

A Roadmap for the Development of Astronomical Adaptive Optics

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EXECUTIVE SUMMARY

Astronomy stands poised for a rapid advance in telescope performance, surpassing by a large margin the formerly fundamental limits set by atmospheric seeing. The key enabling technology is adaptive optics—the high-speed correction of real-world wavefront and mechanical disturbances, allowing telescopes to approach the ideal image quality of textbook and laboratory. The past decade has seen a series of remarkable successes, with astronomers achieving such near-ideal performance viewing relatively bright objects with 1.5-10 meter telescopes. Diffraction-limited imaging of faint objects will soon become possible through use of sodium laser guide stars. By mid-decade, resolution will be improved still further by exploiting the 23-m baseline of the Large Binocular Telescope (LBT).

On a decade time scale, we can anticipate initiating construction of a new generation of still larger telescopes with diameters in the 30-100m range. Such telescopes will rely entirely on adaptive optics to achieve their designed diffraction-limited performance. However, the challenges to successful implementing AO on telescopes of this size are formidable since for comparable performance, the complexity of key systems elements scales as (diameter)⁴.

The required technical developments, and the actual electro-optical mechanisms themselves, will cost only a fraction of the value of the large telescopes they will enable and augment. However, to achieve the enormous potential gains of adaptive optics will require a commitment to long-range planning, additional funding, and new ways of eliciting, supporting and sustaining support of research and development efforts in the academic and private sector. In order to inform an NSF investment strategy matched to the challenges of achieving the promise of AO, we have undertaken to prepare a technical and management roadmap.

This document represents a first draft of the roadmap. It has been prepared by an ad hoc, but broadly-based team of community experts in the field. Its key recommendations are:

- Allocation of new funds reserved for AO technology development
 - Development of robust and scaleable laser systems
 - Sustained support to develop multiple approaches to deformable mirror implementation
 - Sustained support of low-noise, rapid readout detectors—key elements of wavefront sensors

- Support to develop techniques for atmospheric tomography, multi-conjugate AO, and wavefront prediction
 - Development and support of instruments to characterize the statistical properties of the atmosphere above extant and candidate astronomical sites
 - Support of sophisticated software packages to model the performance of the atmosphere and the corresponding response of AO systems
 - Design studies for next generation telescopes aimed at identifying key AO-related technology development
- Active solicitation of proposals via Announcements of Opportunity or similar strategems—aimed at eliciting proposals aligned with needs identified in the roadmap, as well as innovative proposals aimed at achieving long-term community needs
 - A review panel to evaluate AO proposals on their merit and in the context of roadmap goals
 - Award levels and durations matched to technical requirements; in many cases support will be needed for much longer periods than the traditional 3 year grant
 - Delegation to NOAO the responsibility for coordinating the community planning process and working with NSF to implement and manage roadmap elements
 - A mechanism to update the roadmap annually in light of technical advances, successes and failures; and to review progress against plan
 - An initial list of recommended near-term priorities (Addendum)

A key goal for the roadmap will be to enable the adaptive optics capability required for development of a future very large aperture telescope, with a light-collecting diameter of 30 or more meters. At many steps along the way, it will provide technical advances which can be directed to support greatly improved performance of adaptive optics on existing telescopes, extending high performance imaging to fainter stars and wider fields of view, multiplying their sensitivity and permitting observations that could not have been foreseen just a few years ago.

INTRODUCTION

Development of systems to correct for wavefront distortions introduced by the atmosphere represents one of the major advances in astronomical telescope technology of the 20th century.

An adaptive optics system, in its simplest form, measures the wavefront deformation from a reference star image, and places a complementary deformation on an optical surface, as shown in the idealized layout of Figure (cfao.gif). The essential AO-specific components of the system are: a deformable mirror (DFM), which may be rapidly shaped by actuators, according to commands from the actuator control; the wavefront sensor (WFS), which is a fast detector optimized for the purpose; the wavefront reconstructor (computers, software) to execute the wavefront analysis; and the actuator control, which executes the correction required to complement the observed deformation.

Adaptive optics owes its origins to the work supported by DoD at the Starfire Optical Range, and the creative work of astronomical AO-pioneers working in small groups during the 1980s and 1990s. Although fully operational astronomical AO systems have only come on-line within the last few years, new science enabled by AO has increased rapidly. A current list of AO-based, refereed science papers is maintained at http://www2.keck.hawaii.edu:3636/realpublic/ao/ao_sci_list.html. Exciting scientific results include: monitoring of lava flows on Io, detection of new storm patterns on Neptune, mapping of surface topography on Titan, first telescopic discovery of a binary asteroid, mapping of asteroid surface mineralogy, discovery of new moons and ring resonances, detection of jet precession/binary association in YSO's, statistics of binary frequency among young stellar objects, discovery of a very cool dwarf companion, discovery of circumbinary disks, imagery of active accretion disks, imaging of the companion-guided mass-loss spiral in Wolf-Rayet stars, imaging and photometry of stars in the cores of globular clusters and the dense starburst R136, measurement of stellar proper motions in the galactic center, photometry of individual stars in the nucleus of M31, resolution of star burst clumps and giant HII regions in distant galaxies, detection of lensing galaxies, and measurement of AGN cores and QSO hosts.

These early results provide clear evidence of the potential of AO to deliver:

- High fidelity images with effective resolutions equal to the diffraction limit of ground-based telescopes at red and infrared wavelengths;
- Sensitivity gains of 10X or more compared with native seeing sensitivities for imaging and spectroscopy for unresolved sources viewed against the bright background of the earth's atmosphere and/or the telescope;

- Reduction of confusion in crowded fields which are insufficiently resolved with seeing-limited telescopes;
- Significant reductions in the size of auxiliary instruments whose scale is often set by the effective size of the image delivered by the telescope/atmosphere 'system'.

