40+ papers in a few pages of review, but there are some useful lessons to be gained from looking in closer detail at some of the science topics. In the following, reference will be made to papers counted in Table 6, and also to unreferenced papers and to images which have been made available on the WEB. Although the latter often lack descriptive or interpretive text, they are very valuable for forming an appreciation of the current state of the art opportunities which adaptive optics offers to astronomy.

17.1 Young Stars

The stellar disks of young stars, for example T Tauri and Ae-Be stars, are much too small to resolve with the largest filled-aperture telescopes, but they frequently are accompanied by near circumstellar material on scales slightly smaller than 1 arcsec, and hence are well suited for study with adaptive optics.

Use of adaptive optics to study the multiplicity of young stars has been described by Monin and Geofray (1997) and Brandner et al (1997a). Roudier et al (1996) and Close et al (1997a,b,c) have studied multi-spectral infrared imagery of T Tauri stars GG Tau, HL Tau, UY Aur, and R Mon (also observed by Ageorges and Walsh, 1997). Quirrenbach and Zinnecker (1997) studied T Tauri itself. McCullough et al (1995) imaged young stars with envelopes which are evaporating under the influence of stellar winds

and radiation from nearby O stars. Observations have also been reported for possibly related source types, such as the hydrogen line source LkHo 198 (Koresko et al. 1997), Z CMa (Malbet et al. 1993), and NX Pup (Schoeller et al. 1996).

Many new structural details of these systems have been determined, including identification of new stellar companions, discrimination of circumstellar and circumbinary shells, detection of disks, and investigation of scattering (from polarization maps) in the extended nebulosity.

With respect to the study of young stars, adaptive optics seems particularly well suited. Many prototypical and representative sources are amply bright for natural guide star adaptive optics. There are numerous current research topics which gain immediately with improved angular resolution, including multiplicity of the stars, natal disks and related inward flows, jets and related outward flows, proto-planetary disks, planets and brown dwarfs, etc. The scientific issues are profound - the birth of stars, the origin of planets. The physics is complex. The possible investigations are almost unlimited. In this area, adaptive optics is not just an incremental gain, but a substantive advance in the research capability. The study of young stars and their surroundings will probably be dominated by adaptive optics equipped large telescopes within the near future.

Due to obscuring molecular clouds in regions of recent star formation, there is in these regions a paucity of stars sufficiently bright for visible wavefront sensors. Development of sensitive, infrared wavefront sensors (possible now, without any technical developments) will allow much wider use of adaptive optics studies of young stars. Unfortunately, even the largest filled aperture telescopes will scarcely begin to resolve structure within a pre-planetary disk at typical distances of 200-500 parsecs. Distributed telescope arrays will be required.

17.2 Solar System

The solar system is full of sources which have important image detail just beyond the seeing limit, and in many cases the information gain with increased resolution is quite dramatic.

Asteroids are an interesting example and have been the subject of extensive studies with several adaptive optics systems. The few largest asteroids have an apparent diameter of about 1 arcsec at closest approach to earth, so sub-arcsec resolution offers a unique opportunity to access a wealth of structural and compositional information. The shape of an asteroid or other

small body reveals information about the formation history and structural integrity. Saint-Pé et al (1993a) studied the shape of Pallas, Drummond et al (1997) analyzed images of Ceres and Vesta for rotational poles and tri-axial dimensions. It appears that similar measurements could be acquired for a large number of much smaller bodies. Saint-Pé et al (1993b) studied thermal infrared images of Ceres to determine the rotational axis and the thermal density of the regolith. Dumas & Hainault (1996) have carried out an extensive program of near-infrared, narrow band imagery of Vesta, deriving a map of the surface pyroxene distribution.

The atmospheres of the giant planets undergo extensive variations, analogous to weather on earth. Ground based adaptive optics offers an important combination of angular resolution with the possibility of monitoring temporal changes. Roddier et al (1997b) reported the infrared observation of stratospheric clouds on Neptune, including evidence for wind velocities from the rotational period. Rigaut and Arsenault (1996) observed a transient white spot on Saturn. An ESO observer obtained a very nice 2 μ m image of polar haze on Jupiter (DESPA, 1997).

