The US OIR National Observatory beyond 2015
A submission to the 2011 AST Portfolio Review panel
National Optical Astronomy Observatory (NOAO)

Contact: David Silva, NOAO Director (dsilva@noao.edu)

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The Association of Universities for Research in Astronomy (AURA), Inc. operates NOAO under a Cooperative Agreement with the National Science Foundation

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Preamble: NSF request

On 8 November 2011, AST made the following request:

> *[For the period 2020 – 2025, please provide your vision for NOAO]...with a description of how that vision can address, or evolve to address, the science frontiers in the decadal surveys. The vision statement should not be a detailed budget plan. However, as noted in my previous letter, you should assume constant purchasing power over the period. You should also describe a prioritization of capabilities and activities, considering capabilities not otherwise available to U.S. astronomers, if that funding level cannot be maintained.*
>
> *We are not setting a page limit on these documents. However, particularly in the case of the facility vision, conciseness and clarity will be most effective.*

This document was written to fulfill that request.

1 Introduction

Despite looming financial austerity, NSF MPS Astronomy has an unprecedented opportunity to create a coherent, cost-effective, open-access, optical-infrared (OIR) base program that would enable unqualified USA leadership at many of the key Science Frontiers defined by the 2010 Decadal Survey as well as lay the groundwork for an era of extremely large telescopes. Annual investment in such a base program would leverage more than $1B of previous Federal (DOE, NASA, NSF), non-Federal USA, and international capital investment in ground-based OIR facilities and attract additional investment from domestic and foreign entities, especially along the Pacific Rim.

The key components of this NSF base program are funding for Large Synoptic Survey Telescope (LSST) operations (shared with USA Department of Energy and various international entities), open-access time on 8-m class telescopes such as the Gemini telescopes, ultra-wide-field imaging and spectroscopic survey operations on 4-m class telescopes such as the NOAO Mayall and Blanco telescopes (using cutting edge instrumentation funded by the USA Department of Energy), and development of internationally competitive instrumentation for 3 – 10-m US-led Federal and non-Federal telescopes.

Massive, wide-field survey facilities such as Dark Energy Camera (DECam), Big Baryonic Oscillation Spectrometer (BigBOSS), and LSST will enable US-led, international science collaborations to address the following Science Questions formulated by the Decadal Survey Science Frontiers panels:

- Why is the universe accelerating and what is the nature of dark energy?
- What is dark matter?
- What are the properties of neutrinos?
- What is the fossil record of galaxy assembly from First Stars to the present?

- What are the connections between dark and luminous matter?
- How do cosmic structures form and evolve?
- How do black holes grow, radiate, and influence their surroundings?
- What remains hidden in the time-domain (defined as an “area of unusual discovery potential” by two of the five Science Frontier panels)?

The rich datasets from these massive surveys and their associated instruments will be available to the community-at-large, enabling a new generation of survey-based projects on an unprecedented scale.

Many nights of spectroscopy on 4-m and 8-m class facilities, often supported by high-spatial resolution imaging, will be used to augment these massive surveys and execute follow-up research programs. Indeed, some of the key science objectives of these surveys cannot be achieved without such follow-up. The same 4-m and 8-m class facilities will be used for the fruitful exploration of a broad range of other science questions, both independently and in conjunction with other ground-based and space-based facilities, such as James Webb Space Telescope (JWST) and Atacama Large Millimeter Array (ALMA). All these nights will be “open access”, available to all qualified scientists via peer review.

Today, the National Optical Astronomy Observatory (NOAO) is a cost-effective NSF center that enables high-impact scientific research by a broad user community. As the result of a decade-long planning and optimization process, completed with NSF support and broad user participation, NOAO is well-positioned to provide and enable leadership at the Science Frontier within an NSF-funded OIR base program and in concert with other peer facilities throughout the US OIR System. A growing emphasis on well-defined surveys attacking major problems at the cosmic frontier of high-energy physics almost guarantees that the science impact of NSF-funded facilities operated by NOAO will increase at constant or even reduced operations purchasing power.

Section 2 summarizes current NOAO status, planned evolution, and roles its facilities will play in exploring the Science Frontiers. This is a “standalone” or “silo” view. The current scientific impact of NOAO is presented in Appendix A. As instructed by NSF, constant purchasing power through 2025 has been assumed.

Section 3 introduces the US OIR System and then proposes a comprehensive NSF-enabled ground-based OIR program that encompasses, but is not limited to, a strong national observatory built by co-mingling key assets of the current Gemini, NOAO, and LSST programs. A key goal of this comprehensive approach is to maximize science return per NSF dollar invested. Again, constant purchasing power through 2025 has been assumed.

Concluding thoughts are provided in Section 4.

2 NOAO as standalone national center

The fundamental NOAO mission is to provide all qualified researchers access via peer review to a complete set of competitive tools and services. This "open access" approach has enabled many high-impact science results for decades, including the discovery of the accelerating universe recognized by the award of the 2011 Nobel Prize in Physics. In general, the highest impact science results have come from programs awarded significant number of nights over many years. Given that insight, since 1999, NOAO has dedicated 20% of its time to Survey programs and has initiated two Large Science Programs that will receive about 30% of available time per year: Dark Energy Survey (DES, Blanco, 2012 – 2017) and Big Baryon Oscillation Spectroscopic Survey (BigBOSS, Mayall, 2018 – 2022).

2.1 Leadership at the Science Frontier

In partnership with the USA OIR community, NSF, and DOE, NOAO is preparing for continued success via deployment of major new instrumentation (e.g. Dark Energy Camera, higher performance medium-resolution optical and infrared spectrographs), continued or increased access to large aperture facilities (such as Gemini and Keck), initiation of large survey programs (e.g. Dark Energy Survey, BigBOSS, LSST), and formation of partnerships with other leading Federal science and technology centers (Fermi National Accelerator Laboratory – FNAL, Lawrence Berkeley National Laboratory – LBNL, SLAC National Accelerator Laboratory – SLAC, and the National Center for Supercomputing Applications – NCSA).

Thanks to these on-going initiatives, researchers supported by NOAO will be leaders in investigating such topics as:

- Characterization of dark energy and dark matter across cosmic time (imaging surveys with DECam and LSST; spectroscopic surveys with BigBOSS)

- Exploration and characterization of the time domain (spectroscopic follow-up of current surveys such as Pan-STARRS and Palomar Transient Factory; LSST pathfinder surveys with DECam; LSST survey itself)

- Exoplanet characterization and the study of their parent stars (spectroscopic follow-up of ESA Gaia, NASA Kepler, Gemini NICI, and Gemini Planet Imager surveys with single-object and multi-object spectrometers)

- Characterization of stellar populations in our Milky Way and its numerous dwarf satellites (spectroscopic surveys with BigBOSS with and without input data from Gaia; deep, wide-field imaging surveys with DECam to find new local dwarf galaxies)

	Base Funding (M$)
Operations & Maintenance	
Cerro Tololo Inter-American Observatory	6.20
La Serena Base Facility Operations	1.76
Kitt Peak National Observatory	6.57
Tucson Base Facility Operations	1.27
Data management (operations)	1.09
Time Allocation Committee	0.29
Administrative overhead	0.50
AURA fees	0.50
SubTotal	**18.18**
Other Operations	
USA National Gemini Office	1.18
LSST science development	0.80
Office of Science	0.79
Education & Public Outreach	1.06
NOAO Director's Office	1.20
Operational reserve	0.86
Administrative overhead	0.17
AURA fees	0.18
SubTotal	**6.24**
Development	
Instrumentation	2.28
Data management (development)	0.81
LSST Telescope & Site development	1.42
GMST development	0.00
Administrative overhead	0.13
AURA fees	0.14
SubTotal	**4.78**
NOAO Program, Base Funding	**29.20**

2.2 *Programmatic snapshot*

Today, the NOAO program funded by NSF revolves around the operations, maintenance, and improvement of four world-class 4-m aperture telescopes and their instrumentation suite. A strong instrumentation and data system development program supports that activity. Finally, the design, development, and construction of the LSST telescope and associated site facilities are core components of the NOAO development effort.

