Advancing Astronomy in the Coming Decade: Opportunities and Challenges

Report of the National Science Foundation
Division of Astronomical Sciences
Portfolio Review Committee

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Executive Summary

The coming decade promises to be a time of impressive progress in astronomy. New technologies and new ideas are advancing the field at a dizzying pace. Many of the most active research topics, from black holes to dark energy to planets beyond our Solar System, have high impact and visibility with the general public. The recent National Academy of Sciences decadal surveys of astronomy and astrophysics (*New Worlds, New Horizons*, *NWNH*) and of planetary sciences (*Vision and Voyages*, *V&V*), provide bold blueprints for exploration in the coming decade, prioritizing both ambitious new facilities and a vigorous commitment to grants programs at both individual-investigator and mid-scale sizes. The National Science Foundation's Division of Astronomical Sciences (AST) will continue as the primary supporter of U.S. ground-based astronomy effort (while NASA supports space-based astronomy).

Every field of research has ambitions beyond its current means, but AST faces particularly difficult choices in charting a course toward the science goals of *NWNH* and *V&V* within the budgets expected this decade. This Portfolio Review Committee was convened to recommend AST portfolios best suited to achieving the decadal survey goals under two budget scenarios: (A) AST purchasing power drops to 90% of FY11 levels, then rises to 106% of FY11 by FY22, and (B) AST purchasing power drops to 80% of FY11 levels by mid-decade, and remains flat through FY22. *By FY22, the projected AST budget is only 65% in Scenario A and 50% in Scenario B of the budget NWNH assumed in recommending an AST portfolio.* Indeed the AST budget is already $45M short of *NWNH* projections for FY12. This presents a considerable challenge in implementing the strong *NWNH* recommendations for both new facilities and for maintaining the strength of the grants programs. AST must find the proper balance between current facilities and new endeavors, between large projects and small grants, and between risk and reward. It must continue to invest in the training of a highly skilled and creative workforce.

Our recommendations are based on the science goals and program recommendations of *NWNH* and *V&V*. We begin by identifying the capabilities of AST facilities and the astronomical workforce that are critical to addressing the science questions prioritized by the decadal surveys. We then build portfolios for benchmark years FY17 and FY22 that retain or initiate those facilities and programs that are most effective in providing these critical capabilities. We note that while we did not revisit *NWNH* project priorites, we did independently assess these priorities relative to the opportunities of existing programs. Our goal is to assemble a vital, forward-looking, and balanced portfolio that enables scientists to respond quickly and effectively to the most promising new discoveries and technologies of the coming decade.

We find it possible in Scenario A to create an AST portfolio that provides nearly all critical ground-based capabilities for *NWNH* and *V&V* science, albeit with less U.S.

(especially public) share in some of them and substantially less support for the astronomical workforce than *NWNH* recommended.

In Scenario B, our recommended portfolio still provides most critical capabilities and enables U.S. leadership in many current and new fields, but there are major losses from Scenario A: little to no NSF participation in the revolution of 20-30m optical telescopes and next-generation wide-area submillimeter telescopes and a factor-of-two reduction in mid-scale funds for new innovative experiments and upgraded instrumentation.

Either scenario requires aggressive action on divesting the less-critical facilities in the AST portfolio. A status-quo approach to AST facilities would be disastrous for U.S. astronomy in either scenario: by FY17, funds for grants and for upgrading facility instrumentation would be 25-65% of current levels, with none of the new initiatives from *NWNH* nor any funds available to pursue unexpected innovations. Both of our FY17 portfolios contain the same set of divestment recommendations, as the decisions needed to affect the FY17 facility budget will need to be made very soon, well before we know whether the AST budget will tend toward Scenario A or B.

Our recommended portfolios are built by recognizing that the abilities of individual investigators lie at the heart of the scientific enterprise. Therefore, following NWNH, we recommend strong AST commitment to the funding of individual-investigator-grants programs and mid-scale projects. *The Astronomy and Astrophysics Research Grants and the Advanced Technologies and Instrumentation programs should remain top priorities within the AST portfolio.* We recommend continuation of the Research Experiences for Undergraduates and Astronomy and Astrophysics Postdoctoral Fellowships programs. The committee recommends adding a Theory and Computational Networks program, broadening the Partnerships in Astronomy & Astrophysics Research and Education program, and increasing funding for projects aiming to improve minority recruitment and retention in astronomy.

There are numerous mid-scale ($3M-$50M) instruments, surveys and experiments that would tremendously advance the *NWNH* and *V&V* science goals in the coming decade. To enable these bold advances, *we recommend that NSF define a Mid-Scale Innovations Program (MSIP) for projects of fixed ≤5-year term, and a Strategic Investments Program for decade-scale commitments.* We recommend that the competitively-selected MSIP accept proposals for a broad range of mid-scale projects, including fixed-term experiments and surveys, and major new or upgraded instrumentation for national observatory facilities. MSIP would subsume the existing Telescope System Instrumentation Program, Renewing Small Telescopes for Astronomical Research program, and University Radio Observatories program. A vigorous MSIP will spur creativity and innovation. Competitive selection from a wide range of opportunities will drive efficiencies and allocate resources to the strongest science programs in the interval between decadal surveys.

Medium and large facilities are the largest part of the AST portfolio. *Following the NWNH priorities for new facilities, we recommend that construction of the Large*

Synoptic Survey Telescope (LSST) begin as soon as possible. In our more optimistic budget scenario (A), *we recommend that AST contribute funding to the Cerro Chajnantor Atacama Telescope (CCAT) wide-field submillimeter observatory and provide a moderate level of funding for a Giant Segmented Mirror Telescope (GSMT).*

The national facilities currently operating or under construction with NSF funding provide a powerful and broad range of capabilities. Our committee assessed each facility's ability to provide capabilities critical to the *NWNH* science program. Our recommended portfolios for FY17 include operations of the Atacama Large Millimeter/submillimeter Array (ALMA), Advanced Technology Solar Telescope (ATST), Karl G. Jansky Very Large Array (VLA), Gemini Observatory North and South, Victor M. Blanco Telescope, Southern Astrophysical Research (SOAR) Telescope, Arecibo Observatory, Dunn Solar Telescope (DST), and National Solar Observatory Integrated Synoptic Program (NISP). The Dunn Solar Telescope would end observations two years before ATST commissioning, and AST funding of the NISP would be reduced. We also recommend that continued AST involvement in Arecibo and SOAR be re-evaluated later in the decade in light of the science opportunities and budget forecasts at that time.

Our portfolios for Scenarios A and B do not include the Nicholas U. Mayall, Wisconsin-Indiana-Yale-NOAO (WIYN), and 2.1-meter telescopes at Kitt Peak National Observatory, the Robert C. Byrd Green Bank Telescope, the Very Long Baseline Array, nor the McMath-Pierce Solar Telescope. We recommend that AST divest from these facilities before FY17.

Divestment from these highly successful, long-running facilities will be difficult for all of us in the astronomical community. We must, however, consider the science tradeoff between divesting existing facilities and the risk of devastating cuts to individual research grants, mid-scale projects, and new initiatives. Even with the divestments outlined above, our Scenario B budget forecasts a 24% drop in purchasing power of the small grants and mid-scale programs in FY17, a severely stressed level that is well short of the *NWNH* recommendations for augmentations. Retaining the above facilities in the face of declining budgets risks significantly greater shortfalls, which would be a far more severe loss to the forward momentum of the field. The Portfolio Review Committee feels strongly that investing in creativity and innovation at the individual investigator and mid-scale project level is critical to achieving bold new discoveries and progress in the next decade. Without adequate grant support, we will not achieve the expected science return from the many powerful AST and non-AST facilities that will be operating in the coming decade. Without mid-scale projects, we will not adequately harness the ongoing technological revolution with novel instruments and ambitious surveys. Difficult choices about reductions and divestments are needed *now* if the field is to maintain strong grants programs and pursue any of the new *NWNH* initiatives. *We recommend that AST avoid the risk of drastic reductions in small grants and mid-scale funding by configuring its facility portfolio assuming more pessimistic budgets (e.g., Scenario B). If stronger budgets are realized, then re-investments can be made through the small grants and mid-scale programs.*

Further discussion of our recommended portfolios can be found in Chapter 10. A full listing of the report recommendations is included in Chapter 13.

While the current economic climate poses a severe challenge, we remain optimistic in our belief that the AST portfolio will be a vibrant force for astronomical research in the next decade. New facilities such as ALMA, ATST, VLA, and LSST will define the astronomical frontier. In stronger budget scenarios, AST can collaborate in the ground-breaking CCAT and GSMT projects. The MSIP and small-grants programs will allow AST to foster the best peer-reviewed ideas, to develop new technologies and instruments, maintain the health of the profession, and to leverage the opportunities provided at non-AST facilities. The coming decade carries great scientific promise, and we believe that AST's broad and balanced portfolio will be central to the continued success of U.S. astronomy.

1 Introduction

Astronomy is in a remarkable period of discovery. In the last two decades, we have constructed and tested a standard model of cosmology that includes a new cosmic force, discovered over a thousand planets orbiting other stars, tracked galaxies back to the first half billion years after the Big Bang, mapped black holes and the relativistic Universe, dissected the Milky Way galaxy along with its local neighbors in amazing detail, uncovered brown dwarfs that challenge the distinction between stars and planets, and explored our home in space from the Sun's core to the outer edges of the Solar System. These achievements have been driven by stunning improvements in technology and research tools and a creative and innovative cadre of professional astronomers. The combination of larger telescopes and better instrumentation has improved our technical capabilities by several orders of magnitude over a wide range of wavelengths. This has fueled an explosion in data quantity and quality, with modern computing allowing us both to process and analyze the data far more effectively, and to perform detailed simulations of the complex outcomes of astrophysical theories. These opportunities have attracted new researchers, and the field has grown substantially both in the U.S. and around the world.

We are poised to maintain this remarkable progress in the coming decades. Computing and other advanced technologies continue to improve at a tremendous rate, and this will drive the field on many fronts: from large-format detectors and interferometry to computer-aided design and control of telescopes to processing of massive data sets to data archives to numerical simulations. Astronomers worldwide are designing ambitious new programs to explore and understand the physical Universe. These improvements are not incremental, but often involve factors of tens and hundreds. Our workforce continues to expand and broaden, bringing new ideas and fresh perspectives to bear on the challenges ahead.

The United States is currently at the forefront across a broad array of astronomical disciplines, resulting in achievements that embolden and inspire both the public and our future researchers. Based on American Astronomical Society (AAS) membership statistics, there are over 6,000 practicing astronomers in the U.S., covering all active areas of research. U.S. astronomy benefits from an enormous diversity of institutes and university departments and a network of federal, state, university, and philanthropic support for facilities, projects, and individuals. The U.S. operates many of the best and largest telescopes in the world across all wavelengths, largely through a mix of National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), Department of Energy (DOE), and state and private funding. However, whereas the U.S. dominated the entire astronomy landscape for most of the last century, we are now faced with increasing competition and comparable financial investments from Europe, Japan, Australia, and several other international players.

The National Science Foundation plays a critical role in supporting and developing the national astronomical portfolio, primarily through the Division of Astronomical Sciences (AST), but also through Physics (PHY), Polar Programs (OPP), Atmospheric and Geospace Sciences (AGS), and the Office of Cyberinfrastructure (OCI). NSF has built and operates several of the most powerful facilities currently in existence, such as the Atacama Large Millimeter/submillimeter Array (ALMA), the Karl G. Jansky Very Large Array (VLA), and the Gemini Observatory, as well as major centers, notably the National Optical Astronomy Observatory (NOAO), the National Radio Astronomy Observatory (NRAO), and the National Solar Observatory (NSO). These facilities and centers provide open access to astronomers from any U.S. scientific or academic institution, as well as to astronomers from other countries. The NSF is also a primary source of individual research grants and mid-scale project support, which is critically important for maintaining U.S. leadership in ground-based astronomy. Annual peer-reviewed competitions have allowed swift response to new discoveries, as well as rapid pursuit of the newest opportunities and ideas. The robust individual-investigator program and the policy of open access to national facilities have enabled astronomers across the U.S. to pursue cutting-edge research both individually and via networks of small groups.

Since 1964, astronomers in the U.S. have coordinated their recommendations for large federally-funded projects through "decadal surveys." These surveys have been conducted by the National Academy of Sciences (NAS) via funding from NSF, NASA, and, recently, DOE. The surveys use community assessments of the most important science priorities of the coming decade to prioritize candidate projects within suitable funding mechanisms. The most recent process for astronomy and astrophysics was Astro2010; its survey report, *New Worlds New Horizons* (*NWNH*), was released in August 2010. Over 200 leading scientists served on the main panel, the Science Frontier Panels, the Program Prioritization Panels, and the Infrastructure Study Groups. Over 300 white papers and more than 100 project proposals were contributed in response to Astro2010 calls for input. A similarly ambitious decadal survey for planetary science was also completed in 2011; we use its report *Vision and Voyages* (*V&V*) to augment the science goals from *NWNH*.