Planetary satellites are also well suited for adaptive optics observations. Titan has been observed in the infrared, at wavelengths chosen to optimize the penetration of the atmospheric haze and to distinguish surface features. Combes et al (1997) were able to rule out a global ocean from their Titan imagery. Infrared images of Io (Dumas et al, 1997) reveal volcanos, some previously known and some new, clearly showing the utility of adaptive optics for monitoring volcanic activity on this satellite of Jupiter.

Several groups studied the rings and satellites of Saturn at the recent ring crossing. Beuzit et al (1997b) and Roddier et al (1996a,b) and Roddier (1997) reported new discoveries of satellites and/or ring clumping. Roddier et al (1997a) reported observations of arc structure near the E ring, which they interpret as the result of an expected gravitational interaction of the ring with both Mimas and Enceladus. These observations profited from the unusual opportunity to view the rings edge-on, as well as choice of wavelengths at which the planetary disk is quite dark due to molecular absorption in a cold atmosphere.

There are also numerous adaptive optics images of comet Hale-Bopp, currently in preprint form (Marro et al, 1997), or on various WEB sites. The recent burst of results from infrared spectroscopy suggests that combining spectroscopy with high angular resolution would be a powerful observational technique for comets.

For solar system studies, adaptive optics equipped ground-based tele-

scopes are surprisingly competitive with spacecraft. As an illustration, as of this writing, ground based adaptive optics can obtain higher resolution images of the Jovian face of Io than can the Galileo probe in orbit around Jupiter. (Of course this will change if Galileo is repositioned for an Io fly-by.) So in spite of continuing NASA missions, it is likely that adaptive optics will provide unique solar system observations for many years to come. Adaptive optics has a clear future in solar system observations, and the observing programs mentioned above probably provide an excellent guide to the opportunities. There can be extensive study of asteroids, considerable further detailed investigations of Titan, monitoring of the outer planets and Io, additional studies of planetary rings, and observations of comets as the opportunity arises.

17.3 Extragalactic and Galactic Center

The galactic center is almost ideally suited for adaptive optics study. Observations in the infrared are important. There are nearby bright reference stars. The angular resolution of 4-8 meter telescopes turns out to be just about right to relieve the confusion limit of the imagery, and to measure the transverse motions due to stellar orbits in the deep galactic center gravitational potential (Rigaut et al, 1997).

A number of studies have employed adaptive optics to resolve and study the bright stars in galactic and extragalactic populations. Davidge et al, 1997a,b) studied fields in the galactic bulge and near the nucleus of M31. Bedding et al, 1997) observed NGC5128, IC5152 and NGC200 in addition to a galactic bulge field, and concluded that it should be possible to obtain photometry of the brightest stars in the bulges of elliptical galaxies to a distance of about 3 Mpc.

Another extragalactic topic that will gather significant interest is the study of systems with AGN's⁵. Rouan et al (1997), Alloin et al (1997), and Marro (1997a,b) have reported on images of NGC 1068 and NGC 7469, studying details of the internal structure to refine constraints on physical models. Lai et al (1997) observed the ultra-luminous infrared galaxy Mkr 231, resolving structure in the starburst region near the nucleus.

These studies are both resolution and reference star brightness limited (they usually employ the galaxy nucleus itself as a not-very-satisfactory wavefront reference). The resolution limit will be significantly alleviated by

⁵Active Galactic Nuclei

the advance to 8 meter class telescopes, potentially extending observations to a somewhat larger sample. The reference star limit is more fundamental, but small improvements in wavefront detector sensitivity or control algorithms will be very important. Introduction of laser beacon systems would be the advance required to really open up extragalactic studies with adaptive optics.

17.4 Binary Stars and Star Clusters

The old standby of high resolution astronomy is the study of binary stars, which has the attractions of presenting a relatively easy observational problem, and a unique role in astronomy - the observational determination of stellar masses. Speckle techniques have been quite successful in reaching the diffraction limited angular resolution, but have been most effective with relatively bright stars and modest magnitude difference between primary and secondary. Relative photometry has also been difficult to extract from speckle images. Adaptive optics will probably reach considerably fainter stars and considerably fainter companions, and relative photometry should be more readily achievable.