NOAO operates or supports a large number of smaller aperture telescopes on a reimbursement basis. Base funding is **not** used for operation of small aperture telescope operations except for the KPNO 2.1-m.

NOAO executes these activities in conjunction with well-established scientific and technological collaborations with university-based groups (e.g. Ohio State, Cornell, our WIYN, SOAR, and SMARTS partners), other US-led observatories (e.g. Gemini, Keck, and other operators of 3 – 10-m class telescopes), other US national science centers (FNAL, LBNL, NCSA, SLAC), foreign institutions (e.g. Laboratório Nacional de Astrofísica-LNA, Brazil), major international science collaborations (e.g., LSST, DES, BigBOSS) and – especially – our dynamic and world-leading user community.

The current NOAO program is summarized in the table above. Full programmatic and financial details can be found in the NOAO Annual Program Plan (FY 12), available from the NOAO web site. Planned distribution of base funding is shown, under the assumption that NOAO will receive a total base allocation of $29.2M.

There are three major categories:

- **Operations and Maintenance ($18.18M**) – all activities related to operations and maintenance of four 4-m class telescopes on Kitt Peak (Arizona) and Cerro Tololo (Chile). NOAO has full operational responsibility for the Blanco 4-m and Mayall 4-m facilities and partial responsibility for the SOAR 4.2-m (30%)[1], and WIYN 3.5-m (40%) facilities. The Kitt Peak 2.1-m is oper-

[1] To be precise, NOAO is funding 71% of the annual operations cost of SOAR until 2018, in compensation for the initial larger capital investment of the other SOAR partners. The WIYN partnership had a

ated at very low cost (less than $200K per year) in the margin of Mayall and WIYN operations. NOAO receives additional, non-base funding from clients (not shown here) for the operation or support of smaller facilities on Kitt Peak and Cerro Tololo. Administrative Services and AURA Fees are the proportional share of costs related to, respectively, typical business services (e.g. human resources, procurement, contracts, etc.) and the AURA management fee. The amount and cost of business services is driven by Federal requirements for financial tracking and reporting.

- **Other Operations ($6.24M**) – includes the USA National Gemini Project office (mandated by international Gemini agreement) and Office of Science (responsible for academic affairs, science user workshops, staff research support, etc.). The operational reserve is a buffer maintained to allow reaction to currency fluctuations and major unexpected events (e.g. Mayall exoskeleton damage in early 2011, lower then expected FY 12 base funding from NSF).

- **Development ($4.78M**) – base funding allocated for development of instruments (e.g. SOAR ground layer adaptive optics system and imager, NOAO share of WIYN One Degree Imager project), data systems (e.g. data calibration software for new ReSTAR Phase 1 instruments[2], WIYN One Degree Imager, NOAO part of DECam community pipeline), and LSST telescope and site. At this time, NOAO has allocated no base funding for GSMT development, although we are involved in contractual work for both TMT and GMT.

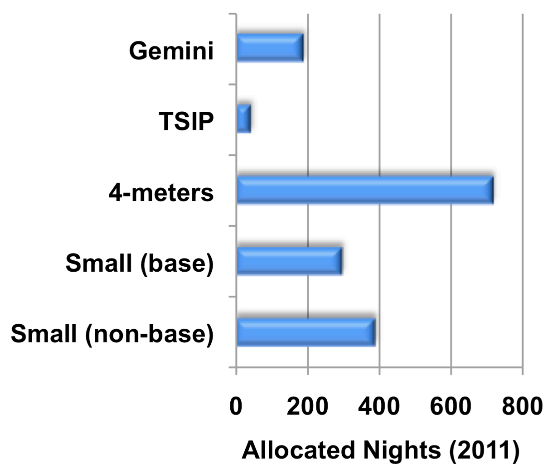


Figure 1: Number of Nights Allocated by NOAO (2011) – Gemini and TSIP nights were funded by NSF. Most 4-meter nights (Blanco, Mayall, WIYN, SOAR) were funded by NOAO base funds except 20 Palomar Hale nights (ReSTAR). "Small (base)" nights are KPNO 2.1-m while "Small (non-base)" nights comes from various facilities that NOAO operates on behalf of other organizations (e.g. SMARTS), many of which offer open access nights that are allocated by NOAO in acknowledgement of earlier NSF investment in those facilities.

In 2011, NOAO allocated 1645 nights to almost 1400 scientists from small undergraduate teaching colleges, large public and private universities, and major DOE and

similar arrangement initially (more capital from non-NOAO partners, more operations funding from NOAO).

[2] Renewing Small Telescopes for Astronomical Research, supplemental funding from NSF in 2009 following 2007 NSF/AST Senior Review recommendations. A community based program, see: http://ast.noao.edu/system/restar/

NASA centers (see Figure 1 and Section A-2). As an ensemble, this research community is extraordinarily diverse, reaching all of the groups considered to be underrepresented in the allied STEM fields by NSF, especially during the critical early-year phases when young scientists are establishing their independence and preparing to compete in the academic or commercial marketplace for jobs. NOAO users support their research through grants from NSF, NASA, and other organizations, distributed roughly evenly among those categories. The DES, BigBOSS, and LSST Science Collaborations have or will engage hundreds more researchers, including many scientists from the US and international physics community not served by NOAO in the past.

Despite declining purchasing power (see Figure 2), NOAO has continued to enable scientific success by making science-driven investment choices, using supplementary funding wisely, and choosing strong partners. Appendix A provides an overview of NOAO science impact in the last five years. **Over the next 10 years, our strategy of new, general-purpose, high data throughput instrumentation and more survey programs should dramatically increase science impact at constant (or reduced) annual operations purchasing power.**

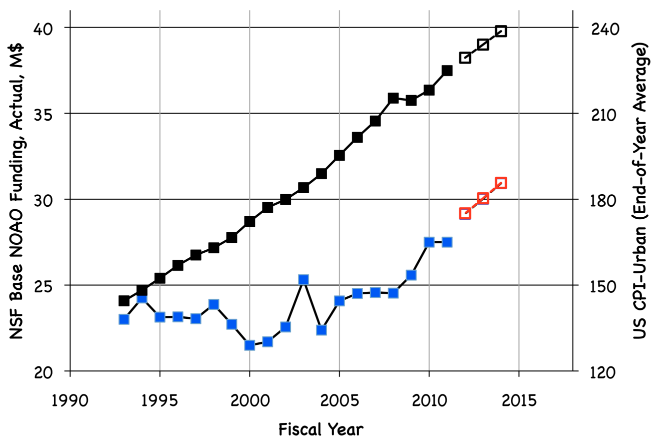


Figure 2: NOAO base funding (blue) compared to Consumer Price Index (CPI-U, black). Filled boxes are actual data points; open boxes are projected data points (CPI-U = 2% annual, NOAO = projections from 2011 February NSF budget tables). *Today, NOAO has roughly 30%* ***less*** *base purchasing power then it did in 1995.* Integrated loss of purchasing power since 1993 has been roughly $122M. Despite declining purchasing power, NOAO continued to enable high impact scientific research (see discussion).

Many additional programmatic and budgetary details can found in the plans and reports located on the NOAO Web site under News & Reports.[3]

2.3 NOAO 2015

The NOAO Long Range Plan (2011 – 2015) describes in detail what NOAO plans to accomplish in the next five years. Plans were developed assuming the base funding guidance provided in February 2011. Planned accomplishments connected directly to enabling research at the 2010 Decadal Survey Science Frontiers include:

[3] http://www.noao.edu/news/

- Three years of Dark Energy Survey (DES) operations, including release of Year 1 and 2 DES data products to the community-at-large and support for community-based mini-surveys.
- Completion of LSST telescope and site facilities design and development, initiation of LSST telescope and site construction, development of LSST follow-up strategy (including requirements for modified or new 4-m class instruments).
- New (some world-best) instruments on all four 4-m class telescopes to enable small and large scale surveys as well as spectroscopic follow-up of those surveys within a mix of exploratory ("discovery") research pursued by NOAO users.
- In addition to DES on Blanco, up to 30% of NOAO time on 4-m class telescopes (and Gemini) devoted to Survey Programs.
- Completion of BigBOSS design and development activity, initiation of BigBOSS (and Mayall adaptation) construction activity
- Become the Federal partner for GMT and/or TMT, pending the implementation of a Federal strategy for investment in one or both projects
- Initiate planning for upgraded or new instrumentation for deployment by 2020, driven by evolving science aspirations, need to replace obsolescent equipment, and requirements for survey follow up, especially the LSST survey.

Instrument		Facility	First Light	Funding	Primary partners	Remark
Dark Energy Camera	DECam	Blanco	2012	DOE, NSF	Fermilab, NCSA	Ultra-wide field optical imager
KPNO OSU Multi-objec Spectrometer	KOSMOS	Mayall	2012	NSF	Ohio State	Medium-resolution optical spectrometer
CTIO OSU Multi-object Spectrometer	COSMOS	Blanco	2012	NSF	Ohio State	Medium-resolution optical spectrometer
SOAR Adaptive Optics Module	SAM	SOAR	2012	NSF	in-house	Ground-layer AO imager
One-Degree Imager (partial)	pODI	WIYN	2012	NSF, WIYN	WIYN	Quarter degree optical imager
TripleSpec	TS4	Blanco	2014	NSF	Cornell	Medium-reslution near-IR spectrometer
One-Degree Imager (full)	ODI	WIYN	2015	NSF, WIYN	WIYN	One degree optical imager
Big Baryonic Oscillation Spectrometer	BigBOSS	Mayall	2017	DOE, NSF	LBL	5000-fiber multi-object spectrometer

2.4 NOAO 2020

Ultra-wide-field imaging and spectroscopic surveys are necessary to address many of the Science Questions defined in the 2010 Decadal Survey. By 2020, NOAO and its partners will have completed the Dark Energy Survey and initiated the BigBOSS and LSST surveys. At the very least, these surveys will dramatically deepen (some might say *transform*) our understanding of the effects of dark energy and dark matter on cosmological scale, as well as open new, richer windows on the time domain, galaxy formation and evolution, and galactic archeology.

To be more specific, by 2020, NOAO will:

- Support completion of the Dark Energy Survey (2012 – 2017), including public release of final DES data products. Continue Dark Energy Camera operations at Blanco 4-m telescope for community via peer review.

- Support completion of LSST construction and commissioning; and begin operations of LSST facilities in Chile on behalf of LSST Collaboration.
- Provide scientific user support for LSST researchers and research teams; enable rapid and steady state spectroscopic follow-up programs of LSST discoveries on NOAO facilities via peer review; develop and deploy new or upgrade instrumentation as necessary to support such follow-up activities.
- Support BigBOSS installation and commissioning at Mayall (2017) as well as three (3) years of BigBOSS science operations for BigBOSS Collaboration and community-at-large via peer review; and enable public release of BigBOSS key project science products.
- Initiate planning for upgraded or new instrumentation for deployment by 2025, driven by evolving science aspirations, need to replace obsolescent equipment, and/or 2020 Decadal Survey report.
- Initiate planning and development activities needed to support the NOAO role in GMT and TMT science operations, likely oriented towards community user support.
- In consultation with NSF and community, ramp down other activities as necessary to stay within the funding envelope of constant purchasing power (general priorities discussed in Section 2.6).

2.5 NOAO 2025

NOAO expects science priorities to evolve rapidly over the next 10 years driven by the results of many ultra-wide-field surveys (DES, BigBOSS, GAIA, Pan-STARRS, LOFAR, PTF-2, HETDEX, etc) combined with results from such small-field facilities as ALMA and JWST. In addition, the 2020 Decadal Survey will certainly review and revise the Science Questions posed by the 2010 Decadal Survey. So, any extrapolation of NOAO planning to 2025 is imprecise at best. Overall, the best strategy for a general use facility such as NOAO is to remain engaged with the scientists it serves and adapt to their research aspirations, as NOAO has by engaging with the DES and BigBOSS collaborations in the last 5 years.

Having said that, by 2025, NOAO expects to:

- Continue operation of LSST facilities in Chile on behalf of LSST Collaboration.
- Continue to provide scientific user support for LSST researchers and research teams; and enable rapid and steady state spectroscopic follow-up programs by LSST research community on NOAO facilities. Demand for rapid follow-up of time-variable objects is likely to be so large that one or more 4-m class telescopes may be devoted solely to that activity. It may be desirable and cost-effective to move BigBOSS from the Mayall to the Blanco to support LSST follow up.
- Continue to provide user support for researchers accessing rich survey datasets from DES, BigBOSS, and other projects to be completed in the next 10 years.

- Depending on needs of research community, support a science-driven mix of general purpose and survey programs, perhaps with new instrumentation
- Initiate planning for upgraded or new instrumentation for deployment by 2030, driven by evolving science aspirations, need to replace obsolescent equipment, and recommendations of strategic review committees.
- Finalize development activities needed to support the NOAO role in GMT and TMT science operations, likely oriented towards community user support.

2.6 Priorities

The NSF letter of 6 November 2011 requests that NOAO "…describe a prioritization of capabilities and activities, considering capabilities not otherwise available to U.S. astronomers, if that funding level cannot be maintained." As discussed in the next section, NOAO believes the science return-on-investment for NSF will be much higher if such prioritization is made within a broader context. Nevertheless, considered as a standalone ("silo") organization, NOAO priorities seem clear and can be enumerated with highest priority listed first:

1. **Maximize number of open-access nights on 4-m class telescopes –** gaining access to world-class research facilities via peer review remains a high priority within the community NOAO serves. Within the constellation of US-led facilities, the Mayall and Blanco provide a unique combination of many open-access nights, world-class instrumentation, and wide-field capabilities. Although WIYN and SOAR are newer and provide better image quality, currently they both have lower scientific impact than the Mayall and Blanco. Therefore, maintaining the current level of NSF/NOAO investment in WIYN and SOAR (roughly $4M per year, combined) has lower priority.

2. **Maximize science return-on-investment of Mayall and Blanco nights –** the primary tactic here is to continue partnerships to execute Large Science Programs (LSPs, i.e., Dark Energy Survey and BigBOSS) that deliver major science outcomes as well as science products and instrumentation that enable other high-impact projects. Secondary tactics include increasing fraction of open access (non-LSP) Survey programs from 20% to 30% and reducing operations costs (e.g. by mothballing less frequently used instruments and downsizing operations staff). *The Mayall and Blanco, combined with world leading survey capabilities and open access, are unique, high impact, low cost facilities.*

3. **Continue leadership roles in LSST development, construction, and operation –** LSST is the highest priority ground-based project of this decade and central to the current future plans of the US national observatory. Indeed, NOAO is one of the four Founding Partners of the LSST Collaboration. Furthermore, the NOAO employees working on LSST now (scientists, engineers, managers) are the nucleus for future facility and instrumentation upgrade and development activity (see Bullet 6 below).

4. **Continue data systems operation** – the volume and complexity of data produced by NOAO will increase by factors of 10 - 15 as DECam, ODI, and BigBOSS come on line. NOAO should be able to capture, process, and deliver data products to community users of these capabilities in a timely and cost-effective manner. NOAO personnel are also expected to be deeply involved in LSST data management and processing *operations* in Chile, although NOAO is currently **not** expected to be responsible for the creation and delivery of survey data products.

5. **Continue data system development** – as with instrumentation (see below), it is not required that NOAO design and develop all the data systems it operates. NOAO personnel are already working closely with experts in large data volume projects at NCSA (DECam), Indiana University (ODI), and LBL (BigBOSS) as well as the LSST data management system development team (LSST, Inc.). NOAO contributions to those projects derive from our expertise in instrumentation calibration, measurement of science quantities, long-haul data transport, and user support. Maintaining that expertise is highly desirable and likely more important moving forward than maintaining expertise in focal plane instrumentation and detector systems.

6. **Continue instrument development** – while NOAO remains capable of end-to-end design, development and deployment of innovative and cost-effective focal plane instrumentation and detector systems, there are other USA groups with similar or greater design, development and deployment capabilities. A vigorous internal instrumentation program is *ab initio* highly desirable, but NOAO may be able to acquire new instrumentation at lower cost to NSF by working with external groups to develop and deploy 4-m class instruments. This has the added benefit of supporting community-based instrumentation development programs. Indeed, such an approach enabled wide-field optical and near-IR imagers (i.e. Dark Energy Camera and NEWFIRM) as well as new medium-resolution optical and near-IR spectrometers. However, care must be taken to maintain the engineering and technical capabilities required for integration, maintenance and upgrade of operational facilities and instrumentation (see Bullet 3 above).

The overall NOAO program contains a number of ancillary activities, including the USA National Gemini Office, Education and Public Outreach (EPO), support for staff science and technical research activity, and LSST community science development (see table on Section 2.2). Each of these activities expends between \$0.5M and \$1.0M per year. Many such activities are executed in response to NSF requirements. Prioritizing the ancillary activities against the major activities listed above is a matter of fine-tuning and requires negotiation with NSF.

3 Towards an NSF OIR base program with a stronger national center

3.1 Ground-based OIR System today

NOAO does not, should not, and cannot operate most effectively in isolation.

Therefore, since the 2000 Decadal Survey, NOAO has supported the concept of a ground-based US optical-infrared (OIR) System to maximize science return from the combination of Federal and non-Federal investment. As an ensemble, the OIR System is the most scientifically productive constellation of such facilities in the world.

Recently, the OIR System Roadmap Committee (chair: T. Soifer, Caltech; vice-chair: B. Jannuzi, NOAO) surveyed the community and asked them which facilities they had used in the last three years[4]. More than 1200 people responded. The top 10 facilities by demand: Keck-2 (281), SDSS (272), Gemini-North (259), Keck-1 (249), Mayall (222), Gemini-South (199), MMT (192), Blanco (190), Magellan-Baade (177), and IRTF (167) (with WIYN a close 11th at 165). More importantly, the survey data make it clear that most respondents are using multiple facilities regularly – we are not a research community of single-facility users. For example, Keck-1 users not only use Keck-2 (not surprising), but also make significant use of Gemini (North and South), SDSS, Hale, Mayall, MMT, Subaru, Shane, Magellan (both), WIYN, and Blanco. Overall, the data indicate the most widely used and inter-connected facilities are (ordered by aperture size): Keck-1, Keck-2, Gemini-North, Gemini-South, Magellan-1, Magellan-2, MMT, Mayall, Blanco, and SDSS. Crabtree (2011)[5] has shown these facilities had high science impact between 2005 and 2009 (see Figures A-3 and A-4). **In short, the ground-based US OIR System exists, is operational, and is being used as an ensemble by a large segment of the US research community to produce high-impact science.**

The award of the 2011 Nobel Prize in Physics for the discovery of the accelerating universe is a beautiful illustration of the use of the NSF-supported ground based OIR System for transformational science. Much of the foundation work establishing Type Ia supernovae as standard candles relied on observations made with 1-m class telescopes at NOAO facilities. Later, candidate distant SNe Ia were found via wide-field digital imaging systems on the 4-m Blanco telescope. Spectroscopic observations with other telescopes (Keck, MMT, ESO 3.6-m) were used to confirm which candidate objects were really SNe Ia and to measure their redshifts. Actual distances were determined from supernova light-curves constructed from observations using 2-m and 4-m class telescopes, many operated by NOAO. NSF provided significant financial support via direct PI grants as well as funding for facility development, improvement and operations. Today, a similar multi-facility approach is required for such topics as time-domain investigation (e.g. gamma ray bursts, supernovae, new

[4] Soifer, Jannuzi, et al. plan to submit a more detailed survey summary to the Portfolio Review committee by the end of January.

[5] Crabtree (2011) is a short report circulated broadly by e-mail within the international observatory operations community by Dennis Crabtree (NRC/HIA, Dennis.Crabtree@nrc-cnrc.gc.ca). A publication is in preparation. NSF program officers for Gemini and NOAO should have this report.

phenomena being discovered by Pan-STARRS and Palomar Transient Factory) and characterization of exoplanet host stars. Indeed, full scientific exploitation of the LSST survey (a top-priority planned investment by NSF) will **require** a similar System-wide approach to obtain sufficient follow up observations on timescales both short (minutes to hours) and long (months to years).

3.2 Towards an NSF base program

Taking into account the existence of a functioning ground-based OIR System and finite NSF financial resources, a base program of NSF investment that maximizes science return per dollar for a large cross-section of the US astronomical community can be defined.

Such a base program should:

- Optimize the number of open access nights across aperture sizes greater than 3-m. Open access ensures that all qualified researchers gain access to NSF funded capabilities based on merit alone.
- Enable survey programs (both large, long-duration projects and smaller, short-duration projects) and survey follow-up programs. Such programs have proven to have high science return-on-investment in the past and are clearly needed to advance understanding of many important topics including the nature of dark energy and the distribution of mass on cosmological scales.
- Maximize accessibility and usability of the large, rich datasets produced by surveys funded by Federal agencies.
- Fund instrumentation and data system development on a competitive basis across the entire OIR System with a preference towards facilities that provide a significant amount of open access time.
- Enable a coordinated data management strategy across the core facilities to maximize use of data enabled by NSF funding while reducing duplicated effort. Care must be taken to segregate data processing strategies (usually instrument or research topic specific) from data management operations (often generic in design and driven by data volume and requirements on processing and retrieval turn-around time).

Consistent with recommendations from the 2010 Decadal Survey, an attractive base program model for discussion includes:

- **LSST** – highest ground-based priority for the 2010 Decadal Survey, LSST data products will be used by hundreds (perhaps thousands) of researchers from the international astronomy and physics community as well as a large number of "citizen scientists" (e.g. students, educators, amateur astronomers, journalists). LSST is the ultimate open access machine.
- **Gemini** – the primary vehicle for open-access large aperture science for USA researchers. Demand for Gemini North is already high and demand for Gemini South will likely grow dramatically with the advent of multi-conjugate

adaptive optics and new instruments (high-spatial resolution near-IR image = GSAOI, multi-object near-IR spectrometer = FLAMINGOS-2, high-contrast planet imager = GPI, and optical echelle spectrometer = GOES). Both Gemini facilities will be critical for follow-up of DES and LSST observations (as well as other major surveys such as Pan-STARRS and PTF) and will remain essential even in the GMT/TMT era. Over the next 10 years, it will be possible for NSF to acquire more open access Gemini nights for fewer dollars per night than on any other large aperture platform. Such an increased investment would be well justified by current and expected large demand for access by US community, if the Gemini instrumentation program meets current expectations. Gemini usage would be oriented more towards smaller, exploratory ("discovery") programs rather than larger surveys focused on specific science experiments.

- **Mayall and Blanco** – the primary platforms for open-access medium aperture research for the US community, these machines will be used more and more for wide-field surveys as the decade progresses. Surveys will come not only from the DES and BigBOSS Collaborations but also from other groups using the survey systems delivered by those collaborations. Follow up observations in support of DES, BigBOSS, and LSST will be critical roles for these machines by the end of the decade.
- **Ground-based OIR System Development Fund** – in recent years, AST has invested in a number of programs to develop OIR System capabilities (all values approximate and per year): LSST design & development ($3M), Gemini development ($5M), TSIP ($3M), and ReSTAR ($3M). In principle, these funds could be combined into a System Development fund ($15M/year) to: (a) enable development of new instrumentation across the entire OIR System constellation (with preference towards facilities with significant open access and aperture 4-m or larger); (b) develop direct 3 – 5 year relationships with high impact, high-demand facilities such as Keck to acquire open-access nights;[6] and (c) a centralized data archiving and processing operations center coupled to data systems at various key facilities. Gemini and NOAO (or their successor organizations) would have to compete for funding under the same conditions as other US-led OIR facilities. Experience demonstrates that such NSF funds can be highly leveraged to attract similar amounts from Federal, state, and private sources. In other words, NSF investment at this level is likely to attract at least as much non-NSF funding.

In parallel to this base program, community-funded 4-m and larger aperture telescopes can and should carry a large part of the load for teaching, training, and small

[6] Note that the number of nights available for NSF acquisition on non-Federal platforms is limited, as most facilities are highly subscribed by their own user communities and (understandably) those communities are reluctant to "sell" nights they want to use for their own research. In recent years, Keck and MMT have made tens of nights available per year but most other facilities have offered a much smaller amount.

team projects. NSF can and should support that activity through PI grants and some instrumentation support.

Possible inclusion into the proposed base program of Giant Magellan Telescope (GMT) and/or Thirty Meter Telescope (TMT) has been explicitly ignored in this document under three assumptions: (1) NSF will not make a significant contribution from AST divisional budget to GMT/TMT design and development; (2) any significant contribution to GMT/TMT construction costs would come from MREFC budget; and (3) significant post-construction contributions to GMT/TMT operations and/or development will not begin until 2025. For comparative purposes, note that a hypothetical $1B project operating for 20 years at $50M per year (5% of initial capital investment, optimistic lower bound) has a total cost of $2B without new instrumentation and ignoring all depreciation and inflation effects. Therefore, a 10% share (25 – 30 nights per year) costs at least $10M per year. Understanding the real annual cost and potential return-on-investment (in both absolute and relative senses) is presumably a key goal of the recent program initiated by AST.[7]

3.3 Funding the base program

In recent years, AST has invested roughly $64M annually in OIR System operations and development as follows (all values approximate and per year): NOAO ($28M), Gemini ($20M), TSIP ($3M), ReSTAR ($3M), LSST design & development ($3M + $1.5M from NOAO $28M), and miscellaneous (e.g. OIR System awards from ATI and MRI, Sloan-III, DES data management systems, etc., at least $5M). Today, these activities are managed more or less independently.[8] **Under the assumption of constant purchasing power, the current level of funding (~ $65M) is sustainable indefinitely**.

Activity	Annual Cost (M$, 2011)
LSST operations (NSF share)	20
Gemini operations (63% USA)	18
NOAO operations (reduced)	18
System development fund	15
SubTotal	**71**

Is $65M enough for the four-element base program outlined above? Taken at face value, the table at left suggests the answer is “no”. However, as shown, the table is highly non-optimal in financial terms. In particular, it assumes implicitly that LSST, Gemini, and NOAO operations and maintenance remain separated, Gemini retains its current science operations model, the USA share of Gemini remains high, and NOAO services have been dramatically curtailed. **These are costly assumptions that are clearly not motivated by maximizing science return per dollar invested across the entire NSF OIR investment portfolio.**

[7] Program solicitation NSF 12-526, *Planning a Partnership Model for a Giant Segmented Mirror Telescope*

[8] Many of these individual investments will ramp down in FY 12 and 13, especially TSIP and ReSTAR (both zero in FY 12) as the overall AST budget is squeezed at the same time ALMA operations support must increase.

3.4 Towards a stronger national center

The four components of the proposed NSF base program could be managed separately, maintaining the current *status quo*. However, collecting the operational components within a single integrated management structure would lower annual operations costs through elimination of duplicated services, managers, administrators, oversight committees, etc. and global minimization in the number of science and technical operations personnel.

Such a consolidated NSF OIR center with a broad range of science and technical capabilities would be an attractive focus for the creation of bi-lateral or multi-lateral partnerships, especially with emerging international research communities in the developing world. A consolidated center would also stand on more equal footing with other members of the GMT or TMT partnerships and with other international organizations.

Within the context of an NSF ground-based OIR base program, the consolidated center would:

- By roughly 2015, assume responsibility for the operation, maintenance, and development of some or all of the current Gemini and NOAO facilities. Obviously, some accommodation would have to be negotiated with the current Gemini partners within the framework of the expiration of the current Gemini International Agreement in 2014.
- By 2017, assume responsibility for the operation and maintenance of LSST facilities in Chile on behalf of the LSST Collaboration as well as provide scientific user support to US community-at-large. Until then, remain engaged in LSST development, construction, and commissioning at the level supported by NOAO today.
- Seek to gain more open-access nights on large aperture telescopes. At present, NSF can acquire Gemini nights for lower cost per night than other facilities with similar aperture. A less conventional approach would be to reduce Gemini share (or NOAO funding) to free up funding for more, e.g., Keck nights. Reprioritizing investment among Gemini, NOAO, and other facilities is more straightforward if NSF investment is consolidated, eliminating potential conflicts in strategic vision among the unconsolidated facilities and greatly reducing the overhead and inertia associated with rebalancing staffing. In any case, the goal is to shift "discovery" science towards larger apertures and concentrate on surveys at 4-m facilities.
- Upgrade and add instrumentation on high-demand, high-impact platforms with significant open access, preferably via cost-sharing partnerships (current candidates: Blanco, Mayall, Gemini-North, Gemini-South, Keck-1, and Keck-2)

- Re-distribute Gemini night allocation to achieve more productive balance between PI-class and survey-class research programs (prepare for LSST follow-up)
- Between 2015 and 2025, dedicate most Mayall and Blanco nights to massive, wide-field imaging and spectroscopic survey programs such as Dark Energy Survey and BigBOSS to increase science impact and reduce annual operations costs (retain ability for survey follow-up). After that, decide what is needed for LSST follow up and divest excess capability.
- Be the US Federal partner on behalf of NSF with Giant Magellan Telescope and/or Thirty Meter Telescope
- Retain a capability to deploy upgraded or new data systems and instrumentation (via a proactive, collaborative borrow, buy, or build strategy).
- Retain the capability to operate data systems
- Form bi-lateral partnerships with other interested parties (both USA and international) for new capabilities of general interest in return for access (e.g. Dark Energy Survey brings Dark Energy Camera and DES data products in return for 525 nights)

Such a consolidated national center would naturally:

- Minimize operations, maintenance, and technical development costs of Gemini, LSST, and NOAO in the ensemble through elimination of duplication and more focused attention on science return per dollar invested.
- Create a more uniform interface for the NSF supported OIR user community.
- Enable transition from 4-m oriented operations to 8-m oriented operations, accompanied by transfer of some Federal 4-m nights to the university-community (especially at WIYN and SOAR).
- Maximize ability to plan and execute LSST-oriented research across remaining Gemini and NOAO assets.
- Be a focus for bi-lateral international partnerships with emerging astronomical communities (e.g. Brazil, Korea, mainland China, India) that would bring new expertise, energy, and funding into the US OIR System.
- Be a stronger partner for GMT or TMT.

By 2025, it seems natural to imagine a consolidated national observatory that is focused on the operations and development of Gemini, GMT, LSST, and TMT within well-structure partnerships. In that world, legacy 4-m class telescopes can be operated in the margin, transferred to university partnerships (in part or in whole), or decommissioned.

4 Now is the time

The reality of finite funding and infinite aspirations makes regular strategic reviews a necessity. Quantitative metrics of *investment* (e.g. numbers of nights allocated, ratios of requested vs. awarded, number of grants awarded, dollars invested per activity) are important to consider, but quantitative metrics of *return per dollar invested* (e.g. numbers of papers published, number of high-impact papers published, numbers of users served, citation rate per paper published), provide deeper insight into what investment strategies are most effective scientifically.

Despite continuously decreasing purchasing power, NSF investment in NOAO over many years has produced quantifiable science productivity excellence, competitive with or beating any other ground-based astronomical facility in the world at any wavelength. Our current transition to increased emphasis on large, high data throughput, ultra-wide field imaging and spectroscopic surveys in partnership with major international collaborations of astronomers and physicists is expected to dramatically boost science return per NSF dollar invested. This strategy has already attracted significant investment from outside NSF and created strong linkage to research at the cosmic frontier of high-energy physics. It also anticipated and responds directly to important science questions posed by the 2010 decadal surveys. At the same time, NOAO will continue to provide hundreds of open access nights, ensuring a level playing field for all qualified researches and enabling the kind of "discovery" science that results in unpredictable breakthroughs. This evolution in the NOAO balance between experimentation and exploration, and between large and small research teams, is responsive to and supportive of emerging trends within the international astronomy and astrophysics community.

As a standalone organization, the US OIR national observatory, NOAO, is already well prepared for high impact success in its current configuration and well aligned with science priorities established in the 2010 decadal survey reports.

However, an opportunity clearly exists for NSF to create a stronger national observatory within an OIR base program that recognizes and invests in the US OIR System, a program that responds to the aspirations of the largest and most active population within the US astronomy and astrophysics research community. This opportunity can be achieved within the current NSF OIR investment envelope if current purchasing power can be maintained.

Establishing an OIR base program and a new, consolidated national observatory would send three important positive signals:

1. USA is committed to furnishing peer-reviewed access to a strong system of high impact OIR research facilities fully aligned with priorities established by the recent decadal surveys.

2. USA will support an OIR national observatory with resources commensurate with other major national and international OIR observatories.

3. USA has a level of commitment to its OIR national observatory worthy of trust and confidence by potential international partners.

The time to seize this opportunity is now – while the Gemini international agreement is open for re-negotiation, while LSST Collaboration is in flux as it seeks new partners for operations, while the Federal strategy for GSMT investment is under development, while the GMT and TMT projects seek to complete their capitalization and finalize their partnerships, while major experiments at the cosmic frontiers of high-energy physics are under development at major US national physics centers.

What happens if NSF OIR investment is significantly decreased? What happens if the US OIR national observatory is significantly diminished? At the very least, hundreds of open access nights on high impact facilities are lost, damaging the whole concept of NSF-funded open access, impoverishing the research careers of hundreds of American scientists, and hindering the coordinated maximization of science return from NSF investment in LSST. Major new surveys under development to address many science questions posed by recent decadal surveys would also be endangered or become closed to the general community, along with their unique, world-leading instrumentation. Harder to quantify, catalytic leadership roles played by NOAO personnel in science, technology and community organization would at best become much less effective and at worst lost completely.

Over many years, NSF has made a significant investment in ground based OIR astronomy to quantifiable great effect. That investment leveraged a much greater investment from non-Federal sources and enabled the emergence of a US OIR System. Today, that System is highly productive and, taken as a whole, second to none in the world. NOAO, the US OIR national observatory, has made notable scientific, technical and organizational contributions to that success. Now is not the time to divest in the OIR System or NOAO, but to maintain investment and make structural changes within an NSF OIR base program with the goal of maximizing scientific return per NSF dollar invested and maintaining the world leadership of the US OIR System and its national observatory.

Appendix A: NOAO is a cost-effective, high-impact center

NOAO is a cost-effective, highly engaged national center with high scientific impact, both in an absolute sense and relative to peer organizations across the globe. Here, statistical information is presented to support that assertion.

Although the Portfolio Review panel has been instructed to ignore past performance, NOAO does not intend to change its basic strategy (open access via peer review + world-class instrumentation) and therefore does not expect the outcome to change (high-impact science results by broad, world-class user community).

A.1 Science impact statistics

Figures A-1 and A-2 (NOAO, extracted from NOAO Annual Reports submitted to NSF) illustrate two key points: users demand versatile, general-purpose instrument suites and users of Blanco and Mayall publish more papers per year than users of other facilities offered by NOAO.

Figure A-3 (adapted from Crabtree, 2011, private communication but widely circulated within the OIR observatory community) shows that the Blanco and Mayall publication rates are highly competitive with all other ground-based OIR facilities, independent of aperture size and investment. Obviously, there is some delay between data acquisition and data publication, but NOAO has seen similar publication performance from Blanco and Mayall for many years.

The number of papers published is irrelevant if most papers published are ignored. As Figure A-4 (also adapted from Crabtree 2011) shows, that has not been the fate of papers based on Blanco and Mayall observations. During the study period, the ensemble science impact of papers from these NOAO facilities was highly competitive with all other ground-based OIR facilities, independent of aperture and number of papers published per year.

Despite declining purchasing power (see Figure 2), NOAO has continued to enable scientific success by making science-driven investment choices, using supplementary funding wisely, and choosing strong partners. **Over the next 10 years, our strategy of new, general-purpose, high data throughput instrumentation and more survey programs should dramatically increase science impact at constant (or reduced) annual operations purchasing power.**

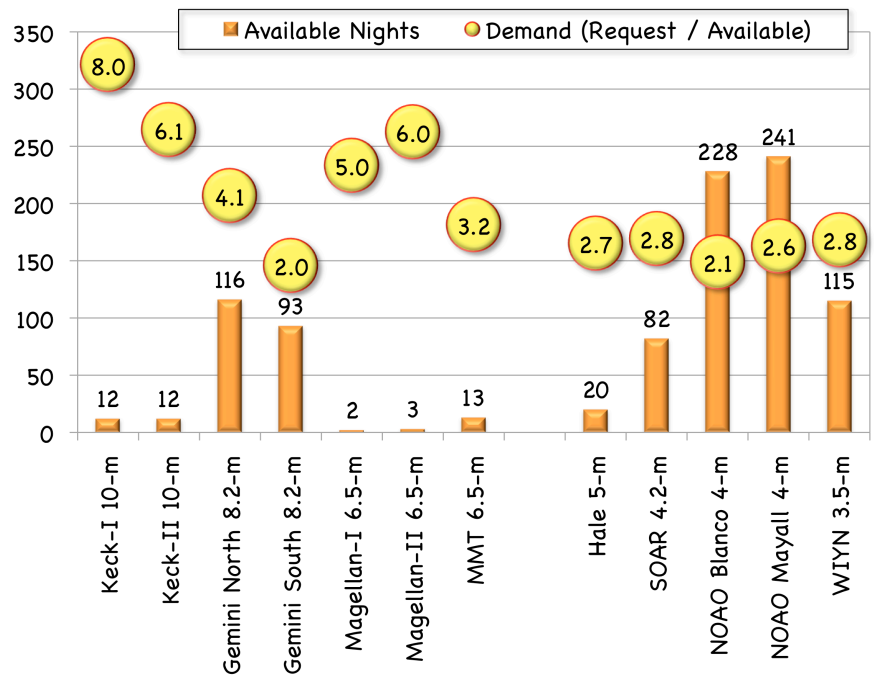


Figure A-1 – number of nights allocated by NOAO and proposal pressure (2011). Nights allocated on telescopes with aperture smaller than 3-m not shown (see Figure 1). High demand is driven by a combination of scarcity (not enough nights) and instrument suite. Although the community-based ReSTAR committee argued that demand ~ 2 was optimal, NOAO considers demand > 3 to be "healthy" and demand < 2 to be "worrisome". NOAO expects Blanco, Mayall, and Gemini-South demands to increase sharply (from new user interest) as new instruments are deployed in next 12 – 24 months. Blanco demand will also rise (from reduced available nights) when Dark Energy Survey starts consuming 100 nights per year.

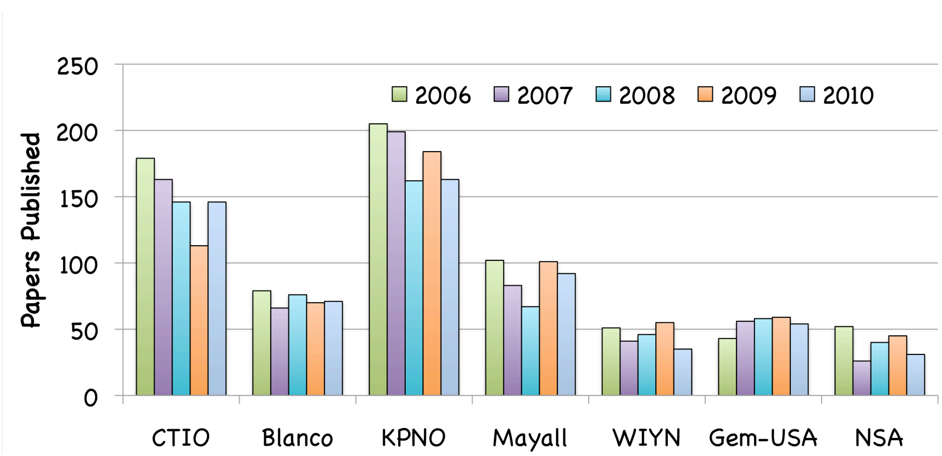


Figure A-2 – papers published as a result of time allocated by NOAO. Blanco and Mayall are subsets of CTIO and KPNO, respectively. WIYN is the entire partnership, not only the 30% NOAO share. Gem-USA papers come only from time allocated through NOAO, not the entire partnership; thus, these papers are effectively the production of one US community 8-m telescope. NSA (NOAO Science Archive) papers represent data re-used for new projects. Most of the reused data are connected to imaging surveys.

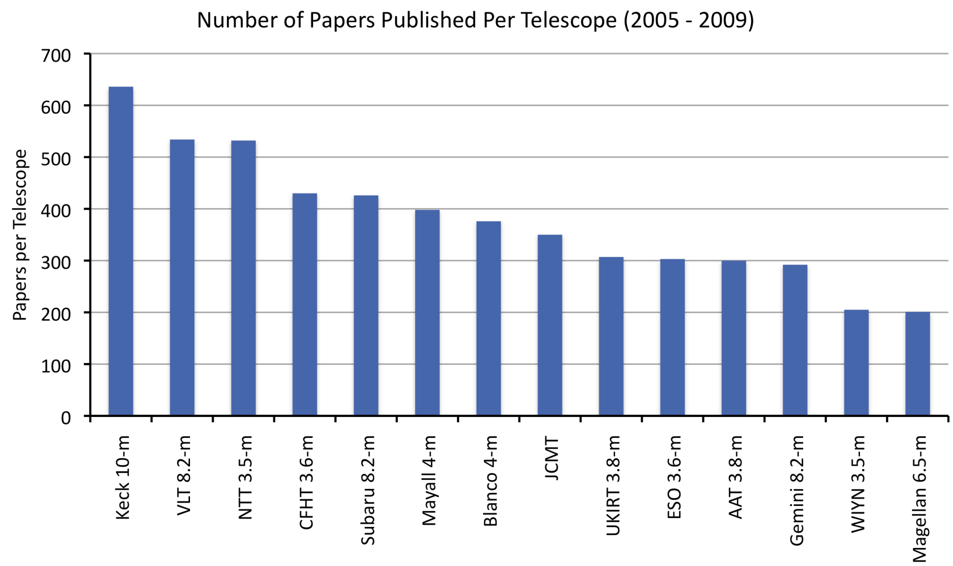


Figure A-3 – comparative, number of papers published per facility (adapted from Crabtree 2011). Numbers are per telescope for facilities with multiple telescopes (Keck, Magellan, VLT). Here, Gemini publications come from entire partnership, not just USA. NOAO Blanco and Mayall maintain world-class publication rates, even relative to more expensive and/or larger aperture facilities.

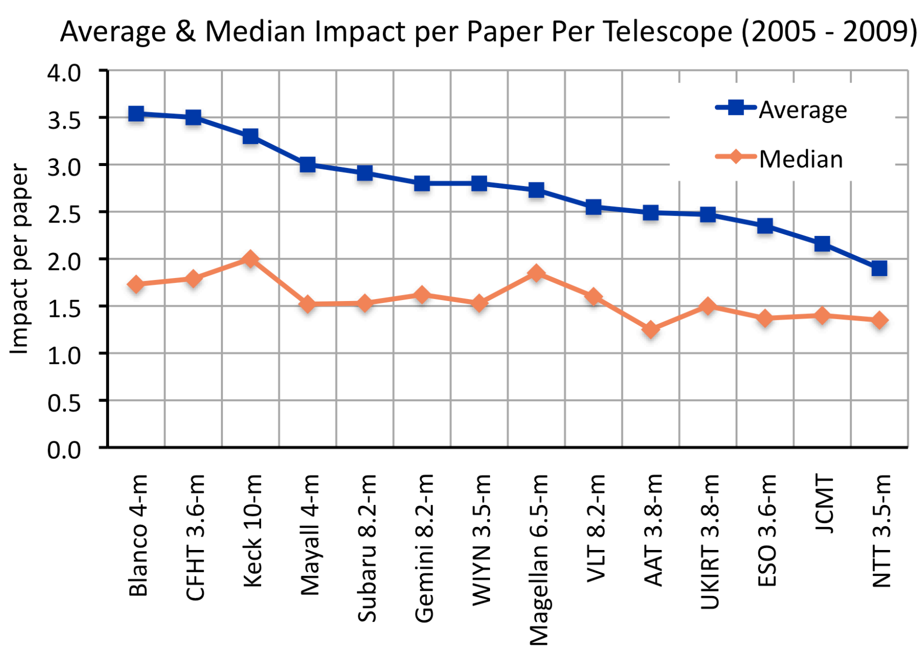


Figure A-4 – comparative, science impact per facility (adapted from Crabtree 2011). Impact is defined as the ratio of the number of citations for a given paper to the median number of citations for an AJ paper of the same year. Numbers are per telescope for facilities with multiple telescopes (Keck, Magellan, VLT). Facilities have been ordered by average impact. NOAO Blanco and Mayall facilities maintain world-class science impact, even relative to more expensive and/or larger aperture facilities.