NWNH recommends major new space- and ground-based facilities, but in addition recommends new investments in mid-scale and small-grants programs. Within AST, individual and collaborative research is supported primarily by the Astronomy and Astrophysics Research Grants (AAG) program, but AST runs other peer-reviewed competitions for grants, such as the Advanced Technologies and Instrumentation (ATI) program, the Research Experiences for Undergraduates (REU) program, and the Astronomy and Astrophysics Postdoctoral Fellowships (AAPF) program. In our report, the phrase "small-grants programs" refers to all competed programs for research funding under about $2M per grant, not just the AAG. The more general terms "grants" or "grants programs" include mid-scale projects as well as small-grants programs.

Unfortunately, between late 2009 – when the agencies informed Astro2010 of suitable budget profiles – and now, the national budget forecasts have substantially worsened. Funding is anticipated to undershoot the *NWNH* assumptions by perhaps as much as 50%. Indeed, these changes are now upon us: the FY12 AST budget is $45M below the *NWNH* model and the gap may grow to $75M-100M by FY14. More details on our assumed budget projections are given in Chapter 3. It is important to understand the seriousness of this financial situation, because it is the fundamental driver of hard choices that are required in order to maintain a positive, forward-looking, and innovation-oriented future.

AST must carefully consider its current portfolio in light of *NWNH* and *V&V* priorities and the anticipated budgets. Doing nothing is a very poor choice, potentially disastrous for U.S. leadership in astronomy: the AST budget is shrinking significantly in purchasing power while the cost of operating its ambitious facilities portfolio is rising. If, for example, current national facilities were maintained at constant purchasing power, the entirety of AST grants programs would have to be nearly zeroed out by the end of the decade, with no progress being made on the top-ranked projects from *NWNH*. Chapter 3 illustrates the danger of the status quo. Clearly, delicate balance is required between grants and facilities, between existing capabilities and new investments, between a program driven by existing science priorities and possible revolutions motivated by new discoveries, between the largest collective efforts and nimble initiatives, and between projects with reliable outcomes and risky undertakings.

The NSF must act decisively to maintain this balance. The AST portfolio is reasonably flexible on the time scale of a decade, but its current commitments create significant inertia on the time scale of a few years. The recent budget downturn will create a shortage of new funding opportunities in the coming year, and this shortage could be prolonged if AST acts too optimistically only to be faced with repeated shortfalls.

In September 2011, AST enlisted a Portfolio Review Committee (PRC) as a sub-committee of the Directorate for Mathematical and Physical Sciences Advisory Committee (MPSAC) to advise the division on how to shape the entire AST portfolio in light of *NWNH* priorities and realistic budget projections. Our committee was charged to:

1) Recommend the critical capabilities needed over the period from 2015 to 2025 that would enable progress on the science program articulated in Chapter 2 of *NWNH*. (This aspect of the charge was later expanded to encompass the planetary science program in Chapter 3 of *V&V*.)

2) Recommend the balance of investments in new and in existing, but evolved, facilities, grants programs, and other activities that would deliver the needed capabilities within the constraints of each of the provided budgetary scenarios.

Our charge included the grants programs as well as facilities, and it encompasses observational, theoretical, computational, and laboratory capabilities. We were asked to consider science merit and priorities (as expressed by *NWNH* and *V&V*), the global astronomical landscape, and consequences for workforce, education, and the health of the profession in reaching our recommendations. While we were instructed not to reopen debate on the recommendations and science program of *NWNH*, we were asked to independently assess the relative priority of the rank-ordered *NWNH*-recommended projects compared to existing facilities, programs, and other activities. We were also asked to provide sufficient detail of prioritization to allow AST to make adjustments in response to national funding levels. The full text of the Portfolio Review charge is in Appendix B.

While the budget crunch is an unavoidable piece of today's context, we stress that periodic portfolio reviews are an essential aspect of stewardship of the field regardless of budget outlook. Astronomy is largely driven by new technologies, new ideas, new projects, new people, and unanticipated discoveries. It is in our scientific best interest to periodically scrutinize and renew the portfolio, which could require divesting from or decommissioning some older and less competitive facilities, or creating new partnerships to rejuvenate and sustain them. Such a review brings a fresh perspective, with the opportunity to design and execute the new projects essential to the vitality of U.S. astronomical research. Astronomy is a high-technology endeavor, requiring ongoing and vigorous development.

This report necessarily focuses on NSF-funded astronomy in the U.S.; it is recognized that a substantial portion of the research capability of the field is supported by other federal agencies or by private and international organizations. NSF funding is most beneficial to U.S. astronomical leadership when it leverages these other investments to improve the capabilities available to U.S. astronomers without needless duplication of non-federal facilities.

Despite the contractions implied by the less favorable budget forecasts, we are very optimistic that U.S. astronomy can and should remain a vibrant, exciting field. The coming decade will bring far-reaching discoveries from ALMA and VLA, ambitious new optical and infrared instrumentation, and vastly improved high-performance computing, among many other successes. It is hoped that this decade will see the completion of landmark facilities such as the James Webb Space Telescope (JWST), Advanced Technology Solar Telescope (ATST), and top recommendations from *NWNH* and *V&V*. We believe that fostering a strong competitive opportunity for small and mid-scale projects against the backdrop of our major astronomical facilities will keep the field healthy, allowing us to continue the record of magnificent achievements of decades past.

The report begins with a statement of principles in Chapter 2, a summary of the current portfolio and budget projections in Chapter 3, and a description of community input in Chapter 4. Chapters 5 and 6 develop a list of critical capabilities needed to pursue the science of the next decade, as called for by phase 1 of the charge. Chapters 7, 8, and 9 use the capabilities to make recommendations and rankings for the small-grants programs, mid-scale projects, and AST facilities, respectively. Chapter 10 presents integrated portfolios based on these recommendations and assesses how these portfolios address the critical capabilities. Chapter 11 discusses the national observatories, and Chapter 12 discusses the open skies policy. We conclude in Chapter 13, including a list of all recommendations. Appendices contain additional information about committee process and the calls for community input.

2 Statement of Principles

In the Charge, the PRC was asked to recommend the critical capabilities needed over the period from 2015 to 2025 that would enable progress on the science program articulated in Chapter 2 of the *NWNH* report that resulted from the Astro2010 process (augmented by the planetary science priorities from Chapter 3 of *V&V*). Furthermore, recommendations are needed as regards the balance of investments in new and existing facilities, grants programs, and other activities that would deliver the needed capabilities within the constraints of each of the budgetary scenarios provided by AST. This is a very broad charge, and at the outset the Committee felt it was important to establish a set of principles that would provide a framework and context for the recommendations of the Committee. There is an inevitable tension between science aspirations and budget realities, and investments in resources and in people. The health of the U.S. astronomy community depends not only on the NSF, but also on other federal agencies and non-federally-funded facilities. The Portfolio Review was designed to be forward-looking, leaving the research community in a healthy state a decade from now.

To accomplish this, the PRC aimed to construct portfolios that:

Maintain U.S. research leadership in astronomy. U.S. astronomy is highly successful, as indicated most recently by the award of a Nobel Prize in Physics for the discovery of the accelerated expansion of the Universe. However, leadership no longer corresponds to sole ownership of the state of the art; large facilities are increasingly international and U.S. institutions account for less than half of the research publications and of the large optical telescope collecting area. Nonetheless, the goal is to maintain and build on a U.S. track record of scientific excellence and technological innovation in all fields of astronomy.

Set funding priorities according to science goals. Every decade the research community expresses its science priorities and aspirations in an open process that leads to a report, and *NWNH* is the primary guiding document for this set of recommendations. Those consensus priorities were not revisited or altered in this exercise. However, *NWNH* made recommendations using budget assumptions that are no longer valid. The Portfolio Review aims to maximize scientific return according to *NWNH* scientific goals and priorities, while acknowledging new fiscal constraints.

Maintain a flexible system of capabilities. There is “inertia” in the long lead times and lifetimes of large astronomical facilities, in various international commitments, and in the education of the astronomical and technical workforce. The U.S. needs core infrastructure such as facilities and telescopes, and specialized engineering and design capabilities that enable us to respond to science opportunities. Within a fixed funding envelope some facilities might have to be reduced or eliminated, or adopt new financial or partnership models, to allow new capabilities to be added. In an era of highly uncertain budgets, it is prudent to tailor long-term commitments to a pessimistic budget, generating fiscal flexibility for new opportunities and challenges, and reducing the risk of forced catastrophic cuts in the rest of the portfolio.

Strive for a balance between investments in facilities and people. U.S. astronomy can only be healthy if it simultaneously develops cutting-edge or revolutionary technologies, constructs major facilities, enables the gathering and scientific use of state-of-the-art data, and invests in the human capital required to maintain a successful research enterprise. A majority (and growing) fraction of the NSF budget is allocated to facilities and their operation, which puts increasing pressure on individual grants and mid-scale initiatives. However, facilities and people are not in opposition; astronomers rely on the facilities and many are trained and employed at facilities. The challenge is to find a balance that gives the profession the best capabilities for realizing its overall aspirations, as articulated in *NWNH*. Appropriate balance also must recognize the central and increasing role of theory and computation in all fields of astronomy.

Value the role of peer-reviewed competition. In addition to the guidance provided by *NWNH*, peer review is essential in selecting our scientific priorities and in funding our investigations. The highly competitive NSF individual-investigator grants programs epitomize this principle in action and it is recognized that any reduction in their capacity will seriously stress the astronomy research community. Peer review and open competition should also guide priorities in funding instrumentation and facilities.

Value openness in the availability of data. Astronomy has an admirable tradition of open access to data, and this obligation is particularly strong when federal funds are involved. Openness should extend to the sharing of technology (including software), and access to competed resources such as funding and telescope time. In an international context, this openness should reasonably include an expectation of reciprocity.

Provide excellent training and career opportunities. Astronomy needs highly trained research practitioners and a superlative technical workforce. Young people need to be prepared for a range of career options that extend beyond academia. To retain top talent, the astronomical profession needs to be an attractive career option. The NSF tradition of encouraging breadth and inclusiveness in professional development is important in the pursuit of this principle.

Fulfill a mission to educate and inform. Astronomy excites the imagination and has great visual appeal. There are many ways to use astronomy effectively to expose the public to scientific concepts and progress and to inspire students to enter Science Technology, Engineering, and Mathematics (STEM) fields. The research health of astronomy will be aided by maintaining a vigorous education and outreach mission. The NSF's "Broader Impacts" review criterion encourages and supports innovative education and public outreach (EPO) by its grantees.

3 Budget Overview and Projections

The AST portfolio serves many constituencies and purposes. AST funds the operations of major national facilities and observatories, but it is also a principal source of individual and project-level grants. The flexibility of the AST grants programs allows AST to support competitively funded science programs across the full range of astronomical topics. We begin this chapter with an overview of the AST budget and then describe the historical trends and future projections for the budget.

We will often have need to refer to a baseline set by the current AST portfolio. To reduce some of the year-to-year jitter between different categories, we adopt the average of the FY10, FY11, and FY12 budgets as this baseline and denote it as FY10-12. We caution that this averaging can also soften some trends in the data.

AST-supported national facilities comprised 56% of the division's budget in FY10-12. These include NOAO, NRAO, NSO, the U.S. partner shares of ALMA and the Gemini Observatory, and partial support of the Arecibo radio telescope.

Additional investments in telescope time occur through the University Radio Observatories (URO), Renewing Small Telesopes for Astronomical Research (ReSTAR), and Telescope System Instrumentation Program (TSIP). AST also invested design funding toward future large facilities such as the ATST, Large Synoptic Survey Telescope (LSST), Giant Segmented Mirror Telescope (GSMT), Square Kilometer Array (SKA), and Cerro Chajnantor Atacama Telescope (CCAT). The total of all of these system investments was 7% of the division's budget in FY10-12.

AST supports a vigorous small-grants program, largely through the AAG and ATI programs. Other smaller programs include the AAPF, Partnership in Astronomy & Astrophysics Research and Education (PAARE), REU, Faculty Early Career Development Program (CAREER), Increasing the Participation and Advancement of Women in Academic Science and Engineering Careers (ADVANCE), and Cyber-Enabled Discovery and Innovation (CDI). Some programs like ADVANCE and the CAREER program are NSF-wide, with required AST funding. Nevertheless, these are competed small-grants programs funding astronomers, and we see no reason to distinguish them from AST-initiated programs. These individual-investigator grants programs totaled 30% of the division's FY10-12 budget.

AST also supports mid-sized projects and facility development programs, largely through unsolicited proposals. These include fixed term projects such as the Atacama Cosmology Telescope (ACT), Hobby-Eberly Telescope Dark Energy Experiment (HETDEX), Precision Array to Probe the Epic of Reionization (PAPER), and Sloan Digital Sky Survey III (SDSS-III). These projects comprised 4% of the division's FY10-12 budget. The sum of small-grants programs and mid-sized projects was 35% of the division's FY10-12 budget.

A new element in the AST portfolio is the Enhancing Access to the Radio Spectrum (EARS) program, which is a new program to fund research to improve the efficiency of terrestrial use of the radio spectrum. EARS was first funded in FY12 at \$3M, but it is planned to increase to \$12M/year in the future. This is important research, sited within AST because AST has been NSF's point of contact on spectrum management. But it is not primarily astronomical research, and so we explicitly separate this line so as not to obscure the funding levels for astronomy.

Finally, AST has a small level of non-research costs, such as travel support for panelists and funding for NRC studies, that fall outside of any proposal opportunity or facility support.

Table 3.1 presents the level of funding in these categories and some notable subdivisions for FY08 through FY12. We note that FY09 had a one-time increase of \$85.8M due to the American Recovery and Reinvestment Act (ARRA). As noted above, we adopt the average of the FY10, FY11, and FY12 budgets as a baseline for comparison to future portfolios; this result for FY10-12 is also shown in Table 3.1. Figure 3.1 is a pie chart of the breakdown of the FY10-12 average budget.

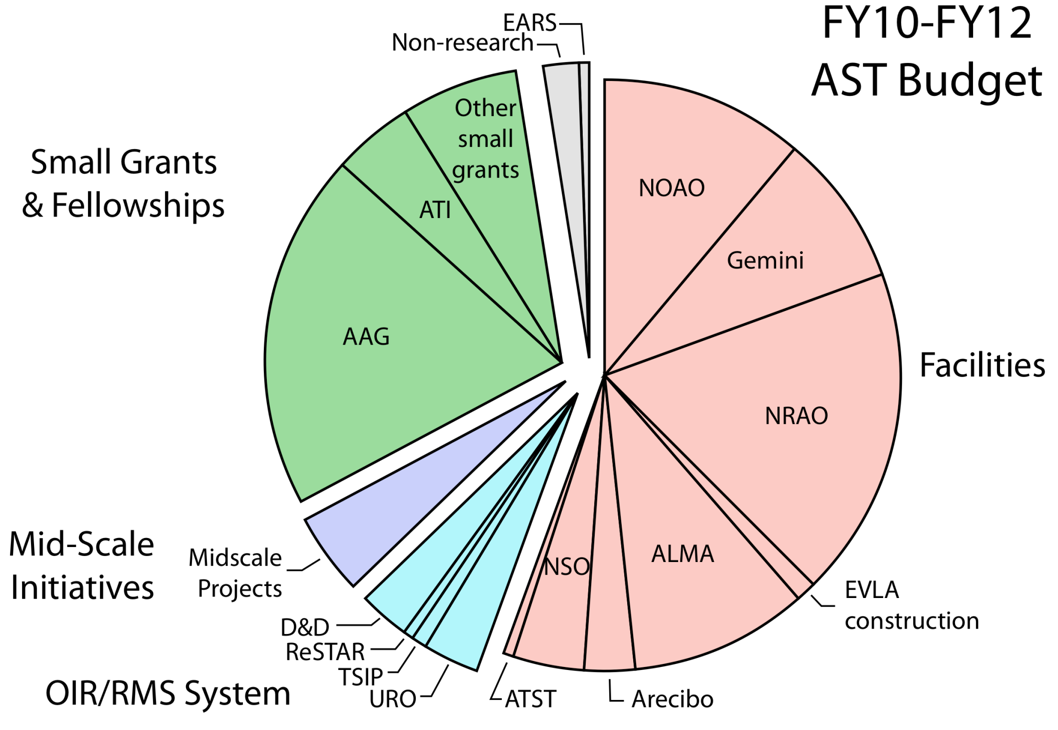

Figure 3.1 — The allocation of the AST budget, based on the average of the FY10-12 budgets.

Table 3.1 — Summary of the AST budget for FY08 to FY12. Major categories include national facilities, other system investments, grants, and other program expenses. Design & Development for Future Facilities has included LSST, GSMT, CCAT, and SKA. "Other small grants" includes AAPF, PAARE, REU, CAREER, CIF21, ADVANCE, CDI, TCN, and conference funding. Note that FY09 was unusual due to $85.8M of ARRA funding. Percentages for each rolled-up category use a denominator of the total AST budget minus EARS funding, so as to provide a consistent comparison. We also construct in the last column the average of FY10, FY11, and FY12 to be used as a baseline of comparison of future budgets; this allows us to average over some year-to-year variations. All dollar values are in then-year $M.

All Budgets are in $M	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY10-12**
NOAO	24.6	32.1	27.5	27.5	26.0	27.0
Gemini	18.7	18.7	19.1	19.5	21.6	20.1
NRAO	39.1	43.6	43.1	43.2	43.1	43.1
EVLA construction	6.0	6.2	6.4	1.1	0.0	2.5
ALMA operations	7.6	11.0	18.2	23.4	28.6	23.4
Arecibo	10.5	12.7	8.4	6.2	5.5	6.7
NSO (incl. ATST)	10.0	9.2	9.1	9.1	9.1	9.1
ATST	0.0	0.0	0.0	2.0	2.0	1.3
Total Facilities	**116.5**	**133.5**	**131.8**	**132.0**	**135.9**	**133.2**
URO	9.0	14.0	8.0	7.1	7.5	7.5
TSIP	4.0	4.0	4.0	2.0	0.0	2.0
ReSTAR	0.0	3.0	3.9	0.0	0.0	1.3
D&D for future facilities	10.7	16.2	7.3	7.0	6.0	6.8
Total System	**23.7**	**37.2**	**23.2**	**16.1**	**13.5**	**17.6**
AAG	42.1	79.6	49.4	48.1	43.4	47.0
ATI	9.0	17.8	10.5	10.5	10.5	10.5
Other small grants	12.9	36.0	17.3	11.7	16.5	15.2
Total small grants	**64.0**	**133.4**	**77.2**	**70.3**	**70.4**	**72.6**
Midscale projects	8.1	5.0	9.7	13.5	7.0	10.1
Total grants	**72.1**	**138.4**	**86.9**	**83.8**	**77.4**	**82.7**
Non-research expenses	5.6	5.4	4.6	4.9	4.7	4.7
EARS	0.0	0.0	0.0	0.0	3.0	1.0
Total AST budget	**217.9**	**314.5**	**246.5**	**236.8**	**234.5**	**239.3**
AST minus EARS	**217.9**	**314.5**	**246.5**	**236.8**	**231.5**	**238.3**
% Facilities	53%	42%	53%	56%	59%	56%
% System	11%	12%	9%	7%	6%	7%
% Grants	33%	44%	35%	35%	33%	35%

Figure 3.2 displays the AST budget since FY01, adjusted to FY11 dollars assuming 2.5% annual inflation.[1] The exact numbers are in Table 3.2. Throughout the report, we will refer to this 2.5% annual inflation correction as "purchasing power," although we acknowledge that real purchasing power can differ from the inflation rate. AST funding grew by 20% in purchasing power from FY01 to FY03, then stayed approximately constant in purchasing power from FY03 to FY08. FY09 saw a 40% boost due to ARRA, and FY10 was still 8% above FY08. The fraction of the AST portfolio supporting facilities dropped from 65% in the late 1990's to 53% in FY10.

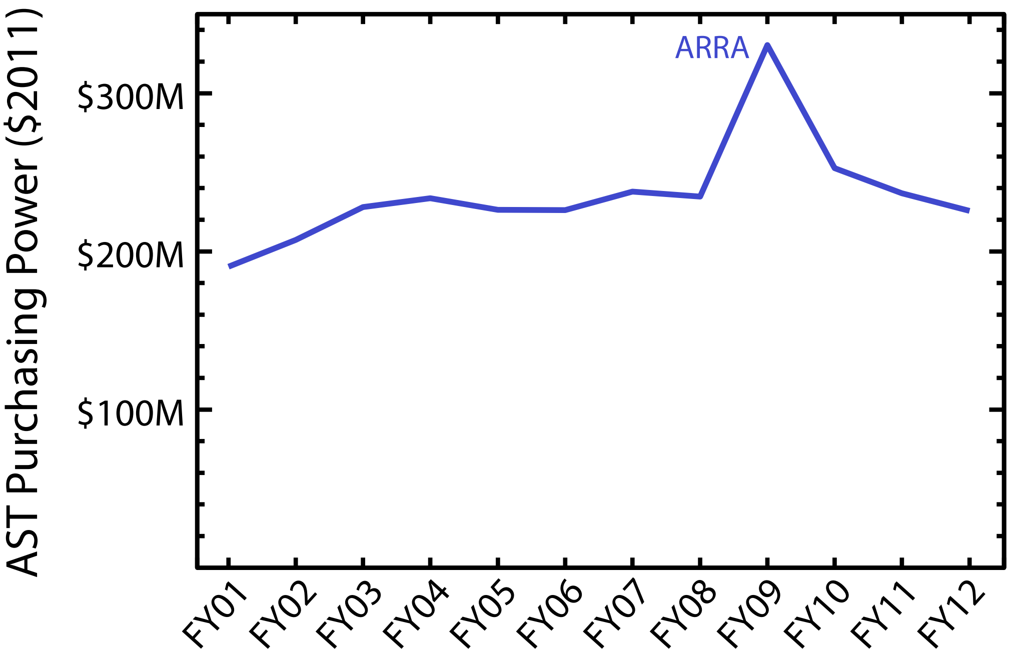

Figure 3.2 — The AST budget since FY01, expressed in FY11 dollars assuming 2.5% annual inflation. FY09 shows the large effect of the ARRA one-time allocation.

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[1] In detail, we have chosen to focus on the non-EARS portion of the AST budget. To do this, we have subtracted the EARS funding from the FY10-12 average so as to establish the level of funding for astronomical research. We then extrapolate this to a different year using 2.5% annual inflation and then add the EARS funding for that year (of course, this is zero prior to FY12). This defines the FY10-12 purchasing power scenario. We compare the actual or projected AST budget to this scenario.

Table 3.2 — Total AST budgets since 2001, followed by our AST budget projections for Scenario A and Scenario B. The percentage change from the previous year and the expected EARS spending are also listed. We then compare these to two other scenarios, a FY10-12 purchasing power scenario and the *NWNH* scenario. The FY10-12 purchasing power scenario is formed by averaging the non-EARS AST budget in FY10, FY11, and FY12, then attaching 2.5% annual inflation, and finally adding the listed EARS funding to create a total for the AST budget projection. The *NWNH* scenario is 6.5% annual growth (4% beyond inflation) starting in FY10, without any adjustment for EARS funding. All dollar values are in then-year $M.

Fiscal Year	AST Budget	% Change from past year	EARS Funding	FY10-12 Purchasing Power Scenario	AST Budget comp. to FY10-12	*NWNH* Scenario	AST Budget comp. to *NWNH*
2001	148.7	—	0	186.1	80%		
2002	166.0	12%	0	190.8	87%		
2003	187.1	13%	0	195.6	96%		
2004	196.6	5%	0	200.5	98%		
2005	195.1	-1%	0	205.5	95%		
2006	199.8	2%	0	210.6	95%		
2007	215.4	8%	0	215.9	100%		
2008	217.9	1%	0	221.3	98%		
2009	314.5	44%	0	226.8	139%		
2010	246.5	-22%	0	232.5	106%	246.5	100%
2011	236.8	-4%	0	238.3	99%	263	90%
2012	234.6	-1%	3	247.2	95%	280	84%
Scenario A							
2013	234.6	0%	12	262.3	89%	298	79%
2014	241.6	3%	12	268.6	90%	317	76%
2015	248.8	3%	12	275.0	90%	338	74%
2016	256.3	3%	12	281.6	91%	360	71%
2017	**269.1**	**5%**	**12**	**288.3**	**93%**	**383**	**70%**
2018	282.6	5%	12	295.2	96%	408	69%
2019	296.7	5%	12	302.3	98%	434	68%
2020	311.5	5%	12	309.6	101%	463	67%
2021	327.1	5%	12	317.0	103%	493	66%
2022	**343.5**	**5%**	**12**	**324.6**	**106%**	**525**	**65%**
Scenario B							
2013	227.5	-3%	12	262.3	87%	298	76%
2014	220.7	-3%	12	268.6	82%	317	70%
2015	220.7	0%	12	275.0	80%	338	65%
2016	220.7	0%	12	281.6	78%	360	61%
2017	**227.3**	**3%**	**12**	**288.3**	**79%**	**383**	**59%**
2018	234.1	3%	12	295.2	79%	408	57%
2019	241.2	3%	12	302.3	80%	434	56%
2020	248.4	3%	12	309.6	80%	463	54%
2021	255.8	3%	12	317.0	81%	493	52%
2022	**263.5**	**3%**	**12**	**324.6**	**81%**	**525**	**50%**

Since FY10, purchasing power (after subtracting the EARS program funding) has dropped by 11% in two years. Moreover, this period has also seen a substantial rise in the ALMA operations budget, which has been only partially balanced by cost-sharing at Arecibo and the ramp-down in construction of the Expanded Very Large Array (EVLA). ALMA construction was funded from the NSF Major Research Equipment and Facilities Construction (MREFC) line, not AST, but operations are ramping up and will soon reach $40M/year, about 15% of the AST budget. The result is a substantial constriction in the rest of the AST portfolio, with the fraction for facilities rising to 59% in FY12. Thus far this constriction has largely been borne by reductions in mid-scale projects (with fewer new starts) and AAG funding, as well as the suspension of the TSIP and ReSTAR programs.

3.1 New Worlds, New Horizons Recommendations

NWNH recommended a number of extensions of the current AST portfolio. Among large programs, it recommended (in priority order):

1. The Large Synoptic Survey Telescope (LSST), an 8-meter wide-field survey telescope to be built in partnership with the Department of Energy and a private consortium. The NSF share of the construction of LSST would come from the MREFC line, but the NSF share of operations support would come from the AST budget. The NSF share of LSST operations costs was estimated at $19M/year.
2. A Mid-scale Innovations Program (MSIP) of $40M/year, approximately twice the current AST funding level for such projects.
3. The Giant Segmented Mirror Telescope (GSMT), a 20-30m-class telescope of which the NSF would acquire a 25% share through contributions to construction, operations, or instruments. The exact scenario employed in *NWNH* was a $250-350M construction share from the MREFC line, followed by annual operations costs of $9-14M, but other scenarios could be considered.
4. The Advanced Čerenkov Telescope Array (ACTA), a gamma-ray observatory to be built in partnership with a European consortium. The U.S. share of construction would be of order $100M and is proposed to be shared between NSF and the Department of Energy. No operations cost estimate was given.

NWNH recommended a single medium-scale project, the Cerro Chajnantor Atacama Telescope (CCAT), a 25-meter submillimeter telescope to be constructed in partnership with a private consortium. The NSF share would be $37M of construction money and $7.5M in annual operations costs.

Finally, *NWNH* recommended a set of small-scale programs (in alphabetical order):

- A $5M/year increase in the budget of the ATI program.

- An $8M/year increase in the budget of the AAG program.
- A $2M/year increase of the U.S. share of the Gemini Telescope.
- An increase in the TSIP budget to $5M/year.
- A new $2.5M/year AST contribution to an inter-agency Theory and Computational Networks (TCN) program.

NWNH did not prioritize between these three scales of programs nor give specific advice on the priority of these new programs relative to existing programs. However, it is worth noting that the summation of these programs does not change the facility-to-grants balance of the AST portfolio substantially. The recommendations call for $15.5M/year of small grants, about $2.5M/year of new TSIP funding, and $20M/year of additional mid-scale investments, generally for fixed-term developments. New facility operations would be of order $40M/year, and amortization of AST's share of CCAT and ACTA construction costs is of order $10M/year. LSST and GSMT construction would come from MREFC funding, not the AST budget. So the proposed new spending for AST is approximately 56% facilities, 44% grants, much like the current AST budget.

All of the above costs are given in FY10 dollars. The rest of this report generally uses then-year dollars for all budgets, with the exception that our figures adjust by 2.5% annual inflation to FY11 dollars to ease the visual comparison across years.

3.2 Budget forecasts

NWNH made their recommendations under the assumption that AST "purchasing power would grow at 4% per year for 10 years." (p. 188) With 2.5% annual inflation this is about 6.5% per year in 2010 dollars. This translates to an AST budget that would, with inflation, approximately double to nearly $500M by 2021.

Only two years into the *NWNH* decade, AST funding is already well behind this growth curve. The FY12 actual budget is $234.6M, $231.6M if one excludes the EARS program, whereas the *NWNH* projection is about $280M. The FY13 budget request is $244.6M, including $12M for the EARS program; even if this is appropriated in full, purchasing power for core astronomy research will have sagged by 2% compared to FY12, instead of 4% growth. Comparing to *NWNH* and assuming full funding of the FY13 budget request, the budget for core astronomy research will be $65M short of the *NWNH* projection, a difference of 22% in just 3 years!

In the current economic climate, projections forward cannot reasonably expect to turn immediately to a 6.5% annual growth rate. The PRC worked with two scenarios provided by AST, which we will refer to as Scenario A and Scenario B. In the more optimistic Scenario A, we assume a flat AST budget in FY13 relative to FY12 (which implies a 5% drop in purchasing power because of the $9M increase in EARS funding), 3% growth per year in FY14-FY16, and 5% growth per year in FY17-FY22. Assuming 2.5% annual inflation, AST purchasing power drops to about 90%

of FY10-12 levels in the next few years before slowly growing to 106% of FY10-12 levels in FY22.

In the more pessimistic Scenario B, we assume a 3% annual drop in the AST budget in FY13 and FY14 (similar to the drop from FY10 to FY12), then flat budgets in FY15 and FY16, then 3% annual growth to FY22. This scenario implies that AST purchasing power for core astronomical research would drop to about 80% of its FY10-12 level by FY15 and stay at approximately that level through FY22.

The inflation-adjusted comparison of these two scenarios to the *NWNH* projection and the historical budgets is shown in Figure 3.3. Our two budget scenarios lead to projections for the FY22 AST budget of $263M to $343M (then-year), an amount 50-65% of the $525M projected in *NWNH* and 82-106% of the $323M that one would compute by taking the FY10-12 budget and applying a 2.5% annual inflation and adding the projected EARS funding. Clearly, such budgets are a severe challenge to the Decadal Survey science goals and facility plans.

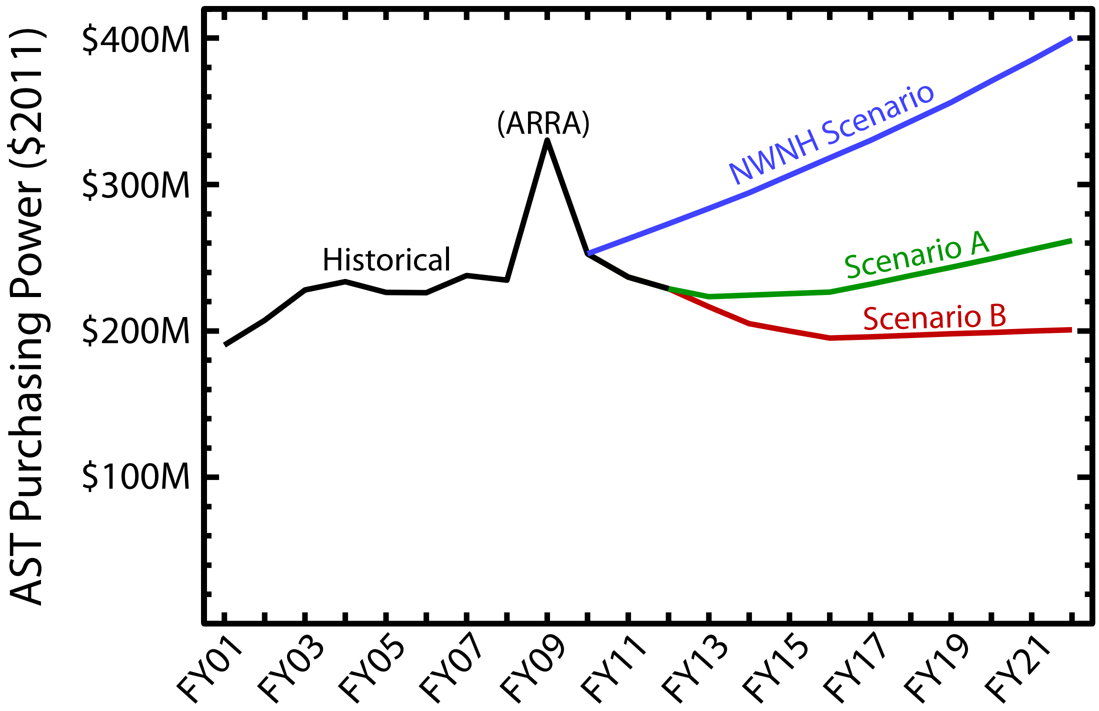

Figure 3.3 — Comparison of our two budget scenarios (A & B) for the AST budget, to the *NWNH* projection, along with actual AST budgets from FY01-FY12. Each is adjusted to FY11 purchasing power assuming 2.5% annual inflation. Scenario B purchasing power contracts by 25% from FY10 and then stabilizes; Scenario A contracts by 15% and slowly recovers by FY22. AST funding is already $45M (in FY12 dollars) below the *NWNH* projection. By FY22, our budget scenarios are only 50-65% of the *NWNH* projection.

We caution that Scenarios A & B do not encompass the possible range of future budgets. For example, the President's FY13 budget request exceeds both of our scenarios, so AST could get 4% more than Scenario A if that were funded in full. However, it is also possible for future budgets to be lower than our Scenario B. For example, the budget sequestration clause of the 2011 Budget Control Act could potentially lead to a 10% reduction in FY13. Beyond these near-term variances, there are countless longer-term economic and political factors that will affect the AST budget.

Our committee designed portfolios for FY17 and FY22. FY17 includes the pressure from the full ALMA operations ramp and most of the ATST operations ramp. Moreover, given that the FY14 budget is already being designed, three years is a plausible time frame for AST to implement major recommendations regarding existing facilities. We note that FY14 to FY16 will likely be difficult budget years. We expect that our FY17 recommendations will provide a clear target toward which AST can navigate as the pressure on the compressible parts of the budget increases.

FY22 brings us to the next decadal survey. It also marks a time scale for operations of two top-ranked *NWNH* priorities, LSST and CCAT. Hence, designing toward this year allows us to express priorities for the full decade.

3.3 Projecting the Status Quo

Before leaving this chapter, we want to present the implications of these budget scenarios under the assumption of the status quo as regards current AST facilities. We consider a strawman budget with the planned operations ramp-ups for ALMA and ATST and a ramp-down to the new AST support level for Arecibo, owing to the cost sharing with the NSF/AGS and NASA, which we extrapolate to the end of the decade. We assume 2.5% annual increases for other AST facilities and the URO program. We also assume that non-astronomy-research expenses are met (e.g., EARS and non-research expenses). In this scenario, these items total $200M in FY17. In Scenario B, this would leave only $27.1M for the combination of other small and mid-scale grants and design work for future facilities, down from an average of $82.7M in FY12 and $102.2M in FY10. These results are shown graphically in Figure 3.4, with the detailed numbers in Table 3.3. *Adjusting for inflation, this would reduce the purchasing power for these crucial programs to only 25% of their average FY10-FY12 level.* In FY22, the facility operations and mandatory expenses would reach $226.4M. In Scenario B, this leaves only $37.2M for the grants programs, 31% of the FY11 purchasing power.

Hence, Scenario B presents a stark choice between the current facility portfolio and the grants programs. Unless spending on facilities is significantly reduced, the grants would be decimated. We stress that this occurs despite omission from this strawman of any new facilities or grant augmentations recommended by *NWNH*.

Scenario A is more optimistic and would yield $68.9M for grants programs in FY17, better but still only 64% of the FY10-FY12 purchasing power. In FY22, Scenario A has recovered to $117.1M, which is 97% of the FY10-12 purchasing power for these programs. However, this is again before any consideration of new initiatives from *NWNH*. For example, LSST operations would add another $26.5M of facility costs, which would reduce the small-grants and mid-scale programs to 75% of the FY10-12 purchasing power. Furthermore, as described above, *NWNH* actually called for substantial increases in AAG, ATI, and TSIP, as well as for a $40M mid-scale project line. Clearly Scenario A is well short of those goals and in fact leaves the grants programs lagging the FY10-12 purchasing power for the next decade.

Our committee strongly believes that these outcomes would be tremendously damaging for U.S. astronomy, both because of the underfunding of the grants programs and because of the failure to progress on any of the *NWNH* recommendations. Without healthy funding to renew instrumentation, pursue major new projects, and train the next generation of researchers, we face a combination of an underdeveloped workforce and a stagnating facility base. Moreover, this tension between the grants programs and the facility portfolio is a near-term challenge, not one merely for the longer term that the astronomy community can ignore for a few years in the hopes that the budgets will improve. The collision is upon us in the next few years: in anything but the most optimistic scenarios (considerably more optimistic than scenario A), grants funding will drop quickly.

Despite this sobering assessment, our committee believes that a contraction of the facility portfolio now can preserve the strength of the grants programs and open essential opportunities for new investment later in the decade that can advance many of the *NWNH* goals.

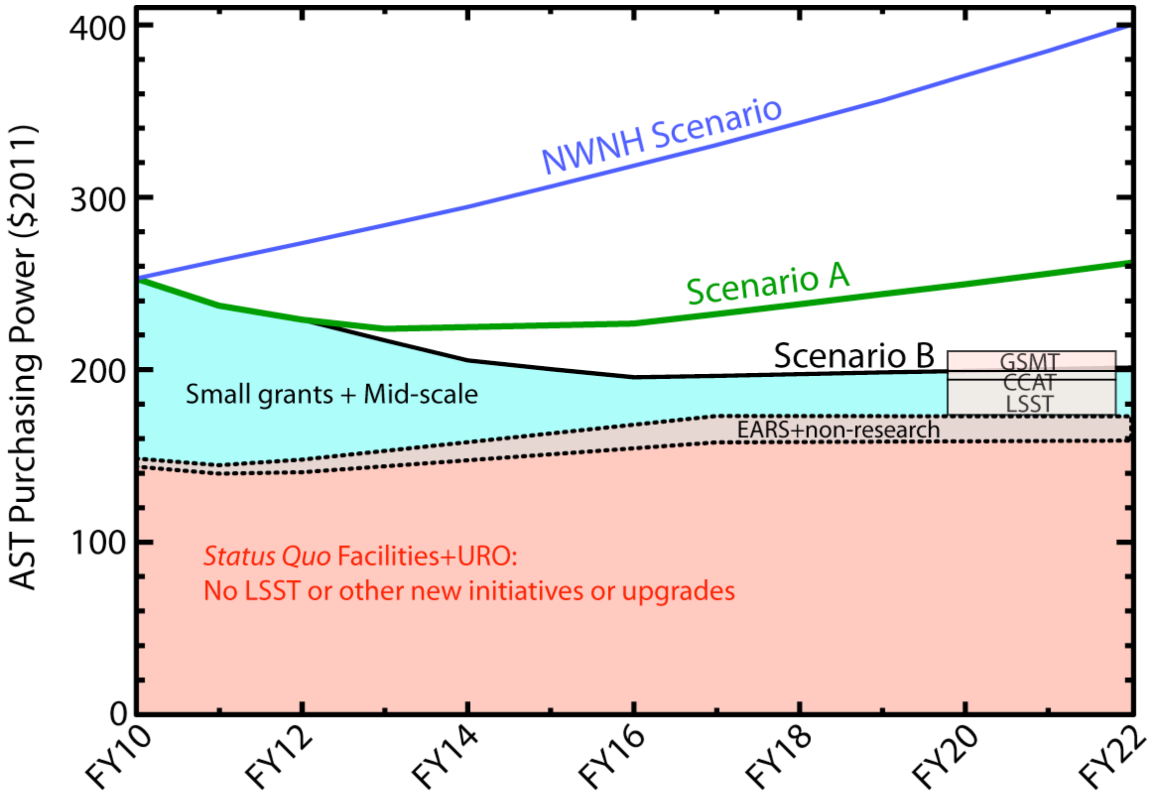

Figure 3.4 — The consequences of a strawman status quo budget (Table 3.3) that extrapolates all current observatory funding through the coming decade. All numbers have been corrected for 2.5% annual inflation. The lowest (red) wedge includes: all current AST facilities; the planned operations budget increases for ALMA and ATST; the reduction of AST support for Arecibo given the new agreement with NSF/AGS and NASA; and the University Radio Observatory program. The next wedge indicates expected funding for EARS and non-research program. The cyan wedge shows the funding remaining for *all grants programs* in Scenario B; this decreases by a factor of 4 compared to the mean FY10-12 level. In budget Scenario A, plotted in green, grants funding still must decrease sharply by FY17 if facilities funding is status quo. These conditions hold even without funding for any new initiatives recommended by *NWNH*. The pink bars at the right-hand side denote nominal operating costs for new facilities LSST, CCAT, and GSMT; adding them to the status quo facilities leaves no grants funding in FY22 in Scenario B, and greatly reduced grants funding in Scenario A.

Table 3.3 — A strawman status quo budget to explore the consequences of continuing all current observatory funding in the coming decade. Annual inflation of 2.5% has been applied to all costs, and operations ramps for ALMA and ATST are included, as is the reduced AST support for Arecibo given the recent agreement with NSF/AGS and NASA. The URO program has been included. To estimate the budget remaining for grants funding, we subtract these facility projections and the expected funding for EARS and program expenses from the budget projections. We then compare the projected grants funding to the FY10-12 grants funding adjusted by 2.5% annual inflation. One can see that in both scenarios, grants funding is significantly impacted, falling short of FY10-12 level by up to a factor of four in Scenario B. This is starkly different from the *NWNH* recommendations, which called for significant increases in the grants programs. All dollar values are in then-year $M.

All Budgets in $M	**FY10-12**	**FY17**	**FY22**
NOAO	27.0	30.5	34.6
Gemini	20.1	22.7	25.7
NRAO	43.3	49.0	55.4
EVLA construction	2.5	0.0	0.0
ALMA	23.4	40.8	46.2
Arecibo	6.7	4.6	5.2
NSO (w/o ATST)	9.1	10.3	11.6
ATST	1.3	16.0	19.5
URO	7.5	8.5	9.6
Total Facilities	**140.9**	**182.5**	**207.8**
Non-research expenses	5.1	5.8	6.5
EARS	1.0	12.0	12.0
Total Strawman Costs	**147.0**	**200.2**	**226.4**
Scenario A Budget	239.3	269.1	343.5
% Facilities	59%	68%	61%
Remaining for grants	92.3	68.9	117.1
% compared to FY10-12	100%	**64%**	**97%**
Scenario B Budget	239.3	227.3	263.5
% Facilities	59%	80%	79%
Remaining for grants	92.3	27.1	37.2
% compared to FY10-12	100%	**25%**	**31%**

4 Community Input

At the start of the Portfolio Review process, prior to requesting broad community input, a letter (included in Appendix B.3) was sent to the managing organizations of Arecibo Observatory, the Gemini Observatory, NOAO, NRAO, and NSO asking them to update their long-range plans and to provide a vision statement. The long-range plans describe a five-year horizon, while the vision statements extend out to 10-15 years. These documents were delivered by January 6, 2012.

An open invitation was issued to the astronomical community for input to the Portfolio Review process in late October 2011 via a letter from AST Division Director Jim Ulvestad (included in Appendix B.4). Contributions were limited to 5 pages in length, but could include a URL link to a longer document if desired. The window for input was open from October 26, 2011 through January 31, 2012, and contributors were asked to submit their input using a special email address, astportfolio@nsf.gov. This solicitation resulted in 131 responses that spanned the breadth of the AST portfolio elements. The Committee grouped the inputs into related "decision units" that included Optical/Infrared (OIR); Radio/Millimeter/ Submillimeter (RMS); Solar; Observatory Culture; Grants/Instrumentation/Mid-scale; U.S. Leadership; Health of the Profession; and Other. Each of the decision units also had several sub-elements, which are detailed below along with the number of responses received in each sub-element shown in parentheses. Many responses touched on more than one decision unit and sub-element. The sub-elements for OIR were: importance of <6-meter-aperture telescopes (57); access to facilities (45); rethinking Gemini (15); role of universities (13). The sub-elements for RMS were: Arecibo (11); CCAT (2), GBT (5), VLA (2), VLBA (8), role of universities (1). The sub elements for Solar were: synoptic science (4); moving NSO (8); Frequency Agile Solar Radio Telescope (FASR) (1). The sub-elements for Grants/Instrumentation/ Mid-scale were: maintaining/rethinking AAG (19); importance of mid-scale (20). The sub elements of Health of the Profession were: diversity (8); student training (33). Observatory Culture (6) and Other (25) had no sub-elements. Each PRC member was asked to read all inputs. One or more Committee members was assigned to each of the decision unit areas and asked to develop a summary of the inputs in that area. The input for each decision unit and its sub-elements was then discussed in at least one of the weekly PRC telecons. Additional focused discussions of decision units on community input occurred in smaller subgroups of the committee through additional telecons.

A second more focused solicitation was made by AST Senior Advisor Vernon Pankonin in February 2012 to Observatory Directors and Principal Investigators of OIR and RMS facilities. These letters are reproduced in Appendix B, B.5 and B.6. This solicitation included specific questions developed by the PRC about the future directions for these facilities. These responses were handled in a similar manner to the community input described above: each Committee member was asked to read all responses; a specific Committee member was assigned the responsibility of developing a summary for each of OIR or RMS; and the inputs in each decision unit were discussed in at least one PRC weekly telecon.

The community input described above encompassed a broad and thoughtful set of materials that were an integral part of the PRC's subsequent discussions.

5 *New Worlds, New Horizons* and Technical Capabilities

To highlight the extraordinary opportunities now within reach and to provide overarching guidelines for the recommended future investments in astronomy, the *NWNH* report laid out three scientific objectives for the coming decade: "Cosmic Dawn: Searching for the First Stars, Galaxies, and Black Holes," "New Worlds: Seeking Nearby Habitable Planets," and "Physics of the Universe: Understanding Scientific Principles" along with the science (and technology) plans required to answer the fundamental questions raised. In support of the main report, the five science frontiers panels of Astro2010 (Cosmology & Fundamental Physics [CFP], The Galactic Neighborhood [GAN], Galaxies Across Cosmic Time [GCT], Planetary Systems & Star Formation [PSSF], and Stars & Stellar Evolution [SSE]) each fleshed out the detailed science cases for the principal objectives, and provided guidance in the form of a total of 20 research questions and five discovery areas (four questions and one discovery area for each panel).

NWNH and the science frontier panel reports further discuss the capabilities, in terms of observational and instrument development programs, computation/theory, and lab approaches, that are needed to make significant headway, especially in the areas of discovery. Throughout *NWNH* it is stressed that such directed efforts must exist side-by-side with opportunities for exploration of the new, and unknown.

To meet charge (1) to the PRC, four sub-teams were formed to assess the capabilities called out by *NWNH* (GAN and GCT were considered together), with an emphasis on identifying those technical capabilities that are critical in addressing the science objectives. Working independently, the sub-teams first analyzed all of the capabilities highlighted in *NWNH* and an initial assessment was made to determine capabilities that were critical to future progress and those that were of a supporting nature. The focus was on those capabilities that are or can be within the AST portfolio; certain wavelength regions (e.g., X-rays, moderate-energy gamma-rays) are accessible only from space, and are therefore unique to the NASA portfolio. The full PRC considered the initial input from the sub-teams to generate an integrated summary of the critical ground-based observational/instrumental and data analysis capabilities, theoretical approaches, and lab measurements recommended by *NWNH*. Within the individual frontier science areas, these critical capabilities were then ranked and presented to the full PRC for discussion and revision.

In the following four sections we briefly summarize the science questions and discovery areas discussed in *NWNH*, and present the ranked technical capabilities judged to be critical, followed by a summary. Several of the most important supporting technical capabilities are also presented, but these are not rank ordered. At the end of these science sections the integrated critical capabilities are summarized in Table 5.1, with brief identifying descriptions. These critical technical capabilities are denoted by the notation **TC-A**, **TC-B**, etc., throughout the text for reference. This technical capability list, driven by the recommendations presented in *NWNH*, is central to the Committee's analysis of the priority of current and future facilities and programs in carrying forward the science plans envisioned by the U.S. astronomical community.

5.1 Cosmology and Fundamental Physics

For over 300 years, astronomical observations have been critical to the discovery of fundamental laws of physics, and application of these fundamental laws to the largest observable realms has in turn revolutionized our concepts of the structure and history of the Universe. This symbiosis has intensified in recent decades: for example, the Nobel-Prize-winning observations of acceleration of the expansion of the Universe reveal the presence of a new form of energy completely beyond current models of particle physics – or perhaps an aspect of gravity that deviates from General Relativity. Physical theories have in turn predicted an inflationary phase in the first 10^{-32} seconds after the Big Bang that resolves many outstanding issues in cosmology, and predicts signatures that should be observable on the sky today, 13.7 billion years later. Astrophysical observations now offer high-precision tests of physical laws in realms of size, gravity, and energy that are far beyond the reach of present or future laboratory experiments. The questions and discovery area laid out by the Cosmology and Fundamental Physics science frontier panel are briefly summarized next, followed by an analysis of the critical and supporting capabilities required to make progress in this area.

CFP-1: How did the Universe begin?

Wilkinson Microwave Anisotropy Probe (WMAP) observations of the cosmic microwave background (CMB) radiation confirm the generic predictions of the inflationary theory of the early Universe: that the seed fluctuations in the early Universe were adiabatic, Gaussian, and deviate only slightly from a scale-invariant power spectrum. Combined with data from Type Ia supernovae (SNe) and baryon acoustic oscillations (BAO), and the local value of the Hubble constant, H_0, these observations also confirm to percent level precision that the Universe is flat, as inflation theories predict. There are further available tests of the inflationary paradigm, and methods to learn which (if any) of many possible variants of inflation correctly describe the early Universe. Most continue the extraordinarily successful program of measuring the manifestations of large-scale fluctuations in the density of the Universe, presumably seeded during inflation. The equations describing the evolution of these large-scale fluctuations are well constrained, making it generate highly accurate predictions for the evolution of large-scale structures using supercomputer simulations. As both the accuracy of theoretical predictions and the accuracy of experimental measurements advance in concert, increasingly powerful tests of nature become possible. These simulations are a critical technical capability for advances in CFP.

Inflation generically produces gravity waves whose amplitude in turn is strongly diagnostic of the nature of inflation. These gravity waves are manifested as "B-mode" patterns in the large-scale polarization fluctuations of the CMB. While WMAP detected CMB polarization, its sensitivity was insufficient to detect the B-modes, and ground-based searches for B-modes are a high priority. Telescopes and receivers for large-scale CMB polarization are a critical technical capability; both AST and NSF Office of Polar Programs (NSF/OPP) have funded ground-based CMB experiments, with NASA funding balloon- and space-based experiments.

The precision of tests of the scale invariance and Gaussianity of primordial fluctuations, as well as tests of flatness, can be improved by observations of fluctuations at lower redshift (z), which probe physical scales smaller than are accessible by the CMB. Imaging and spectroscopic surveys of the galaxy distribution trace the evolved descendants of the primordial fluctuations, and can be precisely related to inflation theory at large length scales where gravitational perturbation theory remains viable. When using the fluctuations as cosmological probes, accuracy improves as we survey larger volumes of the Universe. Large increases in survey volume are possible in the coming decade by exploiting technological advances to construct extremely wide-field, high-throughput imaging and spectroscopic instruments – these are critical technical capabilities, as is supercomputing support for the interpretation of these observations and the development of theoretical concepts.

Weak gravitational lensing surveys provide direct measures of the large-scale matter fluctuations in the nearby Universe, free of the uncertain relation between galaxy and dark-matter distributions, by detecting the deflection of photons as they travel from their sources to us. In the coming decade, weak lensing signals will be best detected by optical observations of small changes to the shapes of galaxies. The statistical power of these observations, as measured by number of galaxy shapes measured, is expected to increase by an order of magnitude or more as new wide-field imagers come online; wide-field imaging surveys are here again a critical technical capability. Moderate-multiplex optical spectroscopy on large telescopes is necessary to calibrate the photometric redshifts in large imaging surveys, and is considered a critical technical capability.

Tests of the scale dependence of primordial fluctuations become stronger as the range of measured scales increases. At earlier epochs ($z>2$), the small-scale fluctuations are more pristine, not yet polluted by non-linear and baryonic physics. These fluctuations may become observable by observations of the Lyman-α (Ly-α) forest (using spectra of 10^4 –10^5 quasars) or by observation of the redshifted 21-cm emission from neutral hydrogen in galaxies or, at higher z, from the intergalactic hydrogen in the epoch of reionization. We view facilities enabling these observations as supporting technical capabilities for CFP over the coming decade.

CFP-2: Why is the Universe accelerating?

The acceleration of the Hubble expansion remains the biggest mystery in cosmology and fundamental physics, with weak theoretical guidance at this time.

Progress in the coming decade will be driven by improved observational constraints on the two primary manifestations of dark energy fields or modifications to gravity. The first of these manifestations is the expansion history $a(t)$ of the Universe over the past 10 billion years. This expansion history (along with curvature) determines the observed distance-redshift relation, $D(z)$. The second manifestation of the acceleration is the speed at which gravitational instability overcame the expansion of the Universe to collapse large-scale structures. The latter is quantified by the linear-regime growth function. Since General Relativity makes an explicit prediction for the growth history given the expansion history, comparison of measurements of both functions tests the fundamental assumption that General Relativity properly describes our Universe's cosmological evolution.

Experiments to determine the growth history and expansion history fall into two categories. First, there are those that exploit large-scale fluctuations as high-precision cosmological indicators. Redshift surveys of ever-larger volumes of the Universe can use the BAO feature as a standard ruler for highly improved distance measures at $z > 0.6$. These redshift surveys also yield the statistics of line-of-sight galaxy velocities, measuring the rate of gravitational growth. Exploitation of this velocity signal is in its very early phases. The weak-lensing observations discussed above also can provide precision measures of distances and the growth function. The technical capabilities for visible imaging and spectroscopy of large volumes of the Universe are critical for investigating the acceleration phenomenon in this decade. Gravitational growth is also measurable via a census of the largest collapsed objects in the Universe, galaxy clusters: the clusters are detectable by optical surveys, by submillimeter surveys of the Sunyaev-Zeldovich effect, and by surveys with space-borne X-ray telescopes.

The second class of acceleration experiments observes selected individual objects that serve as standard candles and yield precision distance-redshift relations. The acceleration was discovered by observations of Type Ia supernovae at $z < 0.7$; high-quality ground-based observation of larger numbers of SNe at these redshifts, best discovered by wide-field imaging telescopes, will significantly improve our understanding of these events and improve the low-redshift end of the expansion history. Time-resolved visible imaging and spectroscopy are thus viewed as critical technical capabilities for supernova cosmology. Near-IR imaging on large telescopes should improve the accuracy of low-z supernova cosmology, and is an important supporting technical capability.

Standard candles and rulers also address this question through more accurate determination of H_0, the current expansion rate. The maser system surrounding the nucleus of NGC 4258 currently provides the strongest anchor for the local distance scale; surveys with the VLA and/or single-dish radio telescopes may discover other systems for which very-long-baseline interferometry (VLBI) follow-up would yield more anchors at greater distance, and thus more accurate H_0 values. These are viewed as supporting technical capabilities.

CFP-3: What is dark matter?

A large body of astrophysical observations indicate that the Universe contains six times more matter than can be present in baryonic form, yet a non-gravitational signature of this dark matter has never been detected in any astrophysical or laboratory system. Unveiling the nature of the dark matter will reveal new fundamental physics and is a high priority for the decade. The dawn of dark matter astronomy would also shed new light on the dynamics of galaxy and large-scale structure formation.

Some of the most quantitative and convincing evidence for the existence of dark matter has come from observing the bending of starlight (gravitational lensing) by the gravity of the dark matter, particularly in clusters of galaxies. The suite of observations of galaxy clusters that were noted as unveiling the growth of structure and the nature of cosmic acceleration also serve to map the amount and distribution of dark matter in galaxy clusters and other environments. Although these techniques excel at revealing the *existence* of dark matter, they are less powerful at revealing the *composition* of dark matter, and hence are only supporting technical capabilities for answering question CFP-3.

Detection of a dark-matter particle in the laboratory would be a huge breakthrough in answering this question. Laboratory detectors for dark matter candidates, including weakly interacting massive particles (WIMPs) and axions, are supported by NSF/PHY and DOE. Indirect searches for the annihilation or decay products of dark matter particles in astrophysical systems (from the Sun to galactic halos) involve the observation of cosmic-ray, gamma-ray, and neutrino signatures. Searches for these signatures are being carried out with space- and balloon-based detectors, and ground-based atmospheric Čerenkov telescopes and neutrino detectors. Here again, AST has traditionally partnered with PHY and DOE to support these efforts. The overall contribution of AST in this area is modest and these are considered supporting technical capabilities.

CFP-4: What are the properties of neutrinos?

The definitive detection of flavor oscillations in solar and cosmic-ray neutrinos has shown that the standard model of particle physics is incomplete. These observations determine the *difference* in the square of the masses of different neutrino types, but the *absolute* scale of neutrino masses remains unknown. The finite masses of relic neutrinos from the Big Bang impart percent-level shifts in the power spectrum of large-scale matter fluctuations in the Universe. These should be detectable through the same suite of power-spectrum experiments that are useful for measuring inflation signatures and the cosmological growth function. Hence the high-throughput technical capabilities required for weak lensing and spectroscopic galaxy surveys are also critical for neutrino physics, with potential additional gain from Ly-α and 21-cm observations of higher-redshift, smaller-scale fluctuations. Supercomputer modeling support is critical to theory/data interpretation.

Other fundamental questions about neutrinos can be addressed through the studies at energies near the theoretical upper limit for cosmic rays, the Greisen-

Zatsepin-Kuzmin cutoff, many orders of magnitude beyond that achievable in the laboratory but produced in astrophysical systems. Large Čerenkov and/or radio detectors may discover ultra-high-energy neutrinos in the next decade. Ground-based studies of energetic particles have traditionally been funded by PHY, NSF/OPP, and NASA, with modest support from AST. These are considered supporting technical capabilities.

CFP-D1: Discovery potential - Gravitational waves

Direct detection of gravitational waves (GW) from stellar-mass black hole systems may be possible with the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) this decade. LIGO represents a very large NSF investment with the potential huge payoff of opening a new window onto the Universe. The first astrophysical results from GW detection are likely to improve significantly the understanding of the processes and rates of compact-binary mergers and low-mass X-ray binaries. Any GW detection will be enormously more valuable if an optical counterpart can be identified and studied. Since LIGO localization will be coarse, the critical technical capability is optical imaging with degree-scale field of view, available for very rare but short-notice observations.

Another potential route to detection of gravitational waves is timing of the pulse arrivals from a network of millisecond pulsars. Gravitational waves with nanohertz frequencies would produce coherent delays across the array of pulsars. The amplitude and slope of the GW background in this frequency range could potentially be ascertained, constraining the supermassive black hole population or potential exotic GW production mechanisms. Pulsar timing experiments require regularly scheduled use of specialized broadband backends on large-aperture radio telescopes. Both the fundamental astrophysical limits of the experiment and the strength of the target GW background have large uncertainties at present, but this could be the first route to directly detect gravitational waves. Pulsar timing is considered a supporting technical capability for this discovery area.

Critical CFP Technical Capabilities

Below we list the rank-ordered technical capabilities in AST-supported areas that are needed to address the highest-ranked CFP scientific priorities from *NWNH*. Each capability is mapped to Table 5.1, the List of Critical Technical Capabilities, in Section 5.5.

1. **Wide-field optical imaging, including the time domain (TC-N in Table 5.1):** instrument/telescope combinations with very high survey throughput (telescope area times field of view) are critical to many elements of the CFP program. Multicolor, wide-area surveys of $\sim 10^8$ galaxies will yield photometric redshift catalogs that map galaxy density fields, plus serve as target-finders for spectroscopic surveys that reveal the third dimension of structure, velocity fields, and the BAO distance scale. The same imaging opens up the weak-lensing window on the dark matter distribution and provides a census of galaxy clusters. All these structure tracers are critical to measuring the signatures of inflation, dark energy, and neutrino masses. Wide-field cameras are also needed to

discover $z < 0.7$ Type Ia supernova in large numbers, and to localize any gravitational wave signals discovered by LIGO – the latter use requires rare but rapid responses (~30 min). (critical for CFP-1,2,4, and D1)

2. **High-multiplex, moderate-resolution visible spectroscopy (TC-O):** spectrographs with spectral resolution ($R \equiv \lambda/\delta\lambda$) of $R > 1000$ and ~5000 fibers over degree-scale fields of view on ≥4-meter telescopes are needed for galaxy redshift surveys of a large fraction of the observable $z < 1.5$ Universe, from which precision measures of the expansion and growth histories of the Universe will be derived using BAO and redshift-space distortion signals. These address the questions of the origin of inflationary perturbations, the cause of the acceleration phenomenon, and the applicability of General Relativity. Large surveys of the Ly-α forest using background quasar spectra also may extend our knowledge of the scale dependence of primordial fluctuations. (CFP-1,2,4)
3. **Large-scale CMB polarization telescopes (TC-F)**: for sensitivity to B-mode polarization in the CMB induced by inflationary gravity waves. (CFP-1,D1)
4. **Supercomputing to support suites of 3-D simulations (TC-B):** large suites of survey-sized N-body/hydrodynamical simulations are needed for the highest-power interpretation of data from weak lensing, BAO, CMB, and other probes of structure in the Universe. (CFP-1,2,4)
5. **Moderate-multiplex, $R > 1000$ visible spectroscopy with large-aperture telescopes (TC-P):** workhorse optical spectrographs on large telescopes are required for follow-up spectroscopy of large numbers of Type Ia supernovae and their host galaxies. The success of the imaging-based surveys of 10^8-10^9 galaxies are critically dependent upon obtaining spectroscopic redshifts for 10^4–10^5 representative galaxies to calibrate photometric redshifts. This requires substantial access to moderate-resolution spectrographs on 8m-class telescopes with multiplex factors of 100-1000. (CFP-1,2,4)
6. **Target-of-opportunity optical imaging and spectroscopy on large telescopes (TC-Q):** multicolor and spectroscopic measurements in the weeks after explosion and discovery of significant numbers of Type Ia supernovae at $z \approx 0.5$ would greatly improve our understanding of the low-z expansion history. Such a program will require few-day response with single-object instruments. (CFP-2)

Summarized Ranking of CFP Critical Technical Capabilities

A common theme of the CFP program is continuing the extremely successful use of large-scale fluctuations as probes of the conditions in the early Universe and the physics driving their evolution. The opportunity exists, during this decade, to greatly expand the volume and hence the power of these surveys, and to introduce entirely new probes of large-scale structure that address all of the CFP questions and discovery areas in the AST purview. Hence the highest-priority technical capabilities for CFP questions are high-throughput instruments for wide-field imaging and spectroscopic surveys. If LIGO does detect gravitational-wave sources, wide-field imaging will be critical to identify these sources. The methods, equipment, and theory, required for success in the survey-based experiments are well defined, and there is a very high probability of experimental success – although of course we do not know what will be discovered with these leaps in accuracy. Similarly, CMB polarization experiments of modest cost are expected to make significant gains in the search for primordial gravity waves, reaching a regime where the most straightforward theories predict signals might be found.

The theoretical underpinnings of cosmology are strong enough that we expect the accuracy of theoretical predictions to advance as quickly as the accuracy of measurements; the requisite computational work is the next-ranked critical technical capability. Moderate-resolution optical spectroscopy, for calibration of photo-z imaging surveys and supernova/host spectroscopy, is ranked next, as it is important for some, but not all, of the forefront programs of the coming decade. Rapid-response imaging and spectroscopy are critical to supernova cosmology.

Supporting CFP Technical Capabilities

The following have been identified as supporting capabilities:

- **21-cm array:** for measurement of power spectrum of galaxies (at $z < 6$) and/or the neutral intergalactic medium (IGM) (at $z > 6$), giving precision measurements of BAO and the small-scale primordial power spectrum. Provides tests for scale dependence of inflationary perturbations, neutrino mass, and curvature. (CFP-1,4)
- **NIR imaging on large telescopes:** for extending Type Ia supernovae distance measurements into the rest-frame near-infrared (NIR) for a large sample of events. The lower intrinsic scatter of NIR peak magnitudes may substantially improve accuracy of the supernovae expansion history at the low redshifts where it is more precise than BAO distances. 8m-class telescopes are required. (CFP-2)
- **Large-collecting-area broadband radio telescope:** for pulsar timing array observations, which may have ability to discover nanohertz gravitational waves from supermassive black holes or exotic primordial mechanisms. Searches for active galactic nuclei (AGN) masers may yield targets suitable for improved determination of local H_0 using VLBI followup. (CFP-2,D1)
- **Submillimeter Sunyaev-Zeldovich survey:** for census of galaxy clusters and constraint of the growth function, and consequent tests of the acceleration phenomenon. (CFP-2)
- **Data-driven science infrastructure (TC-C)**: for enhancing high-performance community access to increasingly large observational and simulational datasets, as well as ongoing stewardship of heavily-used astronomical data archives. (CFP 1-4,D1)
- **Atmospheric Čerenkov telescopes with 1 km^2 effective area:** to improve sensitivity to gamma-rays from dark matter annihilation by an order of magnitude over a wide range of energies. (CFP-3)
- **High-energy neutrino detectors with several km^2 effective area:** to discover cosmogenic neutrinos. (CFP-4)

5.2 Galaxies

The study of galaxy evolution through observations of the Milky Way to the most distant high-redshift galaxies is entering a new era. In the local Universe, large surveys of the stellar and gaseous components in the Milky Way and beyond are making it possible to unravel the history of the formation of stellar halos, disks, and bulges over cosmic time. An ever more complete view of the physical processes that shape this evolution is emerging. It involves the conversion of interstellar medium (ISM) into stars and the subsequent return of enriched material to the galactic halos and disks, the build-up of chemical elements, the distribution and properties of the various ISM phases, the possible continued accretion of gas from the intergalactic medium, and the merging with other galaxies. The study of galaxies from low to high redshift provides snapshots of galaxy properties over cosmic time, enabling direct views of the evolution of galaxies from formation to the present day in a variety of environments, from dense clusters to the isolated outskirts. In the centers of galaxies near and far, evidence for black holes is growing and significant progress is being made in measuring the mass distribution and effects of such extreme objects. The rate of discovery and exploration with new technical capabilities offered now or by the end of the decade is expected to further revolutionize our understanding of galaxy formation and evolution.

The broad topic of galaxy properties and evolution was covered in two chapters in the science frontier panel reports, one dealing with the Galactic Neighborhood (GAN), defined as the nearby Universe out to moderate redshift, and one with Galaxies through Cosmic Time (GCT), which centered on the medium to high redshift ranges. The chapters each defined five science questions and several discovery areas. There was significant overlap in the science scope between some of these questions and discovery areas, and the PRC sub-team considered them together. We briefly review the specific questions and scientific motivation for each, and then list the critical and supporting technical capabilities needed to make progress in this area in the next decade.

GAN-1: What are the flows of matter and energy in the circumgalactic medium?

The circumgalactic environment is expected to hold clues to the mass, energy, and feedback cycles that influence the growth of galaxies and that lead to distribution of metals throughout the Universe. It is here where we may find evidence for continued accretion of gas from the intergalactic medium, outflow of enriched gas into the IGM due to star bursts and AGN, and returning enriched gas from less powerful star formation outflows – the galactic fountain phenomenon. The observations are challenging since the nature of the medium involved is not well understood, the column densities are expected to be small, and observations over a broad range in wavelength are required. As noted in the GAN chapter of the science frontier panel reports, the bulk of the energy and metals from the feedback channels is not accounted for observationally. Recent simulations predict that accretion can be in the form of hot or cold gas, depending on galaxy mass. Evidence for outflows is derived from multi-spectral imaging of local galaxies and from metal content measured via absorption-line spectroscopy. Such studies help establish properties and local kinematics of the material in the circumgalactic environment, but direct evidence for widespread accretion from the IGM is much more difficult to obtain.

The critical technical capabilities needed for progress here are high-resolution imaging and spectroscopy, especially that in the cm/mm/submillimeter (both interferometric and direct), and supercomputer modeling support. Supporting technical capabilities for understanding the flows of matter and energy in the intergalactic medium include the ability to make very sensitive images of the diffuse HI between galaxies using a large-collecting-area centimeter-wave telescope.

GAN-2: What controls the mass-energy-chemical cycles within galaxies?

This question is in many ways closely tied to the first, but focuses on the rich area of star and gas physics, including star formation and the processes that shape the interstellar medium. It involves determining how galaxies build up their stellar components over cosmic time. The ISM on large and small scales is at the heart of this question. What is the multi-phase structure of the ISM in the galactic disk and at the disk-halo interface; what controls the radial and vertical transport of mass and metals; what controls the disk-halo interface; where and how does star formation proceed; and what is the structure of the magnetic field in the ISM? The answer to all these questions involves determining the structure and physical state of the ISM in the Milky Way and nearby star-forming galaxies and deducing how star formation proceeds not only in our Milky Way but also in other galaxies, in particular low-mass, low-luminosity galaxies that may be the analogs of star-forming galaxies in the early Universe. The range of environments ranges from the immediate surroundings of the black hole at the center of the Milky Way to the ultra-faint dwarf galaxies in the Local Group. How do molecular clouds form in such an extreme range of conditions?

Technical capabilities critical to this research question are high-resolution submillimeter/mm/cm (interferometric and direct) imaging and spectroscopy, and supercomputer modeling support. Supporting technical capabilities for making progress on understanding the mass-energy-chemical cycles in galaxies include the ability to make very sensitive images of the diffuse HI in and around galaxies using a large-collecting-area centimeter-wave telescope, submillimeter/millimeter imaging spectroscopy of molecular gas and continuum at moderate angular resolution (single dish) to complement the high angular resolution studies with interferometers and laboratory astrophysics support to measure atomic and molecular-line properties and collisional cross-sections/rates.

GAN-3: What is the fossil record of galaxy assembly from the first stars to the present?

Important clues to the formation of galaxies, from the Milky Way to the smallest denizens in the Local Group and beyond, are contained in the stellar populations that we find in the densest to the most remote sections of galaxies. These populations are appropriately referred to as a fossil record, since, with the right tools, they allow us to find stars and organized stellar structures over a wide range of ages and metallicities, thereby enabling a reconstruction of the timeline and processes that shape present-day galaxies. The earliest phases of this record may reveal processes in galaxies in the early Universe at times where they cannot be observed directly.

Critical technical capabilities to this research question are wide-field imaging, multiplex optical spectroscopy, and high-resolution imaging/spectroscopy (including for faint targets). A supporting technical capability for uncovering the fossil record of galaxy assembly is to perform high-spectral resolution optical spectroscopy over narrow fields to determine the properties of faint metal poor stars in Local Group galaxies.

GAN-4: What are the connections between dark and luminous matter?

It is only in the nearby local Universe that we may hope to study the smallest dark matter halos, and possibly dark matter dominated systems, at high spatial resolution. The interplay between dark matter and luminous matter is not well understood. The lambda cold dark matter (LCDM) paradigm makes specific predictions about the concentration of dark matter on various spatial scales. While these predictions have been tested successfully on large scales, on small scales, there is tension between the predicted high central densities and cusped profiles and the lower density and flatter profiles inferred from observations. In addition, there is disagreement on the existence of small dark matter halos that so far have eluded detection. The relation between dark and visible matter may be affected by the complex interplay between dark matter and baryons within galaxies. The local Universe offers the hope to unravel these issues, e.g., by searching for systems where baryons are negligible, by improving observations of the inner halo kinematics, and by direct detections of dark matter interactions at high densities. Areas of particular interest include the distribution of dwarf satellite galaxies in the Milky Way halo, their dark matter content, and the overall distribution of dark matter in the Milky Way. On larger scales, further exploration of the connection between baryons and dark matter in a range of galaxies from detailed observations and theoretical modeling of the gas and stellar kinematics will offer further insights, as well as detection and modeling of gravitational lensing on various spatial scales.

At the other end of the spectrum, a very different form of dark matter occurs in the black holes that are now known to occupy the central regions of galaxies. What controls the masses of black holes? A significant discovery of the past decade has been the relationship between the mass of the supermassive black hole at the center of a massive galaxy and that of the surrounding spheroid of stars. The nearby Universe may offer the best hope of identifying potential seed black holes by direct detection through dynamical studies of nearby systems, by indirect studies of low-luminosity AGNs, and through the possibility of measuring gravitational waves of black hole inspiral events. Refining these relationships will come from a number of areas, including improved spatial resolution in stellar dynamics, more accurate central gas kinematics, improved constraints on kinematics are larger radii and more detailed numerical modeling with existing computing facilities. The Sgr A* region in our Galaxy offers the closest example to observe the environment around a massive black hole and its interaction with the surrounding galaxy.

Critical technical capabilities to this research question are wide-field imaging, multiplex optical spectroscopy, and high-resolution imaging/spectroscopy (including for faint targets), and also supercomputing support. A supporting technical capability is high-spectral-resolution optical spectroscopy over narrow fields.

GAN-D1: Discovery area - Time-domain astronomy

The transient sky offers significant discovery space for galaxy science. In the Galactic neighborhood, transient phenomena offer the best opportunity for exploring the luminosity range of such events and their association with known stellar populations and Galactic structure. Supernovae, variable stars, late-stage mass loss from evolving stars, binary stars, disruption of stars near the Schwarzschild radius of central black holes, the flickering of central engines all directly tie in with the important research areas identified in the two galaxy chapters. Within the local Universe ($z < 0.1$), time-domain astronomy will help secure the distance ladder as well as lead to the discovery of unexpected phenomena. In the more distant Universe, supernovae rates enable measurements of star formation rates and stellar evolutionary histories over a wide range of galaxy types and environments. Co-addition of the time-domain imaging surveys will reach new depths over wide areas, allowing for mapping of the Galactic stellar halo, detailed identification of galaxy samples over wide redshift ranges, and optical identifications of targets found in different wavelength area surveys.

Critical technical capabilities to this discovery area are wide-field optical/infrared imaging and spectroscopy and supercomputer support. Supporting technical capabilities for this discovery area include multiwavelength follow-up observations of transient sources through optical and infrared spectroscopy over narrow fields and radio observations, including VLBI when possible for the brightest sources.

GAN-D2: Discovery area - Astrometry

Several important contributions of astrometry to the topic of galaxy research were identified in the science frontier panel reports. The science applications include: measuring the aberration of quasars from the centripetal acceleration of the Sun by the Galaxy; providing a complete inventory of stars near the Sun with accurate masses for a wide range of stars; measuring orbits of the globular clusters and satellite galaxies of the Milky Way and galaxies of the Local Group; and fixing the properties of the major stellar components of the Milky Way. We are entering the era of larger, deeper, and more accurate surveys from the ground and from space. Space-based optical astrometry (Gaia) will achieve ~20 microarcsecond astrometric accuracy for more than 10 million stars, while ground-based astrometry from large optical surveys can provide proper motions and photometric parallaxes for millions of stars and identify high-proper-motion objects that may be nearby stars or hypervelocity stars. VLBI astrometry of masers yields accuracies approaching a few microarcsecond enabling the most accurate estimates of the distance to the Galactic center and the rotation speed of the local standard of rest and the first proper motions for galaxies other than the Milky Way and its satellites. For the AGN that have suitable accretion disks, VLBI can determine accurate black hole masses and potentially determine the extragalactic distance scale with possibly unmatched precision (better than 1%).

This discovery area is critically in need of wide-field optical imaging, with VLBI observations as a supporting technical capability.

GCT-1: How do cosmic structures form and evolve?

There is now a general understanding of how structure is formed within the Universe under the LCDM model, but there are many unanswered questions, especially at galaxy and galaxy cluster size scales. In addition, the well-known observable correlations between the size, mass, and velocity patterns of galaxies are not fully understood, despite decades of research. The discovery that central supermassive black holes have a tight correlation between their mass and the mass of their host galaxy indicates an evolutionary connection between the two objects that is not well explained. Similar difficulties occur for galaxy clusters: the empirical relations between cluster mass and the properties of the hot intracluster medium are not well understood, and we do not understand how galaxy clusters evolve with redshift.

Critical technical capabilities to this research question are wide-field optical imaging and multiplex spectroscopy, and high-resolution OIR/mm/cm imaging and spectroscopy (including faint targets), as well as support for advanced computational capabilities. A supporting technical capability is moderate-angular-resolution submillimeter/mm continuum imaging over wide-fields.

GCT-2: How do baryons cycle in and out of galaxies, and what do they do while they are there?

In order to understand the life cycle of the intergalactic gas that feeds, resides and is subsequently expelled from galaxies, it is most helpful to study galaxies during the peak of star formation and black hole growth, primarily at $z \sim$ 1-3. Progress in this area is occurring through optical measures of distant star formation, near-infrared observations of stellar-mass growth, submillimeter measures of embedded star formation and mm/cm images of the content of molecular gas. Deep and complete samples of galaxies carried out with sensitive instruments can provide a robust measure of galaxy properties such as star-formation rate, black hole activity, star formation history, stellar mass and metallicity. These properties are obtained mainly through multi-wavelength spectroscopy, which can give dynamical information and reveal stellar populations.

This research question requires all nine of the critical technical capabilities listed for this research theme in the compilation below. Supporting technical capabilities include moderate-angular-resolution submillimeter/mm continuum imaging and imaging spectroscopy and over wide-fields, and workhorse OIR instruments on mid-size telescopes.

GCT-3: How do black holes grow, radiate & influence their surroundings?

The central engines of active galactic nuclei – supermassive black holes – are fascinating objects, and have become a clear candidate for changes in both the structure of galaxies and galaxy clusters. The study of AGN feedback is crucial in our understanding of how galaxies redistribute mass and how galaxy clusters maintain their hot reservoir of baryons. The measurement of black hole spin, a key observable that probes the evolution of supermassive black holes is a major advance in this field. Combined with the high angular resolution observations of radio jets, the AGN properties can be studied over many size scales. The discovery of large numbers of obscured AGN shows us that there is still much to be learned about these objects, especially in the early Universe.

Critical technical capabilities to this research question are wide-field imaging, multiplex optical spectroscopy, and supercomputing support. An important supporting capability is the ability to image jet structures in and around central black holes using VLBI at submillimeter, millimeter and centimeter wavelengths.

GCT-4 & GCT-D1: What are the first objects to light up the Universe and when did they do it? Discovery area: The epoch of reionization.

The study of the first objects to illuminate the Universe encompasses a vast range of redshift never previously explored (from the current observational frontier of $z \sim 8$ to recombination near $z \sim 1000$). Therefore, existing work on this question is based on few observations and an evolving theoretical framework. Future work will include detections of distant transient objects, absorption line studies towards these objects, sensitive studies of the highly-redshifted 21 cm HI emission line to look for fluctuations in the brightness temperature, and detections of molecular gas in the late stage of reionization ($z \sim$ 6-8) population of galaxies. Such observations will rely on very large infrared-sensitive telescopes in space and on the ground, and capabilities at both the high and low-frequency ends of the radio spectrum.

Critical technical capabilities to this research question are multiplex optical and infrared spectroscopy and high-resolution imaging/spectroscopy (including for faint targets), as well as supercomputing support. An important supporting capability is the ability to construct long-wavelength, many-element cm arrays that are very sensitive to the HI emission during the epoch of reionization.

Critical GAN and GCT Technical Capabilities

Below we list the rank-ordered capabilities in AST-supported areas that are needed to address the highest-ranked GAN and GCT scientific priorities from *NWNH*. Each technical capability is mapped to Table 5.1, the List of Technical Capabilities, in Section 5.5.

1. **Wide-field optical imaging, including time domain (TC-N):** needed for many scientific areas, from deep surveys of the Galactic halo to constructing a sample

of galaxies at $z \sim$ 1-3 and beyond. Astrometry is an important discovery area. AGN detection, variability, possibly reverberation mapping for black hole mass determination, and star formation from supernovae rates over wide redshift range will also require this capability. (GAN-3,4, D-1,D-2; GCT-1,2,3)

2. **High-angular-resolution (milliarcsecond to arcsecond) submillimeter/mm imaging spectroscopy of molecular gas, including dust and highly excited molecules (interferometric arrays) (TC-E):** critical for probing star formation regions through different molecular species, determining molecular gas masses and kinematics, studying galactic outflows, feedback, star formation efficiencies. (GAN-1,2; GCT-2)
3. **Supercomputing to support suites of 3-D simulations (TC-B):** needed for cosmological simulations and star and galaxy formation simulations. This capability includes testing LCDM, dark matter/baryon distributions in galaxies and realistic star formation and feedback models, as well as black hole formation, accretion, and feedback. (GAN-1,2,4; GCT-1,2,3,4,D1)
4. **Moderate-multiplex R ~ 2000 optical spectroscopy of faint targets: multi-slit spectrographs on 8m-class telescopes (TC-P):** applications include abundances of Galactic and Local Group halo stars, redshifts, galaxy stellar populations and masses, black hole mass estimates. Different spectral needs include multi-slit, single, or bundled-fiber spectrographs. (GAN-3,4; GCT-1,2,3,4)
5. **High multiplex R ~ 2000 optical spectroscopy (TC-O):** applications include Galactic abundances, Local Group halo stars, redshifts, galaxy stellar populations and masses, black hole mass estimates. Different spectral needs include multi-slit, single or bundled-fiber spectrographs. (GAN-3,4; GCT-1,2,3,4)
6. **High-angular-resolution (sub-arcsecond to arcsecond) mm/cm imaging and kinematics of the cold ISM in galaxies from medium- to high-redshift range (interferometric arrays) (TC-G):** requires medium-baseline interferometers. This capability provides imaging of the cold gas reservoir over substantial redshift range, kinematic studies of galaxies, connection to star formation, feedback. HI observations remain valuable but limited to low redshift for foreseeable future. (GAN-2; GCT-2)
7. **Integral-field spectroscopy on large OIR telescopes, including next-generation extremely large telescopes and adaptive-optics (AO) imaging with imaging resolution of 0.1 arcsecond now, eventually reaching 0.01 to 0.03 arcsecond resolution (TC-V):** applications include resolving stellar populations at large distances, kinematics of high redshift galaxies, studying black hole masses and of stars in Galactic center. (GAN-3,4; GCT-1,2,4,D1)
8. **Moderate-multiplex R ~ 3000 near-infrared spectroscopy of faint targets (TC-W):** example applications include abundances of Milky Way and local group galaxy halo stars, redshifts, galaxy stellar populations and masses, black hole mass estimates. Different spectral needs include multi-slit, single or bundled-fiber spectrographs. (GAN-3,4; GCT-1,2,3,4)

9. **High-angular-resolution (sub-arcsecond to arcsecond) mm/cm continuum observations of thermal, non-thermal emission, and dust continuum in galaxies, with polarimetry at medium to high redshifts (interferometric arrays) (TC-J):** important for probing star formation and energy input through synchrotron and bremsstrahlung radiation, magnetic field and star formation feedback studies. These observations provide an unobscured measure of star formation in high redshift galaxies. (GAN-1,2; GCT-1,2)

Summarized Ranking of Critical Technical Capabilities

A significant portion of the GAN and GCT science questions require technical capabilities, either in space or on the ground, that are unlikely to materialize in the next decade. For those cases, we focused our rankings on those areas where critical progress is most likely forthcoming. For example, the questions of flows of matter and energy in the circumgalactic medium and how baryons cycle in and out of galaxies would benefit enormously from next generation optical/UV and X-ray facilities in space, as well as much increased 21-cm sensitivity for deeper HI data. Also, making progress on understanding the epoch of reionization would benefit from next generation sensitive long-wavelength cm arrays which can map the highly redshifted HI during this critical epoch. Some progress can be made with existing capabilities in these areas, but our priorities reflect the improvements offered by in cm and mm interferometry through the VLA and ALMA for mapping radio and dust continuum, and cold gas content from molecular line emission over vast redshift ranges.

Other scientific questions posed by *NWNH* will also see significant progress in the next decade. For example, Galactic archeology will see major progress through dedicated space- and ground-based astrometry surveys and in general from deep ground-based imaging and large multiplex spectroscopic surveys. Deep optical imaging surveys, including synoptic imaging, will result in large samples of distant galaxies and galaxy clusters. Time-domain imaging in Galactic and extragalactic research will help star formation studies through supernova rates over large ranges in redshift and identification of variable stars in the nearby Universe, allowing mapping of the Galactic stellar halo to large distances.

Supporting GAN and GCT Technical Capabilities

The following have been identified as supporting technical capabilities:

- **Workhorse instruments on mid-size telescopes (modest-field optical and near-infrared imaging and spectroscopy (TC-R):** needed for follow-up of survey science and individual objects. Includes narrow-band imaging of galaxies to map the ionized gas distributions in various emission lines (GAN-1,2,3,4,D1; GCT-2)
- **High-spectral-resolution optical spectroscopy (narrow field) (TC-S):** applications include individual faint metal poor stars in local group galaxies, background quasars and galaxies for IGM/galaxy halo absorption lines. Requires extremely large telescopes (ELTs) for some science areas as existing 8m-class

telescopes are reaching limits in sensitivity. (GAN-1,3,4; GCT-2)

- **Data-driven science infrastructure (TC-C):** needed in support of large surveys of galaxies over the entire redshift range (GAN & GCT)
- **21-cm array:** for detailed studies of redshifted HI emission (21 cm) during reionization of the Universe (GCT-4, D1)
- **Moderate-angular-resolution (arcsecond) submillimeter/mm imaging spectroscopy over wide fields (degree) with polarimetry (single dish) (TC-H):** since mm-interferometers have small fields of view, this would support the study and identification of objects (i.e., galaxies, star forming regions) over wide fields of view, and would improve the efficiency of the interferometers. (GAN-2, GCT-2)
- **Moderate-angular-resolution (few arcsecond) submillimeter/mm continuum over wide-field (degree) with large-format detector arrays (single dish) (TC-K):** applications include study star formation, magnetic fields, supernova energy input into ISM through thermal and non-thermal continuum. (GAN-2; GCT-1,2)
- **Laboratory astrophysics (TC-D)**: to measure atomic and molecular-line properties and collisional cross-sections/rates (especially relevant with the mm through submillimeter interferometers coming on line). (GAN-1,2; GCT-2)
- **VLBI at cm/mm/submillimeter wavelengths**: especially with upgraded receivers to include new maser lines, and sometimes with large single dishes to bolster sensitivity. Science includes studies of maser spots for proper motions, hence accurate distance determinations, in local group galaxies, and detailed studies of jets and of Sgr A*. VLBI at submillimeter wavelengths has the potential to detect the shadow of Sgr A* on accretion disk. (GAN-4,D2; GCT-3)
- **Large-collecting-area radio telescope:** to make very sensitive images of the diffuse HI in and around galaxies. Would use the large collecting area but not the specialized pulsar backend required for critical technical capability **TC-L**. (GAN-1,2; GCT-2)
- **Target-of-opportunity optical and infrared imaging and spectroscopy on large telescopes, including supernovae follow-up (TC-Q):** rapid spectroscopic follow-up of variable sources detected by synoptic surveys. The focus here is not on the objects themselves, but on their use as tracers for galaxy science. (GAN-D1, GCT-3)

5.3 Stars and Stellar Evolution

Stars produce most of the visible light analyzed by astronomers. Yet, while in many ways understood in detail, main-sequence stars, including our Sun, still present fundamental puzzles. Convective motions in the interior are the ultimate driver of the process that generates the evolving magnetic fields threading the stellar interiors, surface layers, outer atmospheres, and winds. The Sun serves as the most accessible object of study for understanding this process. However, recent observations of distant stars are providing new insights via asteroseismology. In parallel, spectroscopic and spectropolarimetric observations have begun to map evolving magnetic fields and starspots and detailed variability whose causes range from stellar flaring to cyclic modulation. Ever-improving simulations are also tackling the question of the generation of these magnetic fields in solar-type and fully convective stars.

Observations of large numbers of supernovae and their importance across many fields of astrophysics have pushed our understanding of the end stages of stellar evolution. Type Ia SNe are now the most important standard candles, as evidenced by their key role in revealing an accelerating Universe. By contrast, core-collapse supernovae are many and varied; mass loss significantly complicates the connection between initial stellar masses and the resulting stellar remnants (neutron stars, white dwarfs, or black holes). These remnants are among the most exotic objects in the sky, and the ongoing efforts to characterize these are generating invaluable insight into physics that is not accessible in the laboratory.

The questions and discovery area laid out by the Stars and Stellar Evolution science frