A Roadmap for the Development of United States Astronomical Adaptive Optics

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1 EXECUTIVE SUMMARY

Over the last decade, adaptive optics (AO) has proven itself as a powerful tool for ground-based astronomical science and has been integrated into the infrastructure of nearly every major US optical/infrared observatory. High-angular-resolution science on the largest apertures has advanced our understanding of the universe around us. The climates of nearby worlds have been mapped, and their evolution with planetary orbit and solar output is beginning to be understood. Stellar and planetary nurseries have been probed with exquisite detail, informing our understanding of the birth of our own solar system and the Earth. The black hole at the center of the Milky Way has been weighed and the properties of our galaxy are being compared to newly accessible understanding of the physical processes that control the assemblage of matter on all spatial scales. The US investment in AO made in the 1990’s and early 2000’s is now resulting in a steadily increasing number of science publications from our major observatories.

Our capability to advance astronomical science using these maturing technologies, however, is now severely threatened by a disparate reduction in US investment in AO relative to the international community. Annual public investment by the US in adaptive optics, already less than one-half the AO investment of the European Southern Observatory alone, is projected to fall to one-quarter of ESO’s level by 2009. As the US astronomical community is now beginning to exploit first-generation laser guide AO for science on four major US observatories, renewed investment is required to expand the benefits of AO to new spectral wavelength regimes, wider fields of view, and toward more precise photometric and astrometric science results. At the same time, the design of a new generation of 30-meter class extremely large telescopes (ELT’s) is making remarkable progress. These revolutionary machines will transform human understanding of the cosmos, but they remain scientifically reliant on the successful development of unproven AO system architectures and capabilities.

Achieving the enormous potential gains of AO on these facilities requires an urgent, renewed commitment to long-range planning, increased funding, and new ways of eliciting, supporting, and sustaining support of research and development in the academic and private sectors.

Since the original 2000 AO Roadmap was composed to guide US investment new science drivers have been identified, new AO architecture concepts have been proposed, alternative technical solutions have emerged, and programmatic lessons have been learned, some of which were incorporated into a 2004 Addendum. In October, 2007, recognizing the rapid adoption of AO into mainstream astronomical science, a broad-based Committee representing the US astronomical AO community convened to review the science role of AO, evaluate technical progress, and to draft

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2 de Pater, I., et al., Journal of Geophys Research, 11, Issue E7, CiteID E07S05.
4 Liu, M., Science 305, 1442.
9 Frogel projects US public investment in AO on all telescopes to decline to $6M/year while ESO investment grows to $26M/year in the same period (assuming currency conversion based on 2006 dollars.)
herein new recommendations for the most cost-effective investments to address critical needs spanning the next ten years.

Recognizing the widespread adoption and growing impact of AO on US astronomy, the unanimous key recommendations of the 2007 AO Roadmap Committee are:

- Recognizing the success of past AO investments, noted by the recent dramatic increase in AO science publications, we encourage strong support for a coordinated national AO science infrastructure in the forthcoming national Decadal Survey, Astronomy and Astrophysics 2010.

- To maintain US science competitiveness and fully realize the science capability of extant and future 30-meter class telescopes, there is an urgent need for significant, sustained federal investment in AO development.

  - To support development of AO for extremely large telescopes, next-generation AO for large telescopes, and targeted propagation of AO throughout the mid-sized telescope infrastructure, federal investment of approximately $40M over the next ten years will be necessary to address top-tiered development needs, above and beyond the construction costs for these facilities.

  - A competitive, peer-reviewed NSF Adaptive Optics Development Program (AODP) targeting the nation’s top-priority needs is an open, cost-effective means of broadly advancing US astronomical science on apertures of all diameters.

- To gain critical quantitative understanding of new concepts and architectures, priority should be placed upon well-controlled laboratory and on-sky AO experiments having proportional impact on science capabilities.

- To foster improved United States science and technological competitiveness, federal resources are needed for training and development of up to 40 expert AO engineer and operators, within the larger framework of improved career paths for astronomical instrumentalists.

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10 We estimate this approximate need using the 2008-2017 AO programs proposed in Section 8, assuming a need for two developers and two operators for each AO facility.
2 SCIENCE IMPACT OF AO IN ITS FIRST DECADE

Since the first technology experiments in the early 1990s, astronomical AO systems have been widely adopted to now form a core capability of modern observatories. Nearly every large US observatory has developed or is developing AO capabilities. Figure 1 illustrates the rapid rise in publication rate from all AO systems (left) and recently from LGS-AO systems (right). The rapid rise in NGS-AO publications in 1997 was coincident with the first high-order AO systems on mid-sized telescopes: PUEO on the CFHT and ADONIS on the ESO NTT. The publication rate has since continued to rise as new NGS-AO systems and science instruments have come online. Similarly, the rapid rise in LGS-AO publication rate since 2005 can be attributed to the commissioning of the first LGS-AO system on a large telescope, Keck II.

Despite the impressive growth, US AO observations and thus AO publications, now approximately 100 per year, remain a small fraction of the total number of US astronomical science publications each year, estimated to be over 3,500 per year\textsuperscript{12} in \textit{ApJ+AJ+PASP} for CY2007. Although we may naturally expect the number of AO publications to grow with the number of facility US LGS-AO systems coming online, the integration of AO into mainstream (if not majority) astronomical use still faces considerable challenges, including:

- Limited wavelength coverage for AO correction (currently near- and mid-infrared only)
- Limited sky coverage due to suboptimal tip/tilt sensing with current LGS systems
- Limited diffraction-limited isoplanatic angle due to single-conjugate wavefront compensation
- Limited application to wide-field science due to relative immaturity of ground-layer AO compensation techniques
- Limited faint object spectroscopy due to lack of AO multi-object spectrographs
- Limited knowledge of real-time AO point-spread-function (PSF)

\textsuperscript{11} http://www2.keck.hawaii.edu/library/biblios/aokeck.php
The goal of the AO Roadmap is to provide guidance in cost-effectively addressing these challenges to accelerate the realization of the benefits of AO compensation to a larger fraction of US astronomical science. Toward this end, the 2007 AO Roadmap Committee proposes herein recommendations intended to maximize the impact of AO development on astronomical science at minimal cost.

3 THE ROLE OF AO ON EXTREMELY LARGE TELESCOPES (25+ METER)

Considerable progress has been made in developing and detailing the designs of a variety of ELT’s since the last revision to the AO Roadmap in 2004. AO remains an essential requirement for many, if not most, priority science cases for these telescopes, and all advanced AO system concepts proposed to date remain critical to fully realizing one or more ELT scientific goals. For a given observing band, the highest angular resolution and best point source sensitivity will be obtained on the largest apertures equipped with adaptive optics. Similarly the highest sensitivity and highest contrast observations are expected with optimized AO systems on ELT’s. To fully realize these benefits, we must demonstrate a number of new AO concepts and technologies.

Budgetary and technical constraints, however, will dictate a phased implementation of these multiple AO capabilities. First- and early-light AO systems will generally be based upon extrapolations of currently implemented and near-term concepts and components; more revolutionary developments will be addressed in the longer term.

The extant ELT projects worldwide favor different approaches to the application of this general philosophy which, in the view of this Committee, promotes a healthy diversity of system concept studies and designs. A number of ELT designs feature large adaptive mirrors to ease the implementation of GLAO and to optimize thermal IR performance; other designs explore an LGS MCAO system providing diffraction-limited performance in the near IR with good sky coverage and minimal PSF variation over the field. In both cases, the wavefront correcting elements, the lasers, and wavefront sensors are all based strongly upon existing technical approaches.

Early AO systems for ELT’s will benefit from the considerable effort going into advancing the state-of-the-art of AO on existing telescopes. For example, new LGS wavefront sensor designs, detectors, and calibration techniques to mitigate guide star elongation have been successfully pursued for 10-meter telescopes. Reconstruction algorithms and processing hardware for very high order wavefront control and MCAO are also receiving attention. Of critical importance to the success of ELT’s are demonstrations of feasible designs using these extended methods on existing large and mid-sized telescopes. Examples of such work are the sodium LGS MCAO system under construction for the Gemini South telescope and the dynamically refocused multi-Rayleigh LGS system being commissioned at the MMT.

ExAO for high contrast imaging and MOAO for multiplexed faint object spectroscopy are now generally viewed as follow-on AO modes for ELT’s. Their implementation generally faces the same technical challenges as are found with the current generation of 8-10 meter telescopes—very high order MEMS or similar wavefront correcting elements, highly photon-efficient wavefront sensing concepts for high-contrast imaging, open loop wavefront sensing and control, and control architectures for the precise detection and control of systematic error sources. All of these issues
become more challenging (and rewarding) with the increased aperture of an ELT. ELT projects remain highly interested in and supportive of pathfinder ExAO/MOAO demonstrations and technology development, even if these capabilities are not yet considered sufficiently mature for implementation as initial ELT AO modes.

In light of these considerations, the Committee:

- Affirms the high priority of laboratory and controlled field demonstration of new AO system architectures and subsystems, and demonstration of new component technologies in real-world observing scenarios.
- Affirms the importance of development of suitable, robust, cost-effective sodium lasers with sustainable availability for the astronomical community.
- Recommends 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.

4 The Role of AO on Large Telescopes (6.5 – 10 meter)

AO systems on telescopes in the 6.5-10 m diameter range play a central role in the scientific productivity of the US astronomical community. Over the past 5 years, AO systems on large telescopes have enabled astronomers to measure the mass of the black hole at the center of our galaxy with unprecedented precision\(^6\), measure the dynamical masses of cool stars in the solar neighborhood\(^1\), probe the structure and composition of circumstellar disks\(^3,4,5\), and track atmospheric phenomena on the most distant planets\(^1\) and moons\(^2\) in our solar system. Due to the dramatic improvements in spatial resolution and sensitivity which AO and large apertures make possible, these systems are among the most highly subscribed instruments on large telescopes.

All current large telescope AO systems operate in the near- and mid-infrared, where they provide comparable spatial resolution to the Hubble Space Telescope at shorter wavelengths. This complementarity is enhanced through the use of laser guide stars, which have extended the reach of AO-corrected observations to nearly the full sky. Two single-conjugate LGS-AO systems are now in routine operation on large US telescopes, with several more planned in the next 1-2 years (Table 1). These LGS-AO systems are in high demand. As an example the Keck-II LGS AO system is typically used ~100 nights per year and is oversubscribed by a factor of two. The deployment of laser guide stars is further broadening the appeal and demand for AO, extending its applicability into the extragalactic realm.

While mid-sized telescopes provide preferred testbeds for technological innovation, new AO concepts will reach their scientific potential on large telescopes. Table 1 lists the types of AO systems operating, planned, and proposed for large US facilities. At least one of every type of AO instrument is currently proposed or planned for at least one 6.5 – 10 meter aperture.

\(^1\) Pravdo, S. et al., Astrophys J., 649, 389.
The currently operating single-conjugate adaptive optics (SCAO), while highly productive, are limited by the current state-of-the-art in lasers, wavefront sensors, focal anisoplanatism, and point spread function stability and knowledge. Improving the laser beacon surface brightness will improve the performance of LGS systems, and enable second-generation AO concepts that require affordable multi-laser architectures to overcome focal anisoplanatism. Improvements in sky coverage are also needed and can be obtained with the development of near-IR tip-tilt-focus wavefront sensors. Finally, improvements in techniques to determine the closed-loop AO PSF will improve photometric and relative astrometric accuracy.

GLAO systems are currently in planning for several of the telescopes. GLAO systems will bring improved seeing performance (1.5 to 3x) over moderate FoV (2 to 20 arcmin) with full sky coverage, massively increasing observing efficiency with current instruments. The essential technology for the largest of these FoV’s is adaptive secondary mirrors, which remain high risk and high cost developments.

The MCAO system schedule for first light in late 2009 at Gemini South Observatory will provide wide-field, diffraction-limited imaging, using an asterism of five LGS to enable a new range of galactic and extragalactic science programs, but further development of tomographic reconstructors is necessary to optimize their scientific return.

An ExAO system, the Gemini Planet Imager, is also currently being built for Gemini South. This system will achieve contrasts of $\sim 10^{-7}$ at separations of less than 0.2 arcseconds, 3 to 4 orders of magnitude better than current AO systems. In order to enable these improvements key developments are: 1) Suppression of static speckles by the use of post diffraction suppression wavefront sensors, 2) Development of computationally efficient wavefront reconstruction and control algorithms, and 3) Development of small high-stroke high actuator count (> ~4000) deformable mirrors with very low wavefront errors.

US competitiveness in high angular resolution astronomy over the next decade will continue to be strongly dependent on the high angular resolution and collecting power of our existing large telescopes. It is therefore critical for these facilities to continue to increase the scientific return from AO.

<table>
<thead>
<tr>
<th>Telescopes</th>
<th>SCAO NGS</th>
<th>SCAO LGS</th>
<th>GLAO NGS</th>
<th>GLAO LGS</th>
<th>MCAO NGS</th>
<th>MCAO LGS</th>
<th>ExAO LGS</th>
<th>MOAO LGS</th>
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<tbody>
<tr>
<td>Gemini – N</td>
<td>Operating</td>
<td>Operating</td>
<td>Planned</td>
<td>Planned</td>
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<td>Gemini – S</td>
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<td>Planned</td>
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<td>HET</td>
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<td>None under development</td>
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<tr>
<td>Keck I</td>
<td>Operating</td>
<td>Planned</td>
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<tr>
<td>Keck II</td>
<td>Operating</td>
<td>Operating</td>
<td>Proposed option</td>
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<tr>
<td>LBT</td>
<td>Planned</td>
<td>Planned</td>
<td>Planned</td>
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<td>Planned</td>
<td>MIR</td>
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<tr>
<td>Magellan (x2)</td>
<td>Proposed</td>
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<tr>
<td>MMT</td>
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</table>

**Table 1.** AO systems operating, planned, and proposed on US 6.5-10 m telescopes.
The Committee therefore makes the following recommendations:

- It is critical to support the understanding and improvement of all the performance budgets that drive the scientific competitiveness of AO. These include not just wavefront error and throughput/background, but also astrometry, photometry, sensitivity, sky coverage, observing efficiency, etc. In particular, the committee recognizes the need for better point spread function stability and knowledge to do quantitative science and the need for AO-corrected near-IR tip/tilt sensors for improved sky coverage.
- AO development and operations need to be affordable in order for observatories to commit to their development and operation. NSF support for the development of lower cost, reliable and commercially available AO components, especially lasers, would benefit the implementation of AO on large and extremely large telescopes.

5 The Role of AO on Mid-Sized Telescopes (1 – 5 meter)

Mid-sized, non-solar, telescopes are out-classed by the large telescopes in angular resolution and sensitivity. However, mid-sized telescopes are compelling in complementary ways (i.e., observing time, flexibility, student access and cost.) Telescopes with apertures between 1 and 5 meter diameter have compelling, if specialized, science potential that can only be realized using AO. In addition, the Committee confirms that these apertures have historically held, and continue to hold, a unique role in development and risk mitigation of new AO concepts and architectures due to their physical and observing time accessibility. In solar astronomy the mid-size telescopes are the only available telescopes and AO is already a core part of this science.

5.1 Extensive AO Surveys

The application of AO to the significant class of high-target-count, single-object astronomical surveys has generally been overlooked to date. Unprecedented sensitivity surveys of nearby stars for binary fraction and orbital parameters could strongly constrain star formation models, particularly for low-mass and late spectral types. Similarly, high-angular-resolution surveys of main belt asteroid families, such as the disrupted Flora family, could constrain models of the evolution of our own solar system. Moreover, extensive AO searches could in general uncover interesting / unusual subclasses of other objects, providing new insight to underlying physical processes. Covering hundreds to thousands of targets each, these surveys would be extremely time intensive on currently available AO systems. The development of robotic, queued LGS AO systems with low time overheads would enable higher sensitivity and therefore greater survey speed.

5.2 Time Domain Astronomy

A major theme of modern astronomy is the detection and follow-up characterization of transient events, including Gamma-Ray Bursts, supernovae, and X-ray binaries in outburst. The advent of Pan-STARRS observations is expected to increase the number of transient objects identified each night by 100-1000 times over current systems, with another 10 times increase expected in the era of LSST. Most such transients will require multi-band photometric characterization, requiring
significant commitments of telescope time. Since many classes of transients reach peak optical brightness of $m_V \sim 15$, the integration time advantage of AO compensated imagery reduced integration time per object and thus increases the fraction of Pan-STARRS transients that can be spectrally characterized.

### 5.3 Solar AO

High-resolution observations of the Sun are essential in solving many of the outstanding problems of solar astronomy. The current high-resolution solar telescopes, such as the Dunn Solar Telescope, are in the one-meter class and utilize AO for $> 95\%$ of the observing time to achieve the diffraction limit at visible and NIR wavelengths. Techniques to estimate the solar AO point spread function from AO system telemetry are under development and have produced first scientific results. Solar AO has revitalized ground-based solar astronomy at existing telescopes. The development of high-order solar AO that is capable of delivering high Strehl in the visible will be absolutely essential for next generation solar telescopes, such as the 4m aperture Advanced Technology Solar Telescope (ATST), which undoubtedly will revolutionize solar astronomy. The technical challenges facing conventional solar AO include development of high frame rate, large format wavefront sensor detectors for the visible, thermally controlled DM's, and powered DM's.

Solar observations are performed over extended fields of view and the isoplanatic patch over which AO provides diffraction-limited resolution is a severe limitation. The development of multi-conjugate AO for the next generation large aperture solar telescopes is thus a top priority. The Sun is an ideal object for the development of MCAO since solar structure provides “multiple guide stars” in any desired configuration. It is therefore not surprising that the first successful on-the-sky MCAO experiments were performed at the Dunn Solar Telescope and at a solar telescope on the Canary Islands. However, further solar MCAO development work beyond these initial proof-of-concept experiments is required and must include laboratory experiments and on-sky demonstrations under controlled or well characterized conditions as well as quantitative performance analysis and comparison to model predictions. It is the committee’s assessment that the international astronomy community as a whole would greatly benefit from a closer collaboration between solar MCAO efforts across international boundaries as well as between the solar and nighttime MCAO.

### 5.4 Optical Interferometry

For the foreseeable future, very high-resolution optical imaging (to scales of a few milliarcseconds and smaller) will be the domain of distributed arrays of telescopes, operating interferometrically. In the current generation of interferometric facilities, telescopes of aperture 1 – 1.8 meters, distributed over hundreds of meters, provide angular resolutions of order 1 milliarcsecond in the near-infrared. The performance of these arrays is limited by the wavefront quality delivered by the telescopes. AO offers higher Strehl with resulting improved sensitivity, stability and measurement precision in the kinds of measurements already in use. Thanks to dramatically improved wavefront quality, AO may be expected to extend the performance of optical arrays into the visible range, and (thanks to improved throughput and reduced image size) enable the use of very high spectral resolution in combination with the highest spatial resolution. The combination of spatial and spectral resolution will greatly extend the scope and diagnostic power of interferometric imaging.
Because the natural science targets of these arrays are bright, compact sources, the observing programs are generally well matched with NGS wavefront sensing requirements. As the required number sub-apertures is small, AO systems optimized for these arrays can be moderate in cost and complexity. AO implementation will be essential to bringing US telescope array facilities into mainstream use.

5.5 AO Technology Development for Larger Apertures

It is worth noting that nearly all of the technical development of astronomical AO now operating on 6.5 – 10 meter apertures originally occurred on telescopes less than 5 m in diameter. This development has required extensive engineering time and operational flexibility that is most readily available on mid-sized telescopes. The AODP Roadmap Committee recognizes the special role that these telescopes have played in AO, and anticipates that such telescopes will continue to be employed for similar benefit in the future. In particular, the Committee specifically encourages the use of mid-sized telescopes for on-sky demonstrations of algorithms and techniques, for field testing of new components, subsystems, and architectures, and for the development of calibration techniques that can be refined and deployed on the largest apertures.

In particular, mid-sized telescopes are particularly well suited for development of AO systems providing atmospheric compensation at visible wavelengths, being commensurate with current deformable mirror technology and providing engineering access to fully investigate the increasingly stringent error budget allocations necessitated for visible light work. On apertures of 3-5 meters, such visible light science capabilities are also highly complementary to the AO infrastructure of larger telescopes, matching the spatial resolution of 6.5 – 10 meter apertures at near-IR wavebands.

Mid-sized telescopes also play a key role in AO education and training. Adaptive optics systems on these telescopes serve to train the next generation of expert AO engineers and technicians. The availability of AO observing time on these telescopes also serves to educate and familiarize young astronomers to the techniques of AO. With their frequent proximity to large population centers, mid-sized telescopes also serve to educate the broader public as to the challenges posed and discoveries enabled by advanced astronomical instrumentation. For these reasons, the Committee strongly endorses targeted investment in AO programs on mid-sized aperture telescopes emphasizing technical innovation.

Based upon all of the above considerations, the Committee finds:

- Mid-sized telescopes provide compelling opportunities for world-class science in specialized fields not typically accessible on larger telescopes due to limitations imposed by schedule / observing model and in some cases specialized capabilities (e.g. solar telescopes)
- Mid-sized telescopes remain compelling platforms for AO development and risk mitigation, accelerating the realization of new science capabilities on larger telescopes.
- Collaborative efforts between the solar and night-time MCAO communities, working on all aperture sizes, would provide particular benefit to both and should be encouraged.
6 MAINTAINING US ASTRONOMICAL COMPETITIVENESS

The United States astronomical community has pioneered the deployment of sodium laser guide star adaptive optics systems. LGS AO publications from US facilities account for nearly all LGS science to date, based in part on the combination of large apertures, mature AO systems, and appropriate back-end instrumentation.

This situation, however, stands to change rapidly over the next decade, as ambitious programs in international development pipelines are completed. European Southern Observatory (ESO) alone has developed since 2004 the following six facility systems:

- An AO 3-D near-infrared spectrograph having between 0.8” and 8.0” squared field of view and J, H, and K-band spectral resolution between 1,000 and 4,000 (SINFONI).
- An AO cryogenic high-resolution infrared echelle spectrograph having R=105 with a 0.2” slit, operating from 1-5 microns, on natural guide stars as faint as mV = 17.5 (CRIRES)
- Four (4) AO systems for the Very Large Telescope Interferometer (VLTI) optimized for high NGS flux (MACAO)
- A laser guide star (LGS) AO upgrade to SINFONI, and
- An LGS upgrade to NACO.

Two ESO demonstrator systems have been proven:

- An NGS MCAO demonstrator utilizing a star-oriented Shack-Hartmann WFS approach in SCAO, GLAO, single-conjugate NGS tomography, and MCAO modes (MAD). The same testbed is also expected to shortly demonstrate a layer-oriented Pyramid WFS in each of the above system modes, and
- A laboratory NGS high contrast, test bench equipped with a pyramid, a filtered Shack-Hartmann WFS, and a 1024 actuators Boston Micromachines MEMS DM (HOT).

And successful preliminary designs for another two major AO capabilities:

- A high-contrast circumstellar material AO system for direct imaging of dozens of extra-solar Jupiter analogues (SPHERE), and
- An all-AO, all-the-time multi-laser AO pathfinder (VLT AO Facility) consisting of:
  - An 1170 actuator, 1.1 m Deformable Secondary Mirror
  - A Four Laser Guide star facility
  - A near-IR 10’ FoV imager (HAWK-I) fed with a Ground Layer AO system (GRAAL)
  - A visible-light, 1 arcmin field of view, 3D spectrograph (MUSE) fed with Ground Layer and Laser Tomography AO (GALACSI) able to provide up to 5-10% Strehl ratio at 650 nm, and
  - A corresponding laboratory end-to-end testing facility (ASSIST)

Finally, ESO has invested significantly in key component development, having developed or launch programs to develop the following:
In light of the formidable array of diverse AO systems under development outside the US, the Committee believes that:

- International exploitation of AO, as measured by both science publication count and other citation metrics (e.g. $h$-index), will surpass current US leadership within five years, without a significant increase in US investment in AO as part of a balanced national investment in instrumentation.
- Concurrently, advances in AO around the world represent an enormous opportunity for collaborative development. The Committee recommends flexibility in responding to joint US-International development opportunities. One mechanism for this might be support for modest, rapid turnaround proposals to AODP that run asynchronously from the annual solicitation schedule. Rapid proposal evaluation will be essential to capturing co-funding opportunities.

7 **Education and Engineering Expertise**

A key element of the US AO Roadmap is the training of the next generation of investigators using and developing AO for astronomy. The astronomical community depends critically on a strong well-versed team. Today, within the US observatories there is already a noted shortage of resources to both support current systems and develop future capabilities (Fugate 2006, "Alliance for Observatory Adaptive Optics: Report to the Directors"), indicating a failure of the US community to develop, place, and retain its young instrumentalists. In contrast, Europe, recognizing a similar need, has maintained significant and continuous support for training AO experts. The Committee estimates a need of up to 40 newly trained AO engineering experts in the coming decade to successfully execute the implementation of the key facilities identified in Section 8.

Noted funding shortfalls relative to Europe will impact the efficacy of the US AO community to lead the world in astronomical high-angular resolution science. To remain competitive, the US AO community must invest in the training and retention of scientists using and developing AO.
To further development of a new generation of expert AO scientists, engineers, and technicians, the Committee therefore recommends that NSF:

- Include hands-on training in AO as an evaluation criterion in AODP proposal reviews.
- More broadly, address the issue of training top-quality astronomical instrumentalists in the US community. One way to do this would be to strengthen existing student and postdoctoral fellowship programs for sustained support for individuals dedicated to careers in AO instrumentation.
- Advocate for fuller career paths for astronomical instrumentalists, including national guidelines on co-authorship on science papers based upon instrument developers contributions, as was previously addressed by the high-energy physics and interdisciplinary community.
- Increase the weight of training aspects in AODP proposal reviews.

(Continued next page)
8 AN ADAPTIVE OPTICS ROADMAP FOR THE UNITED STATES

A robust program for the next decade of US scientific advancement, building upon the successful investments of the 1990’s and early 2000’s, requires coordinated investment in a series of complementary AO facilities on US telescopes and the supporting AO technology development that benefits the entire community.

8.1 Major AO Facilities

The current planned and proposed US national program in AO is presented in timeline form in Figure 2. In the upper row of this timeline, all currently funded US programs are shown in green and proposed second-generation AO systems, still requiring funding, are shown in black typeface. The dates on the chart are estimates of the date of first refereed science publication based on peer-reviewed allocation of telescope time on each system.

The committee notes with concern that only one second-generation United States AO system envisioned for the 2009-17 period, that of the (international) Gemini Planet Imager, is fully funded. Execution of all Roadmap facilities would require an estimated 10-year (public plus private) investment of approximately US$\textsubscript{FY08} 150,000,000, not counting two first generation ELT AO systems, which are additionally expected to require approximately US$\textsubscript{FY08} 50,000,000 each, for a total of US$\textsubscript{FY08} 250,000,000. Combined public and private US AO funding from all sources beyond 2009 is estimated\textsuperscript{8} to fall to less than US$\textsubscript{FY08} 10,000,000 per year unless new funding is identified.

For comparison, total AO investment by ESO alone in the same period is projected to climb to over US$\textsubscript{FY08} 28,000,000 per year\textsuperscript{15}.

At the time of this writing, the next US Decadal Survey for national investment, Astronomy and Astrophysics 2010, is in the early stages of organization. To scientifically exploit past investments that have resulted in US AO science leadership to date, while addressing the key areas of national concerns raised in the Frogel report:\textsuperscript{8}

- 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.

\textsuperscript{14} The largest single subsystem cost for many Roadmap AO systems remains the acquisition or development of sodium D\textsubscript{2}-line lasers. Using demonstrated costing of ~$100,000 per Watt power and demonstrated sodium layer return coupling, the investment in sodium laser procurement for Roadmap system is estimated to be ~$45M (of the $150M) plus ~$15M (of the $50M) for each ELT (all quantities in FY08 US dollars).

\textsuperscript{15} For consistency, we have scaled Frogel’s US$\textsubscript{FY06} to US$\textsubscript{FY08} using 4% per annum inflation. We have not taken into account the currency appreciation of the euro relative to the dollar in this period.
8.2 Risk Reducing Investments

Underlying the major facility investments described above, the nation also requires a robust program of technology development and subscale demonstrations to mitigate risks and amortize costs that are of shared benefit to all US facilities. Section 10 describes our vision for the NSF AO Development Program (AODP) in detail, while a summary of currently envisioned priorities is presented in Section 9.

The lower row of the Roadmap timeline in Figure 2 shows the major AODP-funded development activities that we are recommending to be funded. The dates of these milestones have been chosen to meet the implementation needs of the planned US AO facilities. In this manner, the AODP and the major US Observatories can work together to deliver the cutting edge AO facilities needed to maintain US scientific leadership in high angular resolution astronomy.

Figure 3 shows for comparison a similar timeline for non-US AO facilities. The AO technology development efforts already funded for the European ELT are shown at the bottom of the timeline (and discussed in Section 6.) It should also be noted that Gemini and LBT are joint US and international facilities.

The competitiveness of US high angular resolution astronomy will depend on the ability of AO to meet certain science based metrics. An attempt at defining the key science based metrics that US AO facilities should aim to provide, as a function of time, is shown in Figure 4. A few examples 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.

The final metric in Figure 4 is the number of refereed science papers being produced per year from data obtained with US AO facilities. This is a strong indicator of the demand for and science productivity of US AO facilities.
Figure 2. US AO Roadmap timeline indicating the major planned AO activities in the US and corresponding AO Development needs required for full scientific realization of these systems.
Figure 3. International context for the US AO Roadmap timeline indicating the major planned AO activities. Gemini and LBT are underlined to indicate they are joint US – International facilities.
Science metrics for US 8-10m AO facilities

- **Companion sensitivity**: $10^6$ for 5 MJ, 5 Myr companions, $10^9$ for 1 MJ, 50 Myr companions, and $10^9$ at 10 pc & 5 AU.

- **Astrometric accuracy (mas)**: 0.2, 0.1, 0.05 (progress based on systematics control), and 0.02.

- **Photometric accuracy (mag)**: 0.1, 0.05, 0.02 (improving control laws and PSF estimation), and 0.01.

- **Wavefront error for 30% sky coverage (nm)**: 350 (NIR Science), 170 (Mid-Aperture Visible Science), and 170 (Large-Aperture Visible Science).

- **Refereed science papers per year**: 40, 150, 400.

**Figure 4.** Science metrics for the US AO community, assuming full funding of proposed Roadmap investments. Values associated with timeline 2008 represent the approximate state-of-the-art for AO science performance today.
9 **HIGH PRIORITY INVESTMENT NEEDS**

<table>
<thead>
<tr>
<th>Discipline</th>
<th>Element</th>
<th>Goal</th>
<th>Top-Priority Needs</th>
<th>High-Priority Needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis and experimental</td>
<td>LGS Beacons</td>
<td>Availability of robust, cost-effective LGS AO system lasers</td>
<td>Understanding of the interaction of laser light and mesospheric sodium including models and experiments that spur the development of lasers yielding greater beacon surface brightness per transmitted Watt at lower life cycle cost</td>
<td></td>
</tr>
<tr>
<td>Tomographic Reconstruction</td>
<td>Tomographic Reconstruction</td>
<td>Validation of the tomographic wavefront sensing approaches to predicted small residual wavefront error on the sky and in the laboratory as risk mitigation for precision LTAO, MCAO, and MOAO systems</td>
<td>Development and demonstration of robust closed-loop tomographic reconstructors</td>
<td>Quantitative verification of LTAO, MCAO, and MOAO performance under various observing conditions</td>
</tr>
<tr>
<td>Wavefront Sensor Design</td>
<td>Wavefront Sensor Design</td>
<td>Validation of robust, versatile wavefront sensors making optimal use of available photons to maximize sky coverage and reduce laser costs</td>
<td>Pupil-plane and focal-plane wavefront sensing techniques that take advantage of the coherence of starlight</td>
<td>Strategies to improve the realized contrast in ExAO searches for very faint companions</td>
</tr>
<tr>
<td></td>
<td>High-Stroke Deformable Mirrors</td>
<td>Development of scalable, cost-effective deformable mirror technologies suitable for all appropriate AO system architectures</td>
<td>More cost-effective designs and implementations for adaptive secondaries to enable wide-field correction</td>
<td>High stroke, high actuator count mirrors to enable correction at high spatial frequencies over narrower fields of view</td>
</tr>
<tr>
<td>Calibration</td>
<td>PSF Estimation</td>
<td>Understanding of the delivered science PSF in order to obtain very accurate relative photometry and astrometry</td>
<td>Derivation of on-axis PSF from real-time AO system WFS and DM actuator telemetry with or without auxiliary C$_n^2$ profile estimates</td>
<td>Estimation of off-axis PSF from C$_n^2$ profile and/or the system optical transfer to mitigate anticipated variations in the PSF across the corrected field.</td>
</tr>
<tr>
<td>Human Resources</td>
<td>Education and Training</td>
<td>Creation of a new generation of experts in order to take full advantage of the burgeoning national demand and infrastructure for AO</td>
<td>Hands-on training for graduate students and postdoctoral researchers in active AO development programs</td>
<td>Better recognition of instrumentalist contributions to science advancement (e.g. national guidelines on science paper co-authorship and full career paths for AO instrumentalists)</td>
</tr>
</tbody>
</table>

The Committee also notes the importance of successful completion of existing AODP programs for the development of a prototype “polar coordinate” CCD array for LGS wavefront sensing on ELT’s and for the demonstration on-sky of the previously-funded AODP sodium laser development efforts.
10 AO DEVELOPMENT PROGRAM (AODP)

10.1 Mission Statement

Recognizing the key importance of the end-product of AO development, the advance of scientific understanding, the Committee recommends adoption of the following mission statement by NSF:

*The mission of the NSF Adaptive Optics Development Program is to advance the field of astronomical science through innovations in AO that support the scientific leadership of the US astronomical community and ensure the continued complementarity of the ground-based optical/infrared telescope system to space-based and longer wavelength facilities.*

10.2 AODP Structure

To have maximum impact on the astronomical community, investments made through AODP need to be driven by astronomical science needs, be responsive to concurrent developments and changing science priority, and result in tangible and enduring advances in AO understanding and availability.

The Committee recommends:

- Annual solicitation of AODP proposals in synchronization with the November ATI program call for proposals.
- Flexible guidelines for the scope of proposed work, including support for extended periods when appropriate for cost-effectively addressing issues of high technical complexity and high potential science benefit.
- Annual review of AODP-funded projects extending more than two years to ensure continuing progress and relevance to the astronomical AO community.
- Top funding priority be assigned to meritorious proposals addressing the needs identified in the Section 9 of the AO Roadmap.
- Annual allocation of up to 20% of AODP funding to support high-risk, high-return proposals addressing AO science goals, but not specifically emphasized as top-priority investment areas in this AO Roadmap.

10.3 AODP Scope

While the scope of potential technical innovation based upon AO is limitless, the Committee has identified the top-priority needs in Section 9 as the key drivers to accelerating science improvements in the next decade. Although the specific scope of the required need will depend upon experts understanding the technical challenge and proposing specific advances, the Committee’s collective experience suggests that addressing the top- and high-priority Roadmap needs is likely to require the following decadal investment levels:
**Estimated Decadal Development Investment Needs**

<table>
<thead>
<tr>
<th>Category</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavefront Sensing including:</td>
<td>$20,000,000</td>
</tr>
<tr>
<td>Laser guide star beacons</td>
<td></td>
</tr>
<tr>
<td>Multi-guide star tomography</td>
<td></td>
</tr>
<tr>
<td>Optimized wavefront sensors</td>
<td></td>
</tr>
<tr>
<td>Wavefront Correction</td>
<td>$10,000,000</td>
</tr>
<tr>
<td>High-stroke DM’s of various diameters</td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>$ 5,000,000</td>
</tr>
<tr>
<td>PSF understanding</td>
<td></td>
</tr>
<tr>
<td>Advances in astrometric and photometric precision</td>
<td></td>
</tr>
<tr>
<td>Human Resources – Education and Training</td>
<td>$ 5,000,000</td>
</tr>
<tr>
<td>Decadal goal of 40 new AO engineering experts</td>
<td></td>
</tr>
</tbody>
</table>

Total Estimated Decadal Investment Need: US$ FY08 40,000,000

**Table 2.** Approximate public investment required to address the priority development needs identified in Section 9 of the AO Roadmap, above and beyond public support for new AO facility capabilities in the ground-based optical/infrared telescope system.

### 10.4 AODP Review Criteria

The Roadmap Committee recommends the following specific proposal review criteria for the AO Development Program (AODP), in addition to standard NSF proposal criteria (without priority):

- Does the proposed work accelerate development of improved AO science capabilities over the state-of-the-art?
  - For example:
    - Is the science benefit of the proposed work clearly identified?
    - Will the proposed work significantly impact our understanding, methodologies, and/or designs of future AO systems?
    - Will the proposed dissemination plan for new knowledge or hardware result in a lasting advance for the community?

- Is the proposed work structured to provide enduring, high return-per-dollar results addressing a need not otherwise addressable?
  - For example:
    - Is the proposed work of high priority for the proposal team?
    - Is progress against the proposed work plan measurable with appropriate program continuation milestones?
    - Is the proposed management plan robust to unexpected difficulties?
    - Does the proposal team possess sufficient AO systems engineering experience to deliver a utilizable work product?
    - Does the proposal team have a record of successful delivery against requirements, budget and schedule?
o Does the proposed work take appropriate advantage of on-going international and interdisciplinary investments?

o For laboratory and on-sky demonstrations, is the proposed experiment plan carefully constructed to unambiguously provide the desired outcome?
   For example:
   o Does the experiment plan treat environmental and other factors sufficiently to expect a quantifiable advance in understanding limitations to future system performance?
   o Does the proposed program include sufficient access to telescope time for successful completion?

Furthermore, the Committee recommends consideration of the following ‘plus factor’ criteria for determining support among proposals of otherwise comparable ranking:

o Will the proposed work advance the goal of training student and early career optical/infrared astronomy instrumentalists, particularly skilled AO engineers?

o Does the proposed work take appropriate advantage of multi-institutional and/or interdisciplinary expertise?

10.5 AODP Acknowledgement

To encourage community visibility to the impact of AODP investments, the Committee recommends that publications based on AODP funding include an explicit acknowledgment of funding under the National Science Foundation Adaptive Optics Development Program.
11 Appendix

11.1 Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AO</td>
<td>Adaptive Optics</td>
</tr>
<tr>
<td>ATST</td>
<td>Advanced Technology Solar Telescope</td>
</tr>
<tr>
<td>CRIRES</td>
<td>An cryogenic infrared echelle spectrograph on the VLT</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>d-IFU</td>
<td>Deployable IFU</td>
</tr>
<tr>
<td>DM</td>
<td>Deformable Mirror</td>
</tr>
<tr>
<td>ELT</td>
<td>Extremely Large Telescope</td>
</tr>
<tr>
<td>ExAO</td>
<td>Extreme-contrast Adaptive Optics</td>
</tr>
<tr>
<td>FoV</td>
<td>Field of View</td>
</tr>
<tr>
<td>HOT</td>
<td>An ESO high-order adaptive optics testbench investigating pyramid WFS, woofer/tweeter control, etc.</td>
</tr>
<tr>
<td>IFS</td>
<td>Integral Field Spectrograph</td>
</tr>
<tr>
<td>IFU</td>
<td>Integral Field Unit</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>GLAO</td>
<td>Ground-layer Adaptive Optics</td>
</tr>
<tr>
<td>GMT</td>
<td>Giant Magellan Telescope</td>
</tr>
<tr>
<td>HET</td>
<td>Hobby-Eberly Telescope</td>
</tr>
<tr>
<td>HOWFS</td>
<td>High-order Wavefront Sensor</td>
</tr>
<tr>
<td>LBT</td>
<td>Large Binocular Telescope</td>
</tr>
<tr>
<td>LGS</td>
<td>Laser Guide Star</td>
</tr>
<tr>
<td>LTAO</td>
<td>Laser-tomography Adaptive Optics</td>
</tr>
<tr>
<td>MACAO</td>
<td>A 60-element curvature WFS AO system for each ESO’s VLT UT</td>
</tr>
<tr>
<td>MCAO</td>
<td>Multi-conjugate Adaptive Optics</td>
</tr>
<tr>
<td>MEMS</td>
<td>Microelectromechanical</td>
</tr>
<tr>
<td>MMT</td>
<td>The 6.5-meter diameter telescope on Mt. Hopkins, AZ</td>
</tr>
<tr>
<td>MOAO</td>
<td>Multi-object Adaptive Optics</td>
</tr>
<tr>
<td>Na</td>
<td>Sodium</td>
</tr>
<tr>
<td>NACO</td>
<td>An abbreviation for the VLT NAOS/CONICA AO system</td>
</tr>
<tr>
<td>NAOS</td>
<td>The VLT Near-infrared AO System</td>
</tr>
<tr>
<td>NGAO</td>
<td>The visible light AO / MOAO Keck Next-Generation AO System</td>
</tr>
<tr>
<td>NIR</td>
<td>Near-infrared (typically 1-2.5 micron wavelength, sometimes used for 1-5 micron wavelength)</td>
</tr>
<tr>
<td>NGS</td>
<td>Natural Guide Star</td>
</tr>
<tr>
<td>P60</td>
<td>Palomar 60” Telescope</td>
</tr>
<tr>
<td>P200</td>
<td>Palomar Hale 200” Telescope</td>
</tr>
<tr>
<td>PALM-3000</td>
<td>A visible light AO upgrade to PALM LGS</td>
</tr>
<tr>
<td>PALM LGS</td>
<td>The Na LGS AO system on the 5-meter diameter telescope at Palomar Mountain</td>
</tr>
<tr>
<td>PSF</td>
<td>Point Spread Function</td>
</tr>
<tr>
<td>RLGS</td>
<td>Rayleigh Laser Guide Star</td>
</tr>
<tr>
<td>SCAO</td>
<td>Single-conjugate Adaptive Optics</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINFONI</td>
<td>An abbreviation for the SINFONI AO / SPIFFI system</td>
</tr>
<tr>
<td>SINFONI AO</td>
<td>A 60-element curvature WFS AO system for ESO’s VLT UT4</td>
</tr>
<tr>
<td>SPIFFI</td>
<td>A near-IR IFS fed by SINFONI AO</td>
</tr>
<tr>
<td>TMT</td>
<td>Thirty Meter Telescope</td>
</tr>
<tr>
<td>TT</td>
<td>Tip/tilt</td>
</tr>
<tr>
<td>TTFA</td>
<td>Tip/tilt/focus/astigmatism</td>
</tr>
<tr>
<td>TWFS</td>
<td>Truth wavefront sensor</td>
</tr>
<tr>
<td>UT</td>
<td>Unit Telescope, any of the four VLT 8-m telescopes</td>
</tr>
<tr>
<td>VLT</td>
<td>The European Southern Observatory Very Large Telescope</td>
</tr>
<tr>
<td>VLTI</td>
<td>The VLT Interferometer</td>
</tr>
<tr>
<td>WFS</td>
<td>Wavefront Sensor</td>
</tr>
<tr>
<td>WMKO</td>
<td>W. M. Keck Observatory</td>
</tr>
</tbody>
</table>

### 11.2 Definitions and Glossary

- **$C_n^2$ or $C_n^2(h,t)$**: Atmospheric Index of Refraction Structure Function Constant, describing the strength of optical turbulence in the atmosphere (as a function of height, h and sometimes time, t).
- **Extreme-contrast Adaptive Optics**: The technique of using a high order AO correction with a diffraction suppression system to maximize contrast. Typical Strehl ratios are greater than ~90%.
- **Extremely Large Telescope**: A telescope having aperture of 25 meters or more.
- **Ground-layer Adaptive Optics**: The technique of applying AO correction to preferentially compensate only low altitude wavefront errors for the purpose of realizing improved effective seeing over moderate to large fields of view.
- **Large Telescope**: A telescope having aperture between 6.5 and 10 meters.
- **Laser-tomography Adaptive Optics**: The technique of utilizing multiple laser guide stars and wavefront sensors for the purpose of mitigating the measurement error induced by focal anisoplanatism (usually used to further indicate single-conjugate correction in contradistinction to multi-conjugate adaptive optics.)
- **Mid-sized Telescope**: A telescope having aperture between 1 and 5 meters.
- **Multi-conjugate Adaptive Optics**: The technique of utilizing multiple wavefront correctors optically conjugated to different altitude for the purpose of extending AO correction over larger field of view.
- **Multi-object Adaptive Optics**: The technique of utilizing multiple parallel optical channels, each possessing one or more deformable mirrors, for the purpose of multiplexing multiobject correction.
- **Single-conjugate Adaptive Optics**: An AO system that applies wavefront corrections at a single optically conjugate height in object space.
- **Truth Wavefront Sensor**: A wavefront sensor utilizing natural guide stars to correct for calibration uncertainties and variations inherent in laser guide star wavefront sensing systems.