In spite of the great progress in AO, only a fraction of its potential has been achieved to date. Sky coverage is typically limited to target sources located near bright stars that provide a measure of wavefront distortions. Corrected fields of view are limited, and images are incompletely corrected owing to limitations in wavefront sensors and the deformable mirrors that compensate for distortions in the incoming wavefront.

To fully achieve the potential gains of AO on current generation telescopes requires across the board advances in AO components and techniques. As we look ahead to the next decade, such advances along with new AO systems concepts will be essential if we are to build next generation 30-100m diameter optical/infrared telescopes having the combination of sensitivity and angular resolution matched to ALMA and NGST.

In view of the centrality of AO to advances in ground-based capabilities, NOAO and the NSF's newly-formed Center for Adaptive Optics sponsored a workshop on 13/14 DEC 1999 aimed at preparing a "roadmap" which would outline investments key to achieving the potential of AO over the next decade. The workshop, comprising 18 individuals, represented a large fraction of US groups involved in AO research. The participants reviewed and discussed:

- Alternate AO systems approaches (e.g. 'wide'-field multi-conjugate AO with laser and natural guide stars; on-axis, high Strehl systems with wavefront corrections derived from natural or laser guide stars);
- Key required technology developments (e.g. lasers; wavefront sensors; deformable mirrors to compensate for atmospheric distortions of the incoming wavefront); —key AO systems issues (e.g. optical design; control and analysis software); required technology/systems tests and appropriate testbeds;
- Key investment areas along with approximate priorities/timing;
- A process for guiding investments and reviewing progress against the roadmap.

Each participant was asked to present issues from her/his perspective. The group then discussed subsystem and system issues and identified investments key to progress—effectively providing a 'roadmap' to the future. An essential complement to the 'roadmap' discussion is a **process** to review and update the roadmap, and to evaluate the efficacy of NSF and other investments in achieving roadmap goals. We summarize below key elements of the roadmap and the process for updating the roadmap and measuring progress against plan.

PROSPECTUS FOR THE NEXT DECADE

New Approaches

As classical AO has been extended to increasingly large apertures - 2 meters, 3.5 meters, 10 meters—and directed to observations of new types of targets, remarkable and unprecedented images have been obtained.

However, as noted in the introduction, current AO systems have numerous, important limitations. "Classical AO" that depends on natural guide stars to sense wavefront distortions delivers a relatively small corrected field (of no more than 2 arc minute at K-band, and 10 arcseconds at J-band), and even within this field, serious point spread function variations are normal.

As a consequence, results from operational AO systems are often limited to one or a few brightest examples of a class of source, and many types of sources are excluded from AO observation due to the absence of bright nearby stars. If all-sky coverage can be developed, AO observing will move rapidly beyond the exploratory and demonstration stage, into the large and long-term campaigns required for many frontier science programs.

One of the most promising new thrusts in AO research is aimed at achieving a relatively uniform PSF over an extended field of several arcmin, by using a technique known as 'multi-conjugate AO.' This technique makes use of multiple wavefront sensors and guidestars to determine the three-dimensional distribution of atmospheric turbulence. Multiple deformable mirrors conjugated to distinct ranges are then used to effect wavefront corrections appropriate to each atmospheric "layer". ESO has recently proposed a novel wavefront sensing approach in which the wavefront sensors are themselves conjugated to the atmospheric layers and drive the deformable mirrors in a one-to-one arrangement.

For optimal realization of multi-conjugate AO, there is need for more accurate and efficient modeling to guide the development of these systems, new types of adaptive elements, multiple laser beacons (including Rayleigh as well as sodium types) and/or natural reference stars, new wavefront sensors, and new control systems, utilizing very high speed computation to enable sophisticated tomographic representations of atmospheric distortions.

In order to overcome the requirement of having a bright 'natural guide star' near an astronomical target of interest, a first generation of laser beacons has been deployed to produce bright artificial stars from which wavefront distortions can be assessed—thus offering extension of AO gains to the faintest sources around the sky. Implementation of laser beacon referencing requires the addition of a laser and launch telescope, plus one or more additional wavefront sensors. Multiple laser beacons require additional lasers and

launch systems, or a multiplexing scheme. Multi-conjugate adaptive optics requires additional deformable mirrors, operating in series, plus multiple wavefront sensors. Intensive work continues on laser beacons, system integration and calibration, and on-sky performance. Crucial areas for further development include reliable and efficient all-solid-state lasers for sodium guide stars, and laser concepts that are scaleable to the needs of 30-100m telescopes.

Improvements in wavefront sensing/correction promise to extend the performance of AO to fainter reference stars, better sky coverage, and/or better image quality. Such possible improvements include lower noise, faster wavefront detectors, better turbulence models and better use of both a priori and real time turbulence data, better integration of natural and laser beacon wavefront information, development of multiple natural guide star and laser beacon wavefront analysis techniques, and more optimal deformable mirrors. Developments that reduce the number of optical surfaces, such as adaptive primary/secondary mirrors, will increase the efficiency of observations by increasing system transmission and decreasing thermal background—thus allowing the design of fully optimized AO telescope facilities.

In combination, steady advances in these multiple directions together promise to advance AO performance on current generation large telescopes dramatically.

Extending AO to Enable Next Generation Telescopes

Extension of AO to much larger apertures will require not only the advances in AO system components outlined above, but as well meeting qualitatively new challenges that cannot be resolved simply by scaling existing AO technology.

To illustrate the challenges we face on a decade timescale, we summarize in Table 1 the specifications for key components of AO systems: (1) currently implemented on the Keck 10m telescope, (2) an example of a "next generation" system now being implemented for the LBT, (3) MCAO performance on Gemini, and (4) the specifications required to achieve diffraction-limited performance with a 30m class telescope.

Table 1

	KECK	LBT	GEMINI MCAO (1-2 FOV)	NBT
START NGS AO OPERATION	1999	2004	2005	2010?
DIAMETER OR BASELINE	10m	23m (2x8.4)	8m	30m
RESOLUTION AT J BAND	26 mas	11x 30mas	33 mas	8.6mas
WAVEFRONT SENSOR	SHACK HARTMANN	2 X PYRAMID	SHACK HARTMANN	SHACK HARTMANN
NUMBER OF ACTUATORS	300	1680	738	10800
ACTUATOR DENSITY AT WF	4/m ²	16/m ²	4/m ²	16/m ²
DM TYPE	PIEZO	DEFORMABLE SECONDARY	PIEZO	PIEZO

AO systems will almost certainly be an integral element of the design of 30-100m telescopes if they are to achieve the linked goals of high angular resolution and large field of view. Consequently AO technology must develop rapidly in parallel with the optical and mechanical concepts for such a telescope. Multiple integrative approaches are possible. Adaptive correction can be implemented at the primary, secondary, tertiary mirror level; multi-conjugate correction can be implemented with reflective or transmissive elements; multiple sodium beacons may be used, or a combination of sodium and Rayleigh laser beacons; purely natural guide star wavefront sensing may be possible for sufficiently large apertures. All of these approaches require new components and new system designs. Extensive field testing on extant facilities will benefit both the design of AO systems for future telescopes and the current generation of 8-10m facilities.

KEY TECHNOLOGY INVESTMENTS

This section summarizes key AO technology investments central to enabling construction of a new generation optical/infrared telescope of power sufficient to drive qualitatively new science and to complement ALMA and NGST. Benefits of these investments to enhancing the performance of current generation telescopes are summarized in Figure 1.

Defining AO Performance Requirements for Next Generation Telescopes

PROPOSED INVESTMENT: Concept studies for several implementations of a next generation (30-100m class) telescope aimed at identifying the role of AO in achieving key requirements and the technology investments needed to implement AO on large telescopes.

EXPECTED RETURN: Deeper understanding of the relative priorities of recommended roadmap investments.

AO is expected to be an integral part of the design of a next generation, 30-100m class telescope. High-speed corrections are required not only to compensate for wavefront distortions induced by the atmosphere, but for wind-induced and other mechanical disturbances that distort the optical figure of the telescope. AO on large telescopes may require novel approaches (complex, multi-conjugate natural guide star and laser guide star systems; adaptive secondaries or even primary mirrors). Plausible approaches need to be defined early in the decade in order to ensure an optimum balance in investment among enabling technologies.

We therefore recommend that significant funding be devoted to developing concept studies for 30-100m class telescopes and to identifying AO system characteristics and enabling AO technologies for each concept. It is expected that NOAO, through its New Initiatives Office will act as to point organization for NSF to fund several such concept studies, and will work closely with the Cal Tech CELT, LBT and ESO OWL projects to ensure that, in combination with innovative members of the astronomical community and the private sector, that investments will lead to thorough exploration of a variety of concepts.

Lasers

PROPOSED INVESTMENT: - reliable, affordable sodium wavelength lasers with power levels of order 10 and 50 watts, and appropriate optical characteristics.

EXPECTED RETURN: - greatly accelerated implementation of laser beacon systems and AO research on current generation telescopes; all-sky coverage with AO; increased Strehl; extension of high quality AO correction to shorter wavelengths.

A single laser beacon, launched by a small telescope attached to the main reflector, excites sodium atoms in the earth's atmosphere producing a bright, artificial star along a site line close to an astronomical target site line—thus enabling AO corrections over (nearly) the entire sky by obviating the need for a nearby bright natural guide star (a faint NGS is needed to enable tip/tilt corrections).

Multiple laser beacons can be employed to achieve higher order correction, to enlarge the corrected field of view, and to improve the uniformity of correction over the field. 'Multi-conjugate' AO systems promise uniform Strehl ratios over fields of view of area 10x or more those of current-generation AO systems.

First-generation sodium lasers have used dye as a lasing medium. They work, but are energy-inefficient and difficult to maintain. Developing a second generation of laser beacons represent a high priority need for national, focused investment. Current market forces will not lead to the required devices. Astronomers need robust, energy- and cost-effective sodium lasers. Units with launched power levels (a) 10 and, in the future (b) 50 watts will offer suitable design flexibility for covering a range of beacon and operating wavelength requirements.

The investment in laser systems should be aimed explicitly at developing systems of reliability sufficient to enable relatively routine operation in remote, somewhat hostile observatory environments.

The studies recommended here should complement the laser R&D demonstrations already funded by Gemini, CfAO and the US Air Force, possibly by either increasing the power levels of these prototype systems or engineering them for field tests at observatories.

Work on other high-altitude beacon types (e.g. Rayleigh lasers) should be continued as well, especially if they prove to promise better performance for 30m class telescopes. Prototyping and experience is needed for low-cost, reliable, properly qualified safety systems for laser beam handling and launch, and for fail-safe aircraft detection. Collision avoidance on summits with multiple telescopes needs further work. Satellite avoidance is currently difficult due to tedious communication procedures; NSF intervention in inter-agency negotiations could help untangle this issue.

Deformable Mirrors

PROPOSED INVESTMENT: Prototyping and testing of advanced wavefront correction elements, including curved optics, telescope M1/2/3 mirrors, transmissive optics, closer actuator spacing, and higher order deformable mirrors (both regular grid and curvature style).

EXPECTED RETURN: Higher order correction, improved optical simplicity and efficiency, reduced emissivity, simplified control systems, enhanced ultimate wavefront quality.

A 'deformable mirror' (DM) is a key element of the AO optical train whose multiple actuators shape it to compensate for distortions in the incoming wavefront. Despite enormous advances over the past decade, DM technology still needs continued investment.

DMs with significantly more actuators are required to improve level of adaptive correction as measured by the "Strehl ratio" (the ratio of power concentrated in the diffraction-limited image 'core' compared to the seeing 'wings' of the image).

The center for Astronomical Adaptive Optics at the University of Arizona has developed the technology for adaptive secondary mirrors. Such mirrors, and their extension to make wavefront correction on the primary or tertiary mirrors in optical systems may enable AO systems that deliver high Strehl with relatively low light losses and low thermal emission in the infrared, as compared to current systems. Continued development of deformable telescope optics, the actuators, sensors, and their control systems should be encouraged.

Transmissive wavefront modulators are still in their infancy, and their realization would add great flexibility in optical design of AO systems. Current prototypes need more dynamic range, faster response, and better transmission and polarization properties.

Design work on DMs capable of enabling successful adaptive correction on 30m class telescopes is critical. DMs with thousands of degrees of freedom will be required. Further work is needed on such mirrors—for example MEMS (Micro-electronic mirrors) and curved piezo mirrors (being developed, for example by the University of Arizona).

Detectors for Wavefront Sensing

PROPOSED INVESTMENT: - Faster, more sensitive, lower noise detectors with more pixels and better wavelength coverage, as well as detectors capable of taking fast movies of pulsed Rayleigh beacons.

EXPECTED RETURN: - Improved AO performance with both natural and laser reference beacons. Rapid detection and characterization of wavefront distortions ideally requires panoramic detectors with a number of picture elements (pixels) large enough to sense high-order distortions, with sensitivity, speed and minimal noise to enable rapid update of the deformable mirror. Efficient, fast detectors with low readout noise enable better performance for fixed natural guide star brightness or laser power.

The desired properties of wavefront detectors—very fast, very low noise—are appealing for a number of other applications, including optical interferometry.

The astronomy community has extensive experience in working with national laboratories and the private sector on detector development. The goal will be 512x512 arrays with 1 kHz frame rate, 1-3 electron noise, and quantum efficiencies > 0.8. Detectors are needed in both the visible/red and the infrared. The level of investment in this area should be adjusted to reflect progress in developing a reliable source industrial source of arrays.

Wavefront Reconstructors and Atmospheric Tomography

PROPOSED INVESTMENT: - development of numerical methods for inversion of wavefront data from multiple reference sources to determine the structure of the turbulence field, and compute the optimum corrections to apply to each deformable element.

EXPECTED RETURN: - greatly enhanced corrected field of view with multi-beacon AO systems, improved uniformity of image quality and shape over the field of view.

“Wavefront reconstructors” are the electronics and software elements that translate wavefront measurements into actuation of the DM. There is extensive work yet to do on advanced wavefront reconstructors and the more complex problem of inferring the 3-dimensional turbulence distribution above the telescope from multiple wavefront reference data. Computational requirements for modeling and real-time control presently scale as a power between 2 and 3 of the total number of actuators/sub-apertures in the system.

Opportunities/needs include the formal and practical determination of optimal reconstructors, development of predictive reconstructors and exploitation of ancillary and statistical information, reduction in electronics latency, and use of new processor types some of which may be custom-designed.

The complex analytical and computational problems offer an opportunity for interdisciplinary work between controls theorists and applied mathematicians, engineering researchers, and computer scientists. Ongoing work by Gemini and ESO to develop control reconstruction algorithms will also be taken into account.

Site Monitoring and Atmospheric Characterization

PROPOSED INVESTMENT: - Site-specific monitoring campaigns, and development of instrument packages for real-time support of AO systems.

EXPECTED RETURN: - Site-characterization needed to design optimum AO systems and continuous updating required to extract optimum performance - resulting in increased Strehl ratio, image stability and uniformity.

It is important to monitor and characterize the atmosphere at least at the few most important observatory sites over an interval of at least a full year. In addition, real-time monitoring of turbulence characteristics and sodium density will allow optimization of AO performance. It will be necessary to develop an inexpensive, automated, real-time sodium-layer monitor. The sodium layer should be monitored, with respect to integrated sodium column density. Measurements are needed of C_n^2 , wind speed and direction versus height. SCIDAR may be able to provide some of these data in real time. The differential image motion monitor gives an integrated image quality measure which offers an important normalization. This information is needed statistically for modeling purposes. Eventually, it is needed in real time in order to optimize operation of advanced AO systems. Such monitoring capability should be developed immediately and implemented on Mauna Kea and Mount Graham, with other sites to follow. The eventual goal of this work will be to develop a facility monitoring package that can be widely used for AO support.

Simulations and Modeling

PROPOSED INVESTMENT: - support several approaches to modeling AO system performance and promote their inter-validation and wide use.

EXPECTED RETURN: - confidence in predictions from the complex modeling required for development of advanced AO. Several investigators/groups have simulation and modeling packages, which are invaluable tools for evaluation of system concepts and detailed designs. We would like to promote wider availability and easier access to these tools and their sequels. This may be an opportune point of collaboration with ESO or DOD. A process, a medium of communication, perhaps meetings and network based exchanges will be needed in order to make this happen. Cross verification of codes has been valuable in the past in building confidence of models, and it should be continued through collaborations. NOAO could play a role in organization of exchanges and workshops.

Software Engineering

PROPOSED INVESTMENT: - support directed specifically at software elements of AO systems operation and data reductions; promote sharing and intercomparison of techniques and algorithms.

EXPECTED RETURN: - systematic progress and timely consolidation of advances in the exploitation of AO for science observing. AO systems are software intensive, and experience shows that the software is difficult to write and easy to get wrong. Existing codes need validation with one another and with data. Experience with software for AO observing varies from facility to facility - we should facilitate learning from the successes. Requirements include observation planning tools, data analysis toolboxes, and associated cookbooks. Real-time optimization of reconstruction algorithms will be increasingly important in high-order and MCAO systems.

Data analysis software for pipeline processing is needed, with development of an understanding of when pipeline processing can be utilized. Much more work is needed on real-time PSF determination, with extension of the work on natural reference stars to various laser beacon and hybrid systems.

AO system software has been commonly late, over budget, and inadequately integrated. There are benefits to inclusion of other communities who address the same or similar problems, eg NASA, ESO. With some success in promulgating standards, at least within a portion of the community, specific shared modules might be possible (eg EPICS, Labview).

AO Optimized Instrumentation

PROPOSED INVESTMENT: - workshops bringing together AO technologists, instrument builders, and astronomers.

EXPECTED RETURN: - improved communication between developers, operators and users of AO systems; coordination of technical capabilities and scientific requirements.

Although the development of AO optimized instrumentation is not the main thrust of this plan, considerable interplay is needed between AO design and instrument design. Among the trades to be considered in optimizing scientific performance, we note the wavelength of operation, the Strehl ratio, the field of view, the throughput, the emissivity, and the PSF shape and stability, all of which are to some extent controllable (though not independent) parameters in AO design. Another key choice may be whether to integrate some or all of the AO-correction system into the instrument. For this reason, close interaction is needed between AO developers, instrument builders, and potential users. During the decade, it may be advisable to organize several conferences or workshops for in-depth review of evolving science goals and investigation into these and other trades.

PRELIMINARY SCHEDULE FOR KEY ROADMAP ACTIVITIES

The schedule must be driven on one end by the urgent need to complete the work, and on the other end by the resources available and the effort required. The following draft schedule is based on very general ideas of both. Possible milestones for the decade are summarized below for key investment categories. Note that the below milestones are best developed for the first half of the decade. We anticipate updating the far-term milestones as part of the process for reviewing the roadmap outlined in the next section.

I. Site monitoring and real-time atmospheric characterization

2001: Begin 3-year program of site tests (at two sites) to provide database for future systems modeling of adaptive optics performance on very large telescopes. Deploy permanent Differential Image Motion Monitor at Mauna Kea and/or SCIDAR telescope for use of all observatories on the summit. Use the data from these facilities combined with the achieved performance of extant AO systems to guide models of delivered AO performance—key ground-truth in using sophisticated modeling to predict the performance of more complex AO systems.

2002: Begin testing methods for measuring isoplanatic angle in real time; compare with measured adaptive optics data. **2002:** Deploy instruments for real-time monitoring of sodium column density, at one Northern and one Southern site. Operate for at least two full years.

2003: Deploy first-generation instrument for real-time measurement of turbulence versus height (e.g. SCIDAR) at least one observatory housing an adaptive optics system. Test turbulence measurements against adaptive optics system performance.

2004: Develop second-generation instruments for real-time site monitoring relevant to adaptive optics performance. Engineer for robustness and ease of use. Consider commercialization for broad distribution to observatories, including 3-5m telescopes.

2004: Deploy instrumentation for long-term studies at several promising sites for giant telescopes.

II. System designs

2001-2003: Solicit several candidate system designs for adaptive optics on 30-100m telescopes. Designs should explore scaling of each of the major deformable mirror technologies to very large telescopes. Other designs should highlight concepts needed for atmospheric tomography and multi-conjugate adaptive optics. Review for ability to meet requirements of 30-100m telescopes. Identify key technological advances needed in order to make each type of design practical and affordable at large scale.

2004-2006: Test at least two of the most promising design concepts in the laboratory, or on existing telescopes, at a greatly reduced scale.

2006-2010: On an 8-10m telescope, build at least one full-up adaptive optics system using advanced technology concepts needed for ultimate implementation on 30-100m telescopes. Test using visible-light adaptive optics and diffraction-limited instruments. Identify areas needing further work.

2009-2010: Develop merged design of 30-100m telescope and advanced adaptive optics system.

III. Deformable mirrors, tip-tilt mirrors, and other phase correction elements

2001: Draft roadmap for development of deformable mirror technologies with $>10^4$ degrees of freedom. Compare predicted scaling of size, bandwidth, cost, optical quality, robustness of major technology choices.

2002-2004: Construct modest-sized prototypes (scalable to very large numbers of degrees of freedom). Develop criteria for performance evaluation of prototypes, based on systems designs in II. above. Test prototypes against these criteria.

2005-2007: Build two or three deformable mirrors with >5000 degrees of freedom, using scalable technologies. Test. Incorporate in at least two complementary full-up adaptive optics systems on 8-10m telescopes. We anticipate that there may be DM solutions specific to particular AO applications rather than a unique, preferred solution.

IV. Wavefront-sensing detectors

2001: Facilitate a consortium of adaptive optics groups to fund foundry runs of fast, low-noise detectors for wavefront sensing in the visible and in the near infrared.

2002-2003: Take delivery of detectors, distribute to consortium members for testing and for use in existing adaptive optics systems. (Detectors of smaller format than needed for 30-100m telescope.)

2004-2006: Fund development and testing of most promising technology for 512x512 detectors (for 30-100m telescope applications).

V. Laser guide star systems and methods

Va. Lasers

2000-2004: Support the ongoing development of sodium guide star lasers.

Fund development of at least two approaches to solid-state sodium-layer laser guide star lasers. As one example, pulsed Sum frequency lasers appear to provide a very promising temporal and spectral format for exciting the sodium layer—reflecting the significant investment of the USAF over the past decade, as well as the NSF support for a solid state version of this laser.

Two types of deliverables should be solicited: an all-solid-state ~15W laser for use at least one existing adaptive optics-equipped telescope in the near infrared, and a prototype all-solid-state laser at the ~50-100W power level such as will be required for extending AO capability toward visible and/or multi-conjugate AO applications.

2003-2006: Test, and make use of these lasers on existing 8-10m telescopes with adaptive optics systems (at least one in the infrared and one in the visible). A 15W laser suitable for the infrared AO system should be available early during this time period.

2004-2008: Fund the commercialization of the most promising concept for each laser power as was done for the LIGO lasers (15W early; 50-100W later during this period).

Vb. Laser guide star methods

2000-2003: Fund several observatories to experiment with ways to optimize astronomical AO using sodium-layer laser guide stars. At least one of these should be at an 8-10m telescope where the effects of guide-star ellipticity will be significant. Methods to be developed should include calibration techniques, methods for PSF measurement, and an assessment of various approaches to excluding Rayleigh scattered light.

2001-2005: Fund innovative approaches to reducing the ellipticity of sodium-layer guide stars as seen by large telescopes. For pulsed lasers these might include real-time clocking of the guide star light across the wavefront sensor detector chip and other techniques.

2002-2008: Test increasingly sophisticated ways to use multiple laser guide stars on 8-10m telescopes (e.g. explore methods to decrease cone effect and increase field of view)

VI. Advanced wavefront reconstruction methods and atmospheric tomography

2000-2003: Computer simulations of various concepts for multi-conjugate adaptive optics, atmospheric tomography, wide-field adaptive optics, predictive correction, and other advanced concepts.

2002-2004: On-sky tests of most of the above, at suitable existing telescopes, using natural guide stars, and multiple-laser-beacon concepts and multi-conjugate AO at existing telescopes (see Vb above)

2008: On-sky test of prototype multiple-beacon, multi-conjugate adaptive optics (or similar concepts) on the largest-aperture telescope available.

VII. Simulation and modeling tools

2000-2010: Facilitate broad use of existing simulation and modeling tools, including documentation and modest user support. Foster collaboration between modeling groups in the US and in Europe, via workshops and network-based exchanges. Orchestrate cross-verification of codes (comparison between codes on the same initial conditions; comparison with actual adaptive optics performance using turbulence parameters measured by real-time monitoring instruments). Fund development of more advanced codes as needed, to run on new generations of supercomputers for the simulation of 30-100m telescope adaptive optics performance.

VIII. Software engineering

2000-2005: Develop and distribute increasingly sophisticated data-analysis tools for adaptive optics data. Develop algorithms for real-time estimation of atmospheric parameters such as r_0 and θ_{0_0} , and of the point spread function during an adaptive optics observation. Sponsor workshops and summer schools to teach the community how to use these tools. Apply techniques developed for natural guide stars to the more complex case of laser guide star observations. Where possible, promulgate standards so that important software modules can be shared between observatories and between different national astronomical communities. Foster understanding of software engineering requirements for real-time control systems in major observatory environments.

IX. AO optimized instrumentation

2000-2010: Organize conferences and workshops to foster close interaction of scientists/engineers involved in the design and construction of astronomical instruments that will use adaptive optics systems. Foster close interaction between adaptive optics system designers, instrument builders, and end-user astronomers.

Approximate Funding Levels

As noted above, we have not yet developed precise cost estimates for each of the key recommended investment areas. However, the following general arguments provide some likely bounds on the level of investment required over the next decade.

The Bahcall committee recommended an investment of \$40M in the area of adaptive optics during the 1990's. Funding from diverse sources (NSF, universities, private foundations, DOE, NASA, and an estimate of the DOD funding which directly supported AO for astronomy) approximately reached the recommended level. The investment was successful in achieving current AO operation. In many cases, parallel efforts were funded. In some cases this paid off (for example in the concurrent development of

Shack-Hartmann and curvature sensing systems), and in other cases, lack of clear focus resulted in duplication and delayed success.

The next decade in AO presents even greater challenges. The body of accumulated experience leads us to believe that these challenges can be met. But a high level, sustained effort will be required. Based on the investment and progress so far and the challenges ahead, we suggest for current discussion purposes seeking decade investment of order \$50M—comparable to the investment of the past decade. Such funding would enable basic technology, component, and system level work sufficient to (1) enable credible design of a next generation telescope; and (2) to provide the building block for implementing robust systems—each tailored to specific scientific problems—on existing large telescopes. It would *not* fund implementation of such systems; rather, such systems would be funded from an enhanced program for astronomy facility instrumentation.

A PROPOSED PROCESS FOR IMPLEMENTING THE ROADMAP

General Remarks

The dramatic successes of the past decade in demonstrating the potential of AO resulted from an investment strategy aimed at developing pilot AO systems or proofs of concept via funding of multiple, modest-sized research efforts. However it is our unanimous view that system and component complexity have reached the point where a more structured, long-term investment strategy is essential.

The founding of the Center for Adaptive Optics (an NSF-funded science and technology center) and the Arizona Center for Astronomical Adaptive Optics represent two recent examples of important steps toward achieving a broad-based approach to AO research and development. CAAO has developed adaptive secondary technology, and the CfAO is expected to play a major role in coordinating the development of specialized technologies for common AO systems requirements of multiple groups, and attempting to build an "industrial base" for AO—ensuring the availability of appropriate detectors etc. However, the level of investment in these centers is insufficient to ensure development of the components and systems critical to achieving the full potential of adaptive optics on current generation telescopes and to planning the complex systems required for the next generation optical/infrared telescope: hence our effort to develop a national **AO roadmap** to guide federal investment and to ensure a broad-based national approach. Absent such an approach, investments will lack the sustained focus that we regard as essential to achieving our goals.

The roadmap laid out in this document provides a 'snapshot' summarizing the best judgement of the active AO groups in the United States. It outlines key elements—design studies, technology investments and component developments—that we believe will

- (1) enable the complex **AO systems** essential to the success of next generation (30-100m) ground-based optical/infrared telescopes
- (2) create the **building blocks** (deformable mirrors, lasers, fast detectors, etc.) essential to constructing advanced AO systems for current generation facilities—critical both for testing system functionality for proposed 30-100m implementations, and for enabling full exploitation of AO on 6-10m telescopes

The roadmap is *not* aimed at prescribing implementations of specific AO systems on current generation telescopes. Each such system (e.g. a high Strehl NGS system feeding a coronagraph; a moderate Strehl LGS multi-conjugate system feeding a wide-field imager/spectrograph) must be tailored to a given facility and/or instrument, to a given user community, and to a particular range of scientific problems—and should

be evaluated and funded on its own merit. Conversely, studies under this roadmap will be complementary with the innovative elements of these existing programs, and not needlessly repeat research which is already underway.

The Roadmap is an Organic Document

We also recognize that AO and its supporting technologies are still maturing, and that the emergence of clever ideas as well as technological innovation and evolution will require periodic adjustments to the roadmap and its implied investment strategy. The roadmap must therefore be an organic document whose evolution is guided by a *process* that incorporates three essential elements:

- A mechanism to review and update the roadmap periodically, including costing of key elements and prioritization of proposed investments
- A mechanism to encourage community proposals aligned with roadmap goals and to review resulting federal investments to ensure alignment with community strategic thinking
- Mechanisms that continue to be open to innovation and new ideas

Broad community involvement is critical to ensuring the continuing soundness of the roadmap, its openness to new opportunities, and its credibility both among astronomers and the funding agencies. We propose to achieve this goal via formation of a steering committee that includes representatives from all U.S. groups actively involved in developing astronomical AO systems or subsystems. Initially, the steering committee will comprise the co-signers of the roadmap, augmented by representatives of groups developing AO systems based on curvature sensing, and by knowledgeable systems and design engineers familiar with development of sophisticated opto-mechanical systems.

Because the AO roadmap is central to the near- and long- term success of the 'system' of US private and public telescopes, we believe that NOAO represents the logical entity for (1) arranging for meetings of the steering committee; (2) ensuring that its membership is broadly representative; (3) circulating the roadmap and seeking feedback from the broader community; and (4) working with the NSF to develop mechanisms for implementing its recommendations.

It is appropriate that a national observatory take the lead in facilitating efforts by the US community to develop a framework for long-term investments in AO, and in working with the community and the NSF to track and evaluate progress in implementing the plan. Indeed, these planning and implementation roles are precisely those recommended by the AASC and the NSF Portfolio Allocation Review for 'an effective national observatory.' Moreover, NOAO's long-range plan assumes that AO development efforts will be centered in the community—thus enabling the national observatory to serve in these roles absent the perception of conflict of interest.

Annual Review of the Roadmap

We propose that NOAO convene the steering committee annually and work with the NSF to develop its charge. The meeting agenda will be circulated to the astronomical community well in advance of the meeting, posted on the NOAO and CfAO Web pages, and open for comments. Representatives of the NSF and other relevant funding agencies would be encouraged to attend. We anticipate that the meetings will have the following structure:

- (1) A review of community progress in achieving roadmap goals;
- (2) A review of the pattern of federal investments in AO to assess (i) progress against the roadmap; (ii) support of innovative approaches; (iii) needed mid-course corrections to the pattern of investments
- (3) A summary of new developments: (i) new systems approaches to AO; (ii) new technologies, software innovations or key advances at the subsystem or component level;
- (4) A summary of proposed changes to the current roadmap and its implicit investment strategy;
- (5) Adoption of changes to the roadmap;
- (6) Recommendations to NSF and other funding agencies outlining the basic elements of suggested "announcements of opportunity" aimed at encouraging proposals from the community matched to roadmap goals.

Steering committee meetings will be timed so that input from the roadmap process can influence budgets and announcements of opportunity at the NSF.

We note that this process is analogous to that used for some time by the physics community (for example, the Nuclear Sciences Advisory Committee (NSAC) which advises the DoE and NSF on investments in nuclear science).

Funding Agency Response to the Roadmap

- Successful implementation of the roadmap will require a significant change in the character of proposal solicitation and review at the NSF. Specifically we recommend that NSF:
- Seek new funds (of the magnitude recommended for AO by the AASC) and sequester them for support of a program of (1) technology and component developments, and systems designs critical to enabling next generation optical/infrared telescopes; and (2) technology and component developments that provide the building essential to

successful implementation of robust AO systems on current generation large telescopes; and (3) proof of concept tests for AO-system/instrument combinations.

- Evaluate and fund "Bread-and-butter" AO systems and AO-fed instruments for current generation telescopes *separately* from this program—specifically in the context of extant competitive instrumentation and/or advanced technology programs.
- Actively seek proposals aligned with roadmap goals via targeted Announcements of Opportunity—a key complement to the traditional approach of open solicitation.
- Appoint a broad-based panel to review AO proposals—comprising astronomers, along with representatives from government laboratories and the private sector familiar with the development of complex optical systems. Prior to the panel review, representatives from the agency and the AO steering committee (whose members should be enjoined from serving on the review panel) should brief the panel regarding the AO goals and their rationale. If desirable NOAO could assume responsibility for logistical support of this process.

The panel would review the proposals with awareness of the context provided by the roadmap, but would be free to respond to all proposals—whether aligned with roadmap goals or not. The proposals would be rated by the panel, prioritized and accompanied by commentary that speaks both to their intrinsic merit and to their role in achieving the broad community goals outlined in the roadmap.

We believe this process incorporates elements that both encourage proposals aimed at achieving roadmap goals *and* ensure that new ideas or approaches receive a fair hearing.

- Develop practices that provide sustained funding for periods appropriate to development of new technologies and complex components/systems. In practice this means making some awards of duration 5 years or more—well beyond the traditional 3 year period. We believe long-term support is essential to building and sustaining teams with the experience base and technical know-how appropriate to such developments. This new approach requires careful management to ensure proper evaluation of progress against plan.
- Delegate responsibility to NOAO and the AO steering committee to work with the astronomical community to develop and update the roadmap, evaluate progress in meeting roadmap goals, and work with the NSF to implement and manage roadmap elements. NSF participation in the annual steering committee meetings, as well as its management relationship vis-a-vis NOAO should provide confidence in the fairness of the process, the soundness of its technical recommendations, and its openness to new ideas.

Addendum

Recommended Adaptive Optics Development Priorities for 2001-2004

The Adaptive Optics Roadmap provides the outline of an integrated program aimed at achieving dual goals: (1) enabling next generation large O/IR telescopes; and 2) advancing the development of systems and components not only in service of this goal but of accelerating deployment of next generation AO systems on extant telescopes. Achieving these goals requires both funding adequate to develop over the next decade the suite of components and subsystems as recommended in the roadmap, and a clear sense of priorities, in order to guide investment early-on in enabling key or long lead-time elements of the program. This addendum is aimed at providing the NSF with a community consensus regarding those priorities for the next 3 years.

We urge that the NSF not only heed these priorities in mapping its near-term investment strategies for AO, but that the Foundation also (1) commit to the process of update and review recommended in the AO roadmap; (2) recognize that AO systems will be incomplete absent eventual investment in development of all components of the integrated systems discussed in the roadmap; and (3) structure announcements of opportunity in service of achieving roadmap goals in a manner that ensures openness to innovation.

In this context, the AO Steering Committee has developed the following prioritization of near-term (3-year) investments aimed at enabling and accelerating AO programs in the US.

The first priority entry is a fundamental requirement for all laser beacon concepts.

1. Successful completion of system integration and demonstration of science operation of developmental laser beacon AO systems (sodium and Rayleigh beacon types), including on-sky characterization of alternative technologies. Numerous systems have been assembled, and several have demonstrated functional laser beacon lock. The next few critical steps will firmly establish the dramatic science performance enhancements expected of laser beacon AO.

Both the first and second priority entries are required if sodium beacons are to be eventually deployed to many extant facilities, are to be implemented in MCAO systems, and are to enable future large aperture telescopes.

2. Realization of practical and reliable sodium guide star lasers in the 10-50 W range, with optimization of pulse, spectral format, spot shape and other characteristics for AO systems on current generation, 30-m class and larger telescopes. Current sodium beacons are just sufficient for system development of the single laser case. There are several concepts for sodium lasers with improved characteristics, promising greatly reduced capital and operating costs.

It is assumed that MCAO (multi-conjugate AO) will be demonstrated in the near future by on-going programs (e.g. at Gemini and ESO). The third through fifth priority entries are required to implement MCAO on extant and increasingly large future telescopes of varying conceptual types.

3. Development of atmospheric tomography by laser beacon techniques (sodium, Rayleigh and/or combined systems), including optimized wavefront sensors, and reduction algorithms. Development of high-speed/low-noise detectors, which are critical to minimize laser power requirements and to reach the faintest natural guide stars. These are required to extend multi-conjugate AO to the full sky.

4. Improved modeling capabilities for AO on extremely large telescopes to more precisely quantify system performance as a function of component parameters. This is necessary to sharpen the science case, set requirements for WFS's, DM's, processors, and lasers, and evaluate potential sites.

5. Demonstration of AO, tomography, MCAO, and diffraction-limited imaging on the largest extant filled and unfilled-aperture telescopes.

As outlined in the roadmap, further development is needed in a number of additional areas in order to achieve the goals outlined in the roadmap. These areas are listed here without explicit priority. Resources should be made available as opportunities arise to follow promising R&D directions, especially those offering possible breakthroughs in cost or performance.

- Deformable mirrors with large numbers of actuators and improved formats, to enable optimized wavefront correction for a large aperture telescope.
- Site monitoring equipment for characterization of candidate large telescope sites, the homogeneous characterization of prime observing sites for CN₂ profiles, sodium column densities, and other critical parameters, and design optimization of large telescope AO, continuous monitoring for optimization of AO operating parameters.
- Software engineering developments for pipeline reduction of AO data from high throughput large telescopes.
- AO optimized instrumentation developments needed to best exploit compact PSF, and tolerate PSF variations with time and wavelength, for both imaging and spectroscopy.

Non-Roadmap Development Programs

In addition, recognizing that AO is a rapidly and richly developing field, it is recommended as an explicit priority that order of 20% of available R&D funding for AO be reserved for programs not foreseen within the Roadmap. The intention of this

recommendation is to ensure an appropriate level of investment in risky but high-leverage technologies with potential AO applications.

The AO Roadmap and Priorities - Reviews and Updates

The priority list above sets out a reasonable prioritization for R&D in AO as of this writing. I. Regular review and updating of both the Roadmap and the Roadmap Priorities will be required at least annually, and any time major additional investments are foreseen. A mechanism is proposed in the Roadmap for carrying out these regular updates.