

Frontier Science and Adaptive Optics On Existing and Next Generation Telescopes

For the ASTRO2010 Decadal Survey Committee

State of the Profession Study Group on
Facilities, Funding, and Programs (FFP)

Submitted by AURA's Coordinating Committee of Observatory Research
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A. Introduction

*'The **Giant Segmented Mirror Telescope (GSMT)**, the committee's top ground-based recommendation and second priority overall, is a 30-m-class ground-based telescope that will be a powerful complement to NGST [now JWST] in tracing the evolution of galaxies and the formation of stars and planets. It will have unique capabilities in studying the evolution of the intergalactic medium and the history of star formation in our galaxy and its nearest neighbors. GSMT will use adaptive optics to achieve diffraction limited imaging in the atmospheric windows between 1 and 25 μm and unprecedented light-gathering power between 0.3 and 1 μm .'*

"The utility of a 30-m or larger aperture telescope depends crucially on its near-diffraction limited performance, particularly in the 1 to 25 μm range." (From Astronomy and Astrophysics in the New Millennium and its Panel Reports (hereafter referred to as "DS2000").

Adaptive optics (AO) systems are playing an increasingly important role in the forefront of astronomical research. Areas of research benefiting from AO range from Solar and planetary studies to the most distant galaxies. Some of the science resulting from AO observations is truly transformative. As one example we have the direct determination of the mass of the central black hole in the Milky Way. As another, we have the direct imaging of extrasolar planets around HR 8799. Other examples of major scientific results with broad impact that have been possible only with AO systems on the largest telescopes include discovery, imaging, and spectroscopy of very low mass companions to bright stars and determination of their dynamical masses; dynamical studies of stars and gas around the nuclei of galaxies; revelations concerning the nature and dynamics of distant galaxies; determination of the dynamics of gaseous outflows from young stellar objects and of proto-planetary disks; and detailed studies of solar granulation and inter-granular solar magnetic fields. All of this has been accomplished in spite of the fact that it has only been since the DS2000 that AO systems have become readily available to astronomers. These examples clearly demonstrate the great value of AO on *existing* telescopes as well as their being crucial for the next generation of extremely large telescopes (ELTs).

A vigorous and well-supported AO program in the US would strongly benefit current *and* future astronomical research at all observatories public and private, nighttime and solar. In spite of its importance, funding for AO research, design, and development work in the US is at a crisis point. The mandated 10 year lifetime of the NSF supported Center for Adaptive Optics is drawing to a close. The NSF funded Adaptive Optics Development Program (AODP) has been shut down; a possible weak alternative funding source to the AODP has been proposed as part of NSF's ATI program. The net result of these terminations is the removal of about \$4M a year from the AO funding stream for astronomical applications in the United States. This amounts to between one-third and one-half of the total of *all* publicly available funds for AO in the US.

As public funds for AO in the US are shrinking, in Europe they are growing substantially. They are growing to the extent that reasonable projections indicate that in 2009 the yearly expenditure for AO related activities in Europe will exceed that in the US from public *and* private sources by about a factor of three. And while the US funds are distributed over about a dozen observatories and institutions, the European funds are concentrated almost entirely on one observatory - ESO.

This white paper is a summary of the current state of adaptive optics in the US and where we need to be going. A considerably [expanded version of this report](#) is included on a [Suggested Reading List for Members of the Astro2010 Panels](#) on AURA's website. This white paper and AURA's report complement the 2008 [Roadmap for the Development of United States](#)

[Astronomical Adaptive Optics](#) (hereafter the “2008 Roadmap”). This Roadmap was produced at the urging of AURA’s Coordinating Council of Observatory Research Directors (ACCORD). It is based contributions from 24 participants and comments from more than 100 knowledgeable individuals in the astronomical community.

B. The Scientific Impact of Adaptive Optics

It is only within the past decade, *since* the publication of DS2000, that functioning AO systems have become readily available on 8-10 m telescopes and are producing significant and important science. Consider the following: from 1991-1996 there was a total of only 19 [published, refereed papers](#) presenting *scientific results* (as opposed to technology and instrumentation) based on observations made with AO systems. In the first few years of the current decade there were 30 to 40 AO-based science papers in refereed journals. In 2006 and 2007 this number was already up over 100 per year. This rapidly climbing number of AO science papers clearly demonstrates that AO offers remarkable improvements to the performance of existing telescopes in addition to being crucial for the next generation of ELTs. Furthermore, the demand for use of these systems is high. Highlights of some recent major scientific results from observations made with AO systems on existing telescopes include:

- New understanding of atmospheric phenomena for the outer planets and their satellites accomplished via imaging *and* spectroscopy at high spatial and spectral resolution;
- Detailed studies of solar granulation and inter-granular magnetic fields;
- Determination of the dynamics of gaseous outflows from young stellar objects and of proto-planetary disks via imaging and spectroscopy;
- Discovery, imaging, and spectroscopy of very low mass companions to brighter stars and determination of their dynamical masses;
- Determination of the mass of the black hole in the Galactic center via high accuracy astrometry and spectroscopy of heavily reddened stars;
- New insights on the stellar content of nearby galaxies;
- Dynamical studies of stars and gas around the nuclei of galaxies.
- Revelations concerning the nature and dynamics of distant galaxies via high spatial and spectral observations.

To illustrate AO’s capability for observing distant galaxies we reproduce in Figure 1 (McGregor et al 2007, *Ap&SS*, **311**, 223; figure caption from same reference) a spectacular image of the central region of Cygnus A taken with the Near-IR Integral Field Spectrograph (NIFS) and the ALTAIR NGS system on Gemini North. NIFS has a pixel size of 0.04 x 0.1 arcsec, 29 slitlets each with 2040 spectral pixels for a total FOV of 3.0 x 3.0 arcsec, a spectral resolution of ~5300, with image quality that can be diffraction limited. The figure shows the remarkably different nuclear structure exhibited by emission from the different atomic and molecular species.

C. Adaptive Optics and Image Quality

An AO system has the potential to deliver diffraction limited images by compensating for atmospheric turbulence. This results in enormous gains for both imaging and spectroscopy. An AO system removes to the greatest degree possible the deleterious effects of both the spatially and temporally varying turbulence in the atmosphere above the telescope from the incoming

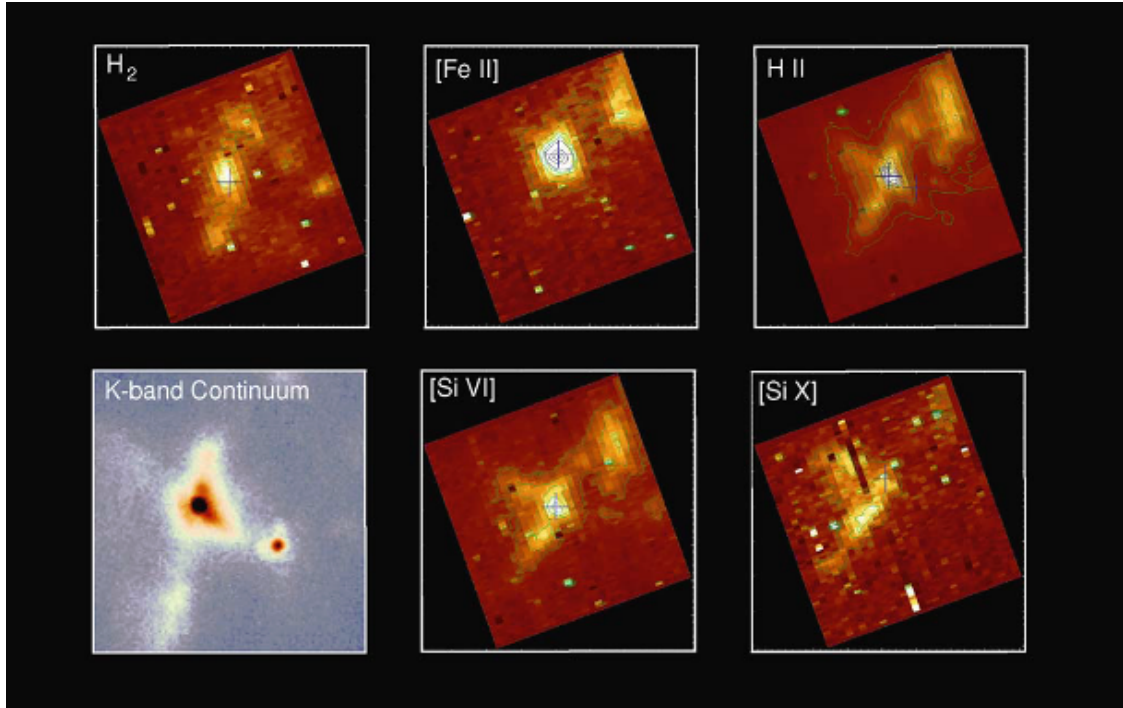


Fig. 1 The morphology of the nuclear regions of Cygnus A in various wavebands from McGregor et al (2007). North is up, and east to the left. The size of each white square is $4 \times 4''$. The NIFS line images are integrated over $\pm 500 \text{ km s}^{-1}$ equivalent waveband. Note how the molecular hydrogen image reveals the bright inner accretion disk and a system of clouds which help define the ionization cone. The [Fe II] line is confined to the circum-nuclear region and the innermost portions of the ionization cone, with a bright feature to the NW which likely represents a cloud illuminated by the central engine. The remaining emission line images show various aspects of the ionization cones discussed in the text. The K-band continuum image is from Canalizo, et al (2003).

beam thereby maximizing the Strehl ratio - the ratio of peak intensity of an aberrated vs. perfect wavefront. Other metrics that measure the efficacy of an AO system include: How variable is the Strehl ratio in time and over the field of view? How rapidly can the AO system respond to these temporal variations? How faint a reference star can be used for AO systems with and without laser guide stars? The last question is especially important to determine the fraction of the sky that is accessible to AO systems.

Without AO on a night of good to excellent seeing on, e.g., Mauna Kea, a typical Strehl might be 0.6% with a FWHM of a stellar image of 340 mas. In contrast, over a recent three month period at the Keck Observatory typical Strehl ratios were between 50 and 70% in the K band, a *two order of magnitude improvement* in the concentration of the light from a star.

In stark contrast to seeing limited imaging where sensitivity gains only go as $(\text{Diameter})^2$, for diffraction limited imaging the flux of photons from a *stellar* source on a detector goes as D^4 for a constant Strehl. Since the size of the diffraction limited core of the image decreases linearly with increasing D , the effective size of a stellar image in pixels is independent of D for the same Strehl, telescope f /ratio, and pixel size. This also implies that a spectrograph's size no longer has to increase with D to achieve the same spectral resolution. It also means that background-limited observations gain in sensitivity if the detector Nyquist-samples the diffraction limit.

As an example of the gains achieved in imaging crowded stellar fields, we show in Figure 2 the core of the globular cluster M13 obtained in 2003 on Gemini North with NIRI during the commissioning run for Gemini's AO system – Altair. The image on the left was obtained without AO but under *exceptional* seeing - $0.26''$ FWHM in H. The one on the right is from the

same night but with the Altair AO system. The FWHM of this is $0.060''$, within $\sim 0.02''$ of the theoretical limit for an 8 meter in the H band.

The advent of laser guide star (LGS) AO systems has had a major impact on AO system performance. An LGS system still requires a natural guide star (NGS) for tip tilt correction. But with an LGS the NGS used can be several magnitudes fainter than a system without a LGS. Thus sky coverage is greatly expanded. As an example for the same required Strehl, a LGS system covers 50% of the sky at $\delta = +45^\circ$ whereas a NGS system would cover less than 10% of the sky at that latitude. A LGS also enhances the uniformity of the images across the field.

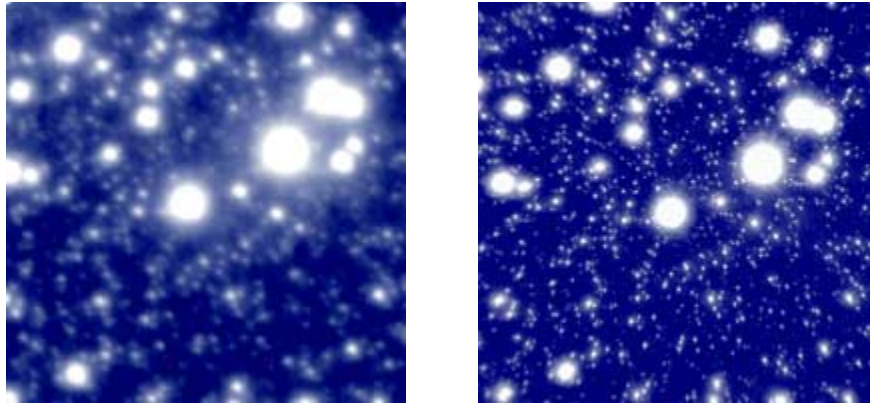


Figure 2: Images in the H band taken with Gemini North and NIRI. The left hand image taken on a night of exceptional seeing has a FWHM of $0.26''$ with no AO. The right hand one uses the Altair AO system and has a FWHM of $0.060''$, only about $0.02''$ greater than the diffraction limit.

In addition to the above advantages, other performance improvements that result from use of a LGS system combined with advances in algorithms used for data processing, have contributed to significant gains in the photometric and astrometric accuracy of observations made with AO especially in crowded stellar fields. Photometric uncertainties of only a few percent can now be achieved even with Strehl ratios as low as 4% in crowded fields. For higher, more typical Strehl ratios, photometric accuracy is significantly better as well.

Two key reasons why AO is capable of making high precision astrometric observations are that diffraction limited imaging on large telescopes yields a significant enhancement in spatial resolution *and* in the signal to noise ratio for an observation of given exposure length over non-AO observations. “*These two effects,*” quoting Cameron et al (2008, arXiv:0805.2153v1), “*reduce the errors in determining stellar centers, increase the number of possible reference stars at small separations, and allow techniques for mitigating systematics...*”

To summarize, what has changed since 1999 years is that the best Strehl ratios have gotten better and good performance as measured by the frequency of high Strehl nights has increased. Laser guide stars have allowed AO to function well with much fainter natural guide stars, and NGS AO improvements now allow the use of somewhat fainter guide stars even without a laser. As mentioned earlier, the ability to use fainter tip-tilt stars immediately implies that a greater fraction of the sky can be observed with AO systems, particularly at high galactic latitudes.

D. Adaptive Optics and the View from Space

In space, of course, without an atmosphere, the whole question of high-bandwidth AO becomes moot. Nonetheless, future space telescopes *will* need AO if they are segmented or made of very lightweight (and hence more flexible) materials. However, while on the ground an AO system

must have a bandwidth of hundreds of Hertz, in space the needed bandwidth is orders of magnitude less with a resulting Strehl ratio that is always at or close to 1 in the *optical* as well as in the infrared. The primary job of an AO system in space is to compensate for variations in the thermal loading on the telescope that causes small scale deformation and, for a segmented telescope such as JWST, to correct for slow drifts in the positions of the mirror segments due to sensor or actuator drift. Furthermore, there is no limitation in sky coverage (except for Sun and Earth avoidance) nor are there weather related or safety restrictions.

Nonetheless, with the largest ground based telescopes having apertures many times larger than the largest space telescope, the potential for diffraction limited imaging in the near and mid-IR from the ground with resolutions many times greater than what can be done from space at the same wavelength creates a powerful synergy between space and the ground, especially important for studies of stellar populations in crowded fields in clusters or galaxies. This point is illustrated in the figure below. The images of Neptune in a and b below were taken on successive days in 2002 on Keck in the H band with the NGS AO system (Gibbard et al. 2003). Image c is with HST/NICMOS at about the same time. There are some obvious “jpeg” artifacts in the latter, but the superior quality of the near diffraction limited image with AO is obvious.

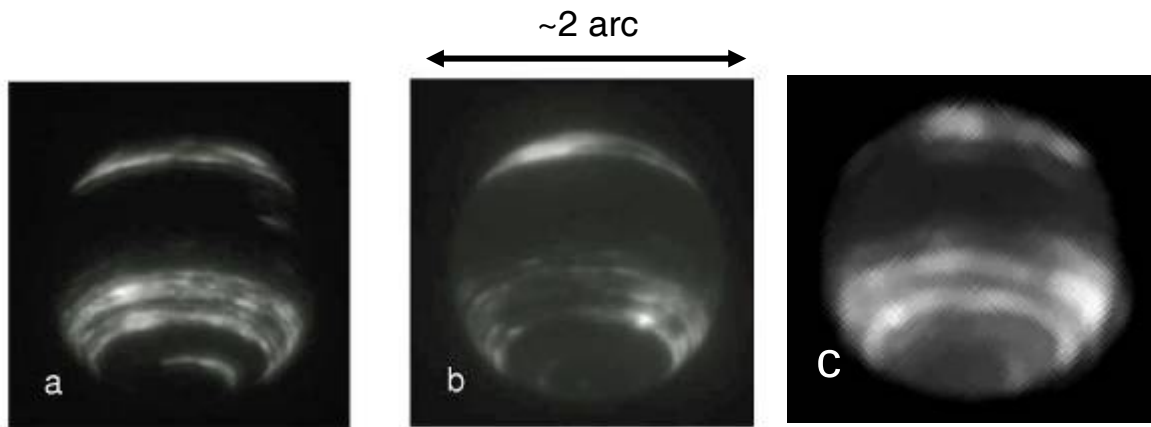


Figure 3 – Neptune with Keck AO (a and b) and with HST/NICMOS; all in the H band. See text for details.

It is also interesting to note that if *only* total lifetime costs and efficiencies as measured by “open shutter” time on targets of interest are considered, the cost per hour of observing time of JWST is about a factor of two greater than the cost of a GSMT, specifically, for this comparison, the TMT. Assumptions that have gone into this comparison are given in AURA’s AO Report.

A detailed case for the synergistic relation between JWST and an ELT may be found at http://www.aura-astronomy.org/nv/GSMT_SynergyCase.pdf on AURA’s [Reading List for the Decadal Survey](#). The central point is that each of these telescopes has unique advantages and that the two working in tandem are considerably more powerful than the two working independently.

E. Beyond simple AO systems: Where we are now

In addition to “simple” AO systems that employ a single NGS or LGS, the past decade has seen considerable development and deployment of several types of more complex AO instruments. These newer more advanced systems not only provide greatly enhanced performance and scientific capabilities on existing telescopes, but also are key stepping stones towards

maximizing the scientific potential of the coming generation of ELTs. Further refinement of these more advanced instruments will be strategically important for making effective use of ELTs. Thus their deployment on existing telescopes provides an important test bed for the future. It is particularly notable that even the concepts which lie behind these more complex AO systems were developed only recently to the point where usable instruments could be deployed – another example of the rapid strides being made in the field of AO and its capabilities for yielding exciting scientific results. Some of these new systems are described briefly below.

A multi conjugate adaptive optics systems (MCAO) relies on 3-dimensional atmospheric turbulence compensation by means of several laser beams and several deformable mirrors (DMs) conjugated to different altitudes in order to more fully sample and correct the atmosphere along the line of sight. With an MCAO system the isoplanatic patch can be significantly enlarged compared with that possible with a single laser. In practical terms this means an order of magnitude or more gain in the area of the field of view over which the PSF is uniform. An NGS based MCAO system has recently been demonstrated on the VLT with the first science results published (Guillieuszik et al. 2008, *A&A*, **483**, L5). A LGS based MCAO system is expected to come on line shortly on [Gemini South](#). Since essentially all solar observations require a large field of view, an MCAO system is a top priority in the planning for the Advanced Technology Solar Telescope (ATST). In contrast to night time observing, though, lasers are not necessary, rather the solar structure itself provides multiple “natural guide stars”.

A ground layer adaptive optics system (GLAO) presents an opportunity of extending partial correction for turbulence to optical light observations via atmospheric tomography of just the lower layers. In the optical, GLAO can improve the FWHM of seeing limited images by a factor of two to three over a field of view of several arc minutes. Thus a GLAO system on an ELT would be especially valuable. At present a [GLAO system on the WHT](#) on La Palma is scheduled to begin science operations in 2008 August; another one is being commissioned on the MMT. A GLAO system for the 4-m SOAR telescope, [SAM](#), is expected to be completed in 2010 and on-going studies are being carried out for GLAO systems on the Gemini telescopes as well as plans for one on the Giant Magellan Telescope (GMT).

Multi-Object AO (MOAO) is an approach where the whole field is not corrected simultaneously. Instead, the results of turbulence tomography with multiple NGS or LGS are used to calculate the correction for a number of selected objects within the field, typically over small sub-fields of only a couple of arc seconds. This approach would be especially valuable for extra-galactic applications with multiple high redshift targets over a several arc minute field of view. A key required technology for an MOAO system is the availability of small deformable mirrors which would have to operate in an open-loop mode, i.e. no feedback. The next generation AO system for Keck (NGAO) would likely implement such a concept.

An Extreme AO system (ExAO) is basically a “classical” AO system of very high order working on a bright NGS to detect faint companions to nearby stars. Two such systems are under development (the Gemini Planet Finder (GPI), and SPHERE for the VLT) with the science goals of direct detection and characterization of extra-solar planets. This is a very competitive field with its own roadmap in Lunine’s (2008) report of the Exo-planet Task Force.

F. AO Systems and OIR Interferometry

The rapidly growing list of scientific publications from the Keck and the VLT interferometers shows that interferometry of celestial sources is beginning to play a more and more important

role in advancing our knowledge. For example, interferometric observations on the VLTI have produced 93 refereed papers since 2002. For both observatories AO systems working in the near to mid-IR are key to the success of their interferometric efforts.

In contrast to Keck and VLT, CHARA is an array of small telescopes for making interferometric observations. To date most of its work has been in the optical without AO. However the predicted gains in sensitivity if AO were implemented on the CHARA telescopes are major and extend down into the R band. For example, for CHARA the estimated gains in the Strehl ratio range from a factor of 1.6 in the K band to a factor of 10 in the R band. AO correction of the incoming beams would be simple compared to what is required on much larger telescopes.

G. Key Technologies needed for the advancement of AO

AURA's AO report and the 2008 AO Roadmap discuss the pacing technologies for the AO instruments that will be required for ELTs to fulfill their scientific potential as well as those that are needed to enhance the capabilities of existing telescopes to do cutting edge science. Below are brief summaries of the most important technology areas that must continue to be pursued.

Sodium lasers are the key components of AO and MCAO/MOAO systems working on faint targets. They are essential for expanding the sky coverage of AO systems, especially at high galactic latitudes where the areal density of suitable natural guide stars is low. The past ten years have seen remarkable advances in their development. Several observatories are now equipped with these lasers. Two big issues have been their cost and the availability of lasers with sufficient power. The cost issue is a major one facing further AO system deployment. Alternative technologies for the production of artificial guide stars are discussed in section 5.

Deformable mirrors (DMs) for AO come in three sizes of interest: large, to serve as secondary mirrors on large telescopes, medium, using glass face sheets and piezo actuators, to small, multi-element electrostatic MEMS based deformable mirrors. An adaptive secondary has been deployed on the MMT; others are being built for the LBT and the VLT. Active development of MEMS for astronomy *and* for vision science has been a major accomplishment of NSF's Center for Adaptive Optics: currently 1000 actuator MEMS for astronomy exist and work well, and the first 4000 actuator device has been delivered for testing for the Gemini Planet Imager. A directed effort may be needed to ensure that the future needs of the astronomical community for MEMS can be met, particularly as MOAO systems for today's 8-10m telescopes and for ELTs will need more actuators and higher stroke.

Near-IR detectors for wavefront sensing: There is a considerable push for the development of near-IR detectors for wavefront sensing. Such a capability would produce two big gains related to enhanced sky coverage. First, many dark clouds and star forming regions of interest have no stars optically bright enough to use even for the tip-tilt correction required by a LGS system; nearly all of these obscured regions, though, have bright near-IR stellar sources. Secondly, since the seeing in the near-IR is measurably better than in the optical, the photon flux is almost always higher, and the iso-planatic angle is larger, AO systems will be able to use fainter guide stars for tip-tilt correction and have a significantly greater area of sky coverage at each pointing.

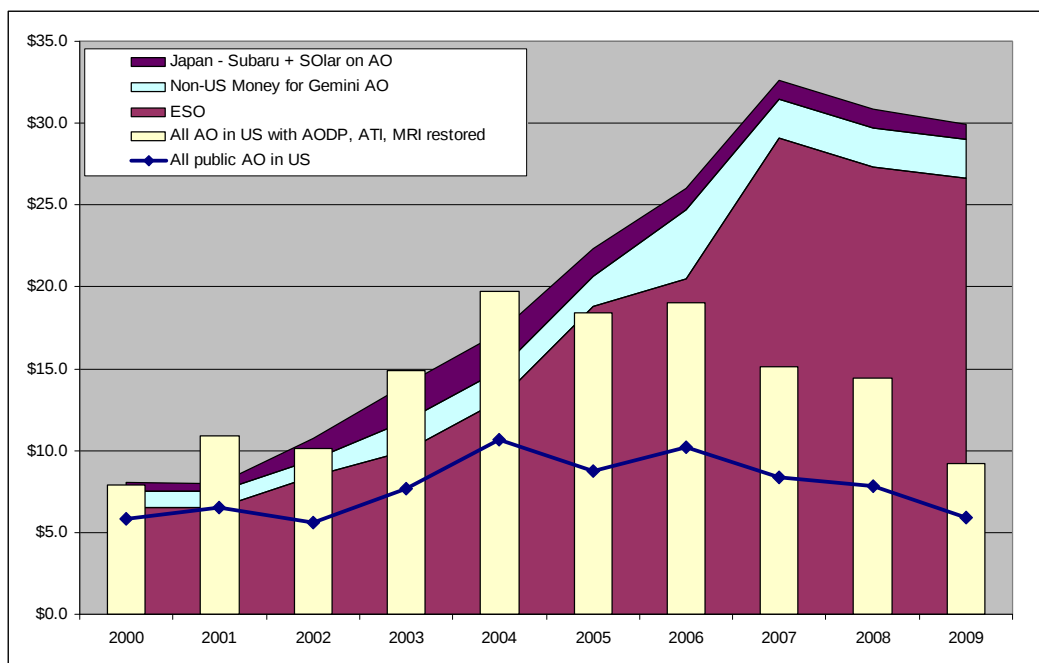
Visible light AO systems will become especially important over the next decade for two simple reasons: At present diffraction limited imaging over moderate to wide fields is for all practical purposes limited to the cameras on HST; HST's projected lifetime is about 5 years after SM4. Secondly, JWST will not be diffraction limited for wavelengths shortward of 2 microns. There

are currently a number of projects that are working on visible light AO systems including ones at Keck, Lick, and Palomar Observatories.

AO Systems: Costs and Operations: There is no getting around the fact that most AO systems are large, complex, and costly both to construct and, at present at least, to operate. The completion of a joint venture (Keck, Gemini, US Air Force) for developing a commercial source for sodium lasers *may* be an important step forward in bringing the costs down for laser systems. Nonetheless, the future cost and continued availability of laser systems remains one of the major risks for both ELTs and for tomographic AO systems on existing large telescopes. A positive step would be for increased inter-observatory collaboration to avoid duplication of similar instruments if actual demand can be met with only one. A way forward here would be to implement more time trading deals such as those pursued by some of the observatories on Mauna Kea. A sharing of R&D costs for needed technology developments would also be helpful. And once an expensive and complex AO instrument is put into use it is often the case that many highly trained and skilled people are needed to use it and ensure that it keeps running.

H. Funding Issues: A Comparison with ESO

Although there is still much to understand about the temporally and spatially varying turbulent atmosphere, we do know enough about it so that modeling of the turbulence can successfully result in the design, construction, and use of AO systems that deliver a high level of performance. Key developing technologies including those summarized above are essential for advancing this work. However, the ability to advance these key technologies needed for both AO development and implementation for astronomical research is strongly limited by the



availability of funds. We give a brief overview of the funding situation drawn from the [article by Frogel](#) (2006, Gemini Focus, p. 82). Unfortunately, since that article appeared there have been no positive developments for AO funding in the US while the projections for funding AO development at ESO have remained valid.

NSF has been the primary *public* source for funding AO R&D for astronomical applications over

the present decade through several channels: the Adaptive Optics Development Program (AODP) initially administered by NOAO, funding to Gemini Observatory for their AO program, and the Center for Adaptive Optics (CfAO). Private sources of funding for AO R&D have typically been about 40% of the public funds on a yearly basis since the late 1990s. However the largest source of NSF funding for AO R&D has been PI grants to universities, observatories, and other institutions especially via the MRI and ATI programs. The Department of Defense (DoD) has also made significant contributions to AO technology. For example the Starfire Optical Range (SOR), an Air Force facility, has been active in the development of laser guide star adaptive optics for two decades now (Fugate 2000, Proc. SPIE, Vol. 407, 422) and is actively collaborating with the broader community in this endeavor (see below).

NSF funding is only a small fraction of the amount that ESO commits to its AO activities. As astronomical AO becomes a mature technology, the level of investment required to move it forward will become higher, especially for the construction of facility instruments. Increasingly, this investment will likely be directed to specific components of AO systems, although the use of technological advances driven by non-astronomical AO applications will still exist.

The Figure below compares AO spending in the US with that being spent in Japan and by ESO *just* on the VLT. We repeat some of the conclusions from Frogel (2006):

- ESO/VLT is the “national” large telescope for Europe; Gemini fulfills that role for the United States. ESO is outspending the *total* (i.e. US plus international partner contributions) Gemini AO budget by a significant factor even when the Gemini numbers are scaled upwards by a factor of two to go from two to four telescopes.
- In 2000 ESO and US *public* expenditures for AO were comparable, ~\$8M. By 2006 public U.S. expenditures had flattened out at \$10M/year while ESO’s had more than doubled to \$20M/year.
- An extrapolation of US public AO expenditures through 2009 based on 2006 spending levels shows a slow decline to \$6M. ESO’s, on the other hand, shows a rise to \$26M, four times greater than the US’ public level. And that’s assuming a restoration of AODP!
- Absent any new monies, current projections have the private plus public total declining to \$9M/year during 2009, compared with ESO’s \$26M, nearly three times as much being spent for one observatory and four telescopes as for about one dozen observatories and more than a dozen telescopes in the United States

I. Where do we go from here: The 2008 AO Roadmap

The 2008 AO Roadmap underscores the critical importance of AO for the various ELT concepts that are currently being worked on and stresses the worrisome decline in financial support for AO R&D in the United States over the past few years. The Roadmap’s recommendation was for \$50M (2008 \$) spread over 10 years for all areas mentioned in the Roadmap, but not including work for first generation AO systems for ELTs, most of which should come from the NSF. This would still be only about half of ESO predicted expenditures over the same time period, and, as noted in the previous section, ESO’s work is concentrated on one observatory and planning for one more (the E-ELT), while in the US AO work is carried out at about one dozen observatories for about the same number of telescopes *plus* planning for two ELTs – TMT and GMT. Thus, the financial support recommended by the Roadmap may be too modest, especially if the US expects to continue to play a leadership role in the development and deployment of AO systems. The AO Roadmap Committee made the following statement in anticipation of ASTRO2010:

“The AO Roadmap Committee strongly endorses a preeminent role for the vigorous exploitation of existing ground-based AO capabilities, particularly precision laser guide star based AO, in the 2010 Decadal Survey. We encourage full support for the development of a complementary suite of next-generation scientifically specialized AO systems and their back-end instrumentation, for visible light, extragalactic, high-contrast, time-domain, and solar astronomy in the 2010’s.”

Such a strong level of support for AO capabilities is needed to exploit the scientific benefits to be realized from past investments in AO that until recently have kept the US in the forefront of AO-produced science and to address *“the key areas of national concerns raised in the Frogel [2006] report”*. The top priorities of the 2008 Roadmap for AO are summarized in their section 9.

The 2008 Roadmap for AO drew three broad conclusions regarding the furthering of ongoing work on the type of AO systems mentioned above with the goal of implementation on ELTs:

- Laboratory and controlled field demonstration of new AO system architectures and subsystems need to have high priority as well as the demonstration of new component technologies in real-world observing scenarios.
- The development of suitable, robust, cost-effective sodium lasers with sustainable availability for the astronomical community is important (see section 6 of this report).
- There needs to be collaborative studies between laser developers and observatories to understand the interaction between laser spectral line and pulse formats, peak power, and polarization state and the mesospheric sodium layer

If AO facilities in the US are to remain competitive with those being developed in Europe for VLT and E-ELT, then AO capabilities must meet certain science based metrics. The Roadmap Committee defined key science based metrics that must be met and provided for. Examples of these metrics include:

- *“Understanding the formation of planets, especially earth-like planets, will require dramatic improvements in the ability to detect and characterize faint objects next to bright objects.*
- *“Measuring strong field General Relativity around the supermassive black hole at the center of our Galaxy requires improvements in astrometric accuracy.*
- *“Accurate photometry will lead to better estimates of the size and shape of moonlets in multiple asteroid systems which will give strong constraints on their formation mechanism.*
- *“All astronomical science will benefit from lower wavefront error, and hence higher Strehls, including the higher spatial resolution and new science wavelengths offered by observations at visible wavelengths.”*

To conclude, we re-emphasize that the development of AO systems is not just for the next generation of ELTs. The AO systems on existing telescopes have already amply proven their worth and scientific impact and hold out considerable promise even for telescopes of smaller size. The ReSTAR report gives some excellent examples of this.