Ten Brummelaar et al (1996) have employed adaptive optics to determine relative photometry for binary stars observed extensively with speckle measurements. Bouvier et al (1997) carried out a survey of low-mass Pleiades stars to determine multiplicity for a study of the influence of companions on proto-planetary disks. Individual binary systems have been studied by Drummond et al (1995), Schoeller et al (1996), and several binary systems were detected and studied in studies of young stars.

The star cluster R136 was first resolved by speckle, and subsequent HST and adaptive optics observations (Heydari-Malayeri et al, 1994; Brandl et al, 1996) have contributed to continuing studies of this remarkable, very rich group of early type stars. Adaptive optics has served as a diagnostic for observations of possibly related objects (Heydari-Malayeri et al, 1997a,b).

It is clear that studies of multiple stars and star clusters will be a staple of adaptive optics for many years. Here also, however, specialized optical arrays will be needed to pursue the important parameter space beyond the single aperture diffraction limit.

17.5 Compact Nebulae and Circumstellar Shells

Though young stars, which are commonly accompanied by circumstellar or nearby nebulae, have been separated out above, there are still many additional types of compact nebulae. As most of these are associated with stars, which may serve as wavefront reference, these should be in many cases well suited for adaptive optics studies.

Morossi et al (1995) detected rings and emission clumps in the shell of the Be star P Cyg. Mouillet et al (1997) employed a coronagraph equipped adaptive optics system to image the disk of the main sequence star β Pic down to 2 arcsec from the star. Beuzit et al (1994) and Roddier et al (1995) observed a possible proto-planetary nebula, known informally as Frosty Leo. Brandner et al (1997b) used adaptive optics to compare a supernova remnant with the Hourglass nebula. Rouan et al (1997) exploited high angular resolution to measure density contrasts in the molecular cloud NGC2023. Feldt and Stecklum (1997) obtained infrared images of ultra-compact III regions for comparison with centimeter wave maps.

The abundance and variety of compact nebulae, and the typical spatial scales, suggests that adaptive optics will support continuing advances in studies of their structure and evolution. Though little work has been done so far, this may be an increasingly active area in the future.

17.6 Summary of Science Directions

In the areas of young star studies, solar system and extragalactic astronomy, select sources, often including the brightest prototypical examples, will be extensively studied with natural guide star adaptive optics.

Other areas, including the additional topics mentioned in Table 6, offer many suitable sources for adaptive optics, and the limited activity in these areas thus far probably is in part a legitimate indication of a somewhat lower level of research effort along these topical lines, and of limited research requirements for the kind of angular resolution improvement that adaptive optics offers. Furthermore, most observational studies of stars, clusters and nebulae are based on visible/UV observations, owing partly to tradition and largely to the tendency for ground state atomic transitions to occur in this wavelength region. HST still has a large performance edge in high resolution visible imaging. It may be that a major ramp-up of activity in these areas with ground-based adaptive optics would be facilitated by implementation of visible optimized adaptive optics systems on large ground based telescopes,

This capability does not seem to be represented in the current active and proposed astronomy programs, and may first appear at the Starfire Optical Range, where access for astronomy programs is extremely limited.

Implementation of laser beacons offers advances particularly in extragalactic applications, and more generally in reaching beyond the most favorable few examples of a class of object to a more representative selection.

18 Future Directions in Adaptive Optics

The initial push to implement natural guide star adaptive optics appears to be tapering off, and the primary effort now is in copying known technical solutions to additional facilities. For scientific applications similar to the ones represented in published research, the performance can be predicted with reasonable confidence.

In laser beacon adaptive optics, the situation is still in doubt. Several major projects are underway, millions of dollars have been committed, and some of astronomy's most talented instrumental groups are involved. Yet the problems to be solved are difficult and the most likely solutions complex. While there is little doubt that the laser beacon systems can be brought to a degree of functionality, the actual utility and effectiveness for particular research programs cannot be predicted.

18.1 Natural Guide Star Adaptive Optics for Improved Imagery

Natural guide star adaptive optics is well on its way to establishing a permanent niche in astronomy. The improved angular resolution in study of compact but resolvable sources is important in its own right, and increasingly valuable with the advent of very large telescopes, which are otherwise often confusion limited. Furthermore, for some science topics, the availability of adaptive optics is likely to be a prerequisite for carrying out competitive work. Thus far, this appears to be increasingly true for study of young stars and for some ground based solar system studies, and other areas are likely to move into this category in the future.

18.2 Sodium Beacon Adaptive Optics

At this time, it appears imprudent to initiate new sodium beacon projects. A large effort is underway at several observatories, and whether they succeed

or fail, a great deal will be learned that will impact the direction of future sodium beacon programs. At this time, it is not yet clear which ideas to copy and which to avoid. It is also unlikely that the existing programs will succeed so quickly and effectively that the have-nots will be left far behind. Members of the second wave may even have an edge.

18.3 Rayleigh Beacon Adaptive Optics

Thus far, results from Rayleigh beacon adaptive optics do not strongly motivate additional development of this technique. Experience has been limited to small aperture telescopes, and since adaptive optics generally yields greater return on larger apertures, the case for and against Rayleigh beacons is really not yet well understood. The UNISIS project at the Mt. Wilson 100" could be an important guide to future work with this technique.

In addition to these main lines of adaptive optics development, there are a number of less well explored paths that are also promising for the future.

18.4 Adaptive Optics for Partial Correction

The achievement of image improvement in the visible with partial correction, though not fully understood, is potentially quite interesting. Reduction in the FWHM of a factor of order $2\times$ is significant. While the corrected field of view is not understood rigorously, it seems likely that it will be on the same order as the corrected field of view in the infrared, hence of order 60 arcsec for 4m class telescopes, and larger for smaller apertures.

Furthermore, there are several techniques available for enhancing the field of view, probably to much more than an arcminute. These options arise from the observation that at typical, high quality astronomy sites, the turbulence is sharply layered. The principle contributors to seeing degradation are in the dome, in a low altitude boundary layer, and in one or a few discrete layers at much higher altitude, typically of order 10 kilometers.

The dome and boundary layer contributions are close enough to the telescope to have a high correlation over a large field of view. If it were possible to distinguish the wavefront aberration due to these components, and to correct for them alone, the resulting wavefront would have only the residual aberration from the high altitude turbulence. The fractional gain in image quality is of course site specific, and in fact is potentially larger at poorer sites. Though this is hardly a solution for poor site selection, it may be a counter-example to the thesis above that "the rich get richer".

To the extent that this technique succeeds, a site will be limited primarily by high altitude turbulence, which is believed to be relatively uniform over good and poor sites. In this limited sense, every observatory is a potential Mauna Kea, with respect to image quality.

There are several methods available to distinguish to some extent the low altitude turbulence from the high altitude turbulence. Using a low temporal bandwidth will tend to reject the high altitude contribution, which will commonly be associated with higher velocity winds than low altitude, or certainly than in-dome, turbulence. Some knowledge of the wind profile could be used to guide the selection of instrument parameters to optimize this discrimination.

Normally, adaptive optics employs only a single wavefront reference star. Wavefront information from multiple reference stars could be combined to partially isolate the common component and correct for it alone.

Interestingly, a Rayleigh beacon might be well suited for discrimination of low altitude turbulence. Instead of forming the beacon at the highest possible altitude, as normally desired if the goal is the highest on-axis Strehl, it could be formed below the high altitude turbulence layers. This would still be high enough to well sample the low altitude turbulence. This concept has been explored theoretically (Ragazzoni & Marchetti, 1995) and experimentally (Chun, 1997), but is still quite undeveloped.

18.5 Adaptive Secondaries

The greatest impediments to achieving gains in sensitivity with adaptive optics are the losses in throughput and the increases in emissivity. In performance estimates above, a throughput of 80% was assumed, but this will be difficult to achieve, and likely will require wavelength optimized components which can be switched in and out. The adaptive secondary can potentially reduce the number of extra optical surfaces to zero, and the number of adaptive optics specific light losses to just one – a dielectric beamsplitter coating on the entrance window of the instrument. This is clearly a very powerful – and potentially expensive – technique, but it will greatly simplify the achievement of high throughput. Some work has been done on control of large deformable mirrors, and at Steward Observatory, a prototype adaptive secondary for the MMT is in an advanced stage of development (Brunns et al, 1997).

Most work reported on adaptive secondary technology has emphasized relatively high order correction. The MMT secondary will have 300 actual,

tors. Low order correction at the secondary could be an interesting option as well. The UH group is beginning to look at low order adaptive secondary mirrors fabricated with the techniques they have used successfully to build very economical bimorph deformable mirrors for their adaptive optics systems.

19 Adaptive Optics at NOAO

Staff at NOAO have been close to adaptive optics development from the beginning. Fast tilt correction was employed for planetary imaging and spectroscopy in the 1960's (Huntten, private communication). Beckers (1986) developed adaptive optics concepts for the NNTT program. Roddier (1988) conceived his curvature sensing and deformable mirror technology while working at NOAO on wavefront sensing problems. Solar adaptive optics experiments by Dunn (1990) and others were among the earliest in astronomy, and work continues today to implement adaptive optics for solar observations. Ridgway (1992) derived adaptive optics performance predictions and used them to predict the sensitivity of ground based optical interferometry. Goad (1989) built a complete prototype adaptive optics system. NOAO partially supported adaptive optics R&D experiments by Kaman Corporation (Gleckler et al, 1994), and has banned wavefront sensor apparatus to Steward Observatory (Lloyd-Hart et al, 1995) for laser beacon experiments. The CHAOS⁶ group is currently carrying out sodium laser beacon experiments at the Sacramento Peak Vacuum Tower telescope. Both KPNO and CTIO have built either prototype or facility tilt correction systems for major telescopes.

In spite of this level of evident interest, NOAO has not implemented adaptive correction at any of its nighttime telescopes. In fact, some staff members with strong interest in this area have left NOAO and continued their work in other organizations. Though there has been some criticism of NOAO's choice to defer further work on adaptive optics during this period, this was an informed decision, based on the actual state of the art, the cost of entering the game, and the probable scientific return. The current status report appears to confirm these decisions. Adaptive optics is just now reaching a level of maturity and becoming scientifically productive. This raises the question of whether NOAO should now plan a move into adaptive optics.

⁶Chicago Adaptive Optics System

From the foregoing discussion, adaptive optics will be seen to have several potential areas of application at NOAO:

- High angular resolution in the infrared.
- Compensation for dome and low altitude seeing in order to obtain a wide field partial correction.
- Correction for static and slowly varying telescope aberrations.

19.1 Adaptive Optics for High Resolution Infrared Imagery at NOAO

The high resolution potential of adaptive optics is greatest for the largest telescopes at the best sites – the rich get richer. Is NOAO rich enough to get richer? The answer appears to be clearly yes, as may be seen with a point-by-point comparison with Mauna Kea. The median image quality actually obtained at the best Mauna Kea telescopes runs in the range 0.55–0.65 arcsec. The median image quality obtained at WIYN on Kitt Peak is 0.8 arcsec. Though lacking a similarly modern telescope, Cerro Tololo normally has somewhat better seeing than Kitt Peak, based on observations with the similar 4 meter telescopes. So Mauna Kea has a modest (but important!) edge in raw seeing. However, Mauna Kea has a reputation among the adaptive optics community for a short atmospheric time constant due to high wind speeds. Since low altitude winds at Cerro Tololo and Kitt Peak are lower velocity, the time constant for correction of low altitude turbulence will be longer. This wins back sensitivity for wavefront detection. An exact comparison of Mauna Kea and NOAO sites requires further characterization, but CTIO and KPNO remain among the elite major observatory locations.

With the installation of SOAR, NOAO will have four telescopes of 4 meter class, two of them among the most modern in astronomy. There is no doubt that NOAO can effectively profit from adaptive optics for high angular resolution. This expectation could be quantified somewhat better with improved measurements of both sites. Such measurements are planned, based on the updated SCIDAR technique (Klucker et al, 1997), in observing campaigns at both Cerro Tololo and Kitt Peak.

Adaptive optics supported infrared imaging at the NOAO 4 meter telescopes would provide improved angular resolution, as noted in Table 7. The Seeing Limited values are scaled by Kolmogorov turbulence theory from 0.8 arcsec seeing at 0.6 μ m. The aperture sizes include those available at NOAO,

Table 7: The angular resolution achieved with several apertures.

| Wavelength | Seeing Limited | 2.0 m | 3.5 m | 4.0 m | 8.0 m | 11.0 m |
|------------|----------------|-------|-------|-------|-------|--------|
| J | 0.74" | 0.12" | 0.07" | 0.06" | 0.03" | 0.02" |
| H | 0.70 | 0.16 | 0.09 | 0.08 | 0.04 | 0.03 |
| K | 0.65 | 0.23 | 0.13 | 0.11 | 0.06 | 0.04 |

at Gemini and at Keck (note that the Keck 10 meter equivalent aperture actually achieves resolution corresponding to the longest chord, 11 meters). Table 7 shows that an aperture of 3.5–4 meters provides angular resolution in an interesting range, a factor of about 5 \times better than seeing limited, and about 2–3 \times poorer than the largest telescopes. In the infrared the field of view is normally detector size limited, and reduced resolution allows larger field of view. In fact the 4 meter class telescope will have a corrected infrared field of view (30–60 arcsec) which is well matched to expected detector sizes of 1–2K pixels, with about an order of magnitude greater areal coverage than will be possible with the same detectors used in diffraction-limited imaging with 8–11 meter telescopes. It appears that an adaptive optics corrected infrared imager would be a good match to NOAO 4 meter class telescopes technically and strategically for programs requiring high angular resolution. This would provide a competitive capability in the research areas in which adaptive optics is already important, as well as in others where the potential has not yet been explored.

The simplest way to implement a high angular resolution capability at NOAO would be to build a dedicated imager, essentially a camera with an adaptive optics front end. This should consist of a large infrared array, functioning in the wavelength range 2.5 μ m and shorter, operating on one or more of the NOAO 4 meter class telescopes. Table 8 summarizes the field of view which can be obtained with diffraction limited sampling for a 1K array size. The observed FWHM of the corrected field is computed from Table 2 and added to this table for comparison, and the good match is obvious.

A possible instrumental concept for this requirement would be a clone of the UH curvature sensing system. The superiority of this configuration for low order correction with the faintest reference stars is now indisputable. The UH group has also repeatedly shown, with several implementations of their system, that it can be economical, transportable and reliable, and

Table 8: The field of view achieved with 1K \times 1K pixels deployed for Nyquist sampling in diffraction limited imagery with a 3.5 meter telescope.

| Wavelength | Diffraction Limit | Detector field of View | Corrected field of View |
|------------|-------------------|------------------------|-------------------------|
| J | 0.07" | 36" | 40" |
| H | 0.09 | 48 | 60 |
| K | 0.13 | 66 | 80 |

adapted to multiple telescopes.

The technical and operational issues of natural guide star adaptive optics for infrared astronomy are now well understood, and the science potential can be accurately estimated. Thus a project of this nature can be evaluated as any instrument project on its scientific and technical merit, rather than as an R&D program.

On 2 meter class telescopes, the angular resolution achieved would fall distinctly short of that available on numerous large and medium aperture telescopes, and so would not be very competitive in programs which specifically emphasized high resolution imaging. An adaptive optics equipped 2 meter class telescope would be very interesting for infrared survey programs, where the potential of adaptive optics to provide improved image quality over a significant field of view would be important. Since the goal would be to improve the speed and sensitivity of observations, it would be critical to maintain the highest throughput, thus an adaptive secondary would be the optimum solution. Adaptive optics would then contribute to wide field of view image quality through the three ancillary benefits - correction of aberrations, focus, and telescope shake. A telescope aperture of 2 meters is small enough to start profiting significantly from the aperture dependence of the isoplanatic angle. A 2 meter would gain in isoplanatic angle about 30% relative to a 4 meter, corresponding to a corrected field FWHM in the K band of about 100", again well matched to available detectors. The discussion of low altitude adaptive compensation, for both the infrared and visible range, is fully applicable in this case as well, and should lead to further wide field image improvement, though the extent of this improvement cannot be predicted accurately without study. Future 2 meter telescopes, especially with an expected significant role in wide field infrared

imaging, should be designed to accommodate possible eventual installation of adaptive secondaries and laser beacon systems.

19.2 Adaptive Optics for Improved Visible Imaging at NOAO

From the pattern of current usage of NOAO facilities, it is clear that nothing would benefit a broad range of observational programs more than an improvement in visible image quality over a wide field of view. This has motivated continuing effort to reduce dome and site seeing and to improve the delivered image quality of NOAO telescopes.

Experience with partial correction adaptive optics is showing benefits in the visible/CCD wavelength range which are modest but significant, and with field of view much larger than the classical isoplanatic angle. This includes the three ancillary benefits described above, as well as the benefits of partial correction which have been reported at several adaptive optics facilities. The possibilities for low altitude compensation can be added to this list. The potential gains in sensitivity and speed for moderate field, but otherwise fairly general, observations is quite significant. To exploit this potential, it is critical to offer a high throughput, and thus an adaptive secondary should be considered. This capability should be evaluated for any new telescope, and could equally be implemented as a retrofit to an existing facility.

19.3 Adaptive Optics for a Modern, 4 Meter Class Telescope

The imminent construction of the SOAR telescope offers a platform for a dedicated infrared imager such as described above. In the expectation that SOAR will offer the best natural image quality of any NOAO telescope, it would be the superior location for deployment of this imager. This would be the most effective implementation of high angular resolution infrared imaging for NOAO.

SOAR may also offer the opportunity to include adaptive optics requirements in the facility design. The highest priority is obviously to do no harm – that is to avoid introducing high frequency resonances in SOAR, such as plague WYN, ARC, and most other high-tech telescopes. This can be achieved easily with conservative design – classical telescopes generally don't have this problem.

A second step, in priority order, would be to provide for an adaptive secondary mirror, allowing high resolution imaging to also offer some gains

in sensitivity. This is obviously much more difficult and expensive, and the technology is still in the prototype stage. It may not be wise to introduce so large a perturbation into the SOAR planning cycle.

The case for implementing laser beacons at SOAR is not yet clear. The best strategy in this case is to attempt to provide an upgrade path for a sodium beacon, which could be implemented if and when the scientific and technical cases are well defined. This beacon would extend the operation of high resolution infrared imaging to a larger fraction of the sky.

The prospects for partial correction in the visible discussed for 2 meter telescopes apply equally to SOAR, but only provided very high throughput can be achieved, probably with an adaptive secondary. The Rayleigh beacon would be an important possible strategy in that case.

19.4 Adaptive Optics for a 2 Meter Class Telescope

The proposed construction on one or more modern 2 meter class telescopes at NOAO offers a unique opportunity to merge the latest experience with adaptive optics into an optimized facility. From the foregoing, it is clear that a 2 meter telescope with an adaptive secondary can both complement the capabilities of larger facilities and provide additional unique benefits.

Based on experience at CFHT, we expect that partial adaptive correction will provide visible image FWHM as good as 0.2-0.4 arcsec. With no special effort, the corrected field of view should be similar to that achieved at Mauna Kea. With additional attention to correcting the low elevation turbulence, this corrected field may be substantially increased.

Table 9 summarizes the expected parameters for visible imagery with partial correction. The first corrected field estimate, 25", can be accepted with some confidence as a minimum to be expected at NOAO sites (a minimum because the NOAO sites are dominated by low altitude turbulence, which will provide a larger partially corrected field). The much larger estimate of an optimally corrected field indicates the goal which could be pursued with the strategies described earlier, which include optimization of the wavefront detection, of the control algorithms, and the use of a Rayleigh laser beacon. The optimally corrected field of view depends on the vertical distribution of turbulence, and could be confirmed with site site studies.

At this time, it is not advisable to move ahead with actual implementation of a Rayleigh beacon. Successful resolution of several key problems with laser beacons would signal a timely transition to this technology.

It has also been noted above that a 2 meter class telescope equipped with

20 Proposal for a Synthesized Program at NOAO

Adaptive optics has been the subject of numerous planning and strategy sessions at NOAO. These always lead to the rediscovery of a disconnect between need and capability. The clear, strong need at NOAO is for improved visible and infrared image quality available for very general imaging and spectroscopic applications. The adaptive capability, as demonstrated so far, offers high resolution in the infrared on bright . This is a specialized capability that is of much lower interest to the full spectrum of NOAO users. This point has also been illustrated when NOAO has made available speckle and tilt correction for improved infrared imaging – the clientele has always been a relatively small subset of the community.

The very large scientific return from generally improved image quality has led to a series of programs to improve seeing and telescope optical quality at all NOAO sites. These have yielded a significant benefit in improved performance. However, the most cost-effective options are complete or in progress, and it will be necessary to move on to other strategies to obtain further gains.

The techniques for general image improvement, discussed above, have not been sufficiently well characterized to motivate a major, expensive program, which at the present time would necessarily involve considerable development and uncertainty about delivered performance. And yet this is the optimal direction for NOAO nighttime astronomy.

The following is an attempt to define a package of adaptive optics technology that offers guaranteed benefits to NOAO nighttime observers at moderate risk and cost, which will specifically lay the foundation for general visible and infrared image quality improvement, and which will keep NOAO well placed to exploit expected future developments in adaptive optics.

New NOAO telescopes should be designed for incorporation of adaptive secondaries and laser beacons. The instrument interfaces should be designed to readily accommodate the wavefront sensor packages required for adaptive optics. The telescope mechanical systems should avoid the kind of resonances that are a known problem for adaptive optics. The control systems should foresee interfaces for transfer of low bandwidth pointing, figure control, and alignment information from adaptive systems.

Separately but in parallel, a transportable adaptive optics system should be built as an instrument (not facility) package, with both narrow and relatively wide field (2–4 arcmin) capability and with both infrared and CCD cameras. This system should adapt to various telescope foci and image

Table 9: The field of view achieved with a 2 meter telescope for moderate resolution visible imaging and Nyquist sampling, compared with the field of view actually achieved at the CFHT, and with a hypothetical expected field of view for selective partial correction of turbulence to an altitude of 500 meters.

| Wavelength | Detector field for 4K×4K pixels | Corrected FOV at CFHT | Optimally Corrected FOV |
|------------|---------------------------------|-----------------------|-------------------------|
| V | 410" | 25" | 490" |

Table 10: The field of view achieved with a 2 meter telescope for diffraction limited infrared imaging and Nyquist sampling, compared with the expected FWHM of the corrected field of view.

| Wavelength | Diffraction Limited | Detector field for 2K pixels | Expected FOV for 2m |
|------------|---------------------|------------------------------|---------------------|
| J | 0.12" | 122" | 43" |
| H | 0.16 | 163 | 66 |
| K | 0.23 | 235 | 94 |

an adaptive secondary would provide a unique infrared imaging facility. The characteristics of such an infrared imager are summarized in Table 10. Here, the size of the corrected field of view is based on an extrapolation of actual CFHT results using a detailed turbulence theory, and no particular advance in adaptive optics technique or technology is required to achieve it.

It is significant that no existing or currently planned astronomical telescope has incorporated adaptive optics in the design from the conceptual stage. As a result, all adaptive optics systems currently in operation or under development are effectively retrofits to more or less conventional optical mechanical systems. NOAO has an opportunity to adopt the cream of adaptive optics technology which has already been proven, and the best ideas of the technology which is still in progress, and to implement these in new telescopes at the most fundamental level. This is certain to be the preferred direction of the future.

scales. For this reason, it may be more convenient to conceive of it as a prototype, but its goal should be extensive operation for scientific programs requiring high resolution infrared imagery and somewhat improved CCD imagery, but for which a modest reduction in throughput is acceptable.

This adaptive optics system gives a virtually guaranteed scientific return in science of the types already demonstrated at other facilities. The study of star formation regions is a popular field among NOAO users, and significant observer demand is reasonably certain.

Actual experience at SOAR will provide the basis for a direct evaluation of the sensitivity gains to be achieved with implementation of an adaptive secondary, prior to committing the substantial resources needed for such a project.

Operation at existing facilities (for example the older 4 meter telescopes) will provide a very direct evaluation of the gains achieved with active/adaptive correction of optical aberrations, telescope tracking errors, wind shake, etc. This will permit confident planning of future upgrade of these facilities incorporating this technology.

Adaptive optics observations at 2 meter class telescopes can be utilized to determine the potential for compensating preferentially boundary layer and low altitude turbulence, and the resulting image quality achievable over extended fields of view.

Further experience with laser beacons in the community will be required before the technology can be properly evaluated for use at NOAO. Even if the potential is strong, NOAO's interest in it may emphasize different directions than in most current development.

The implementation of a simple, natural guide star adaptive optics camera is a compromise of guaranteed scientific return, sensible preparation for possible future scenarios, and caution concerning technology which is still in the R&D phase. The proposed adaptive optics imager will allow NOAO to profit rapidly in of the science areas where adaptive optics has produced frontier results. Its visible and infrared operation at NOAO telescopes will lead to accurate determination of the gains of various levels and strategies of active and adaptive correction, both on new and existing facilities.

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