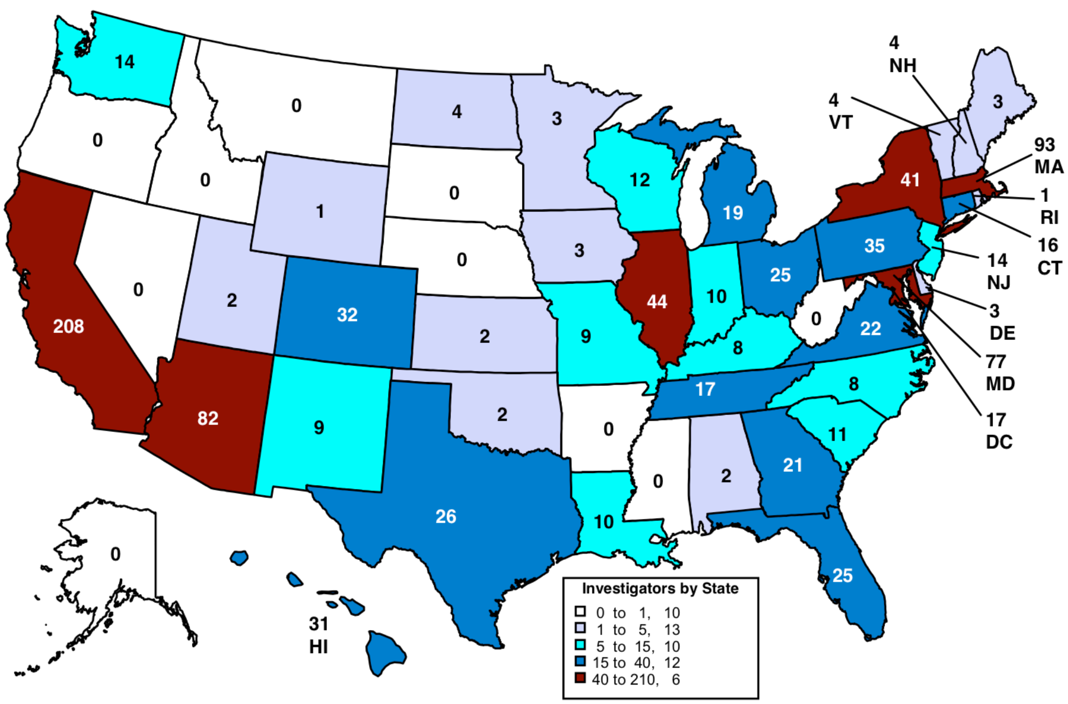
A.2 User statistics

As shown in our Fiscal Year Annual Report (2011) (see extracts one this page and next), the NOAO users community has a broad geographical distribution and is lead by researchers from the most prestigious USA and European institutions.

Annual Summary Data for Semesters 2011A/B Observing Programs (Excludes NOAO staff except for unique observing programs)

Description	US	Foreign
Unique NOAO TAC observing programs scheduled on NOAO telescopes (includes programs under TSIP/FIP on private telescopes)	370	52
Investigators (PIs + Co-Is) associated with approved observing programs	965	422
PhD thesis observers	80	24
Non-thesis graduate students	106	31
Discrete institutions represented	180	167
US states represented (including District of Columbia)	41	NA
Foreign countries represented	NA	31

Breakdown of Investigators from US Institutions for Approved 2011A/B Observing Programs
(Excludes NOAO Staff)



Investigators by Country Observing Programs for Semesters 2011A/B (Excludes NOAO Staff)	
Country*	**#**
USA	975
United Kingdom	83
Canada	64
Germany	55
France	32
Australia	26
Chile	24
The Netherlands	18
Italy	17
Japan	17
Spain	16
Brazil	10
Israel	10
Korea	8
Argentina	5
Czech Republic	5
Greece	4
Poland	4
India	3
Mexico	3
Sweden	3
Denmark	2
Russia	2
South Africa	2
Switzerland	2
Taiwan	2
Austria	1
Belgium	1
China	1
Finland	1
New Zealand	1
Norway	1

* The location of the investigator's institution determines the country of origin for the investigator.

Top 10 US Institutions with the Most Unique Investigators Observing Programs for Semesters 2011A/B (Excludes NOAO Staff)		
Rank	**US Institution**	**# of Investigators**
1	Harvard-Smithsonian Center for Astrophysics	50
2	University of Arizona	39
3	Space Telescope Science Institute	32
4	California Institute of Technology-Dept. of Astronomy	29
5	University of California, Berkeley	25
6	University of Florida	22
7	California Institute of Technology--IPAC California Institute of Technology--JPL University of Chicago	21
8	Georgia State University	19
9	Harvard University	18
10	NASA Goddard Space Flight Center University of Colorado	17

Top 10 Foreign Institutions with the Most Unique Investigators Observing Programs for Semesters 2011A/B (Excludes NOAO Staff)		
Rank	**Foreign Institution**	**# of Investigators**
1	Max-Planck-Institut für Astronomie, Germany	21
2	Max-Planck-Institut für extraterrestrische Physik, Germany	16
3	University of Toronto, Canada	14
4	University of Oxford, United Kingdom	13
5	University of Montreal, Canada	11
6	European Southern Observatory, Germany University of Cambridge, United Kingdom University of Exeter, United Kingdom	10
7	Herzberg Institute of Astrophysics, Canada	9
8	Swinburne University of Technology, Australia University of Leicester, United Kingdom	8
9	Instituto de Astrofísica de Canarias, Spain Laboratoire d'Astrophysique de Marseille, France McGill University, Canada Pontifícia Universtidad Católica de Chile, Chile	7
10	Dr. Remeis-Sternwarte Bamberg, Germany McMaster University, Canada University of Durham, United Kingdom Weizmann Institute of Science	6

A.3 Community engagement activity

NOAO does not work in isolation nor does it wish to work in isolation. Rather, NOAO strives to remain connected to the entire OIR research community, to understand their needs and requirements on NOAO facilities, to help the community find consensus, and to advocate for that consensus at NSF.

Since the 2000 Decadal Survey, NOAO has enabled a broad, inclusive community-based discussion about the US OIR System and the role of NOAO within that System. Since 2008, NOAO has been using surveys to gather information, with good response – the ALTAIR and System Roadmap surveys had more than 1700 and 1100 respondents, respectively. NOAO has recently started using blogs to enable a more interactive dialogue between respondents themselves.

In parallel, NOAO interacts with many committees per year, including: AURA Board (3 times per year), AURA Observatory Council (2), NSF NOAO Program Review Committee (2), NOAO Users' Committee (1), and board of directors' meetings for various partnerships (e.g. LSST, SOAR, WIYN). In all, about 60 people from a broad range of institutions have in-depth discussions with the NOAO management team multiple times per year, ensuring a constant stream of input and feedback on both the top-level NOAO program and various key activities within that program.

On a regular basis, NOAO also forms ad hoc committees of community scientists and charges them to discuss key issues and make recommendations. Over the last 10 years, those committees have focused on issues related to the development of the OIR System (see table below).

Committee	**Date**	**Report available on-line?**
System Community Workshop 1	2000 Oct	Yes
System Community Workshop 2	2004 May	Yes
System Community Workshop 3	2006 Nov	Yes
Future Directions for Interferometry Workshop	2006 Nov	Yes
Science with Giant Telescopes: Public Participation in TMT and GMT	2008 Jun	No
ReSTAR (Renewing Small Telescopes for Astronomical Research)	2007 - 2008	Yes
ALTAIR (Access to Large Telescopes for Astronomical Instruction and Research)	2008 – 2009	Yes
Future of NOAO Committee	2009	Yes
Ground-based OIR System Roadmap Committee	2011	Work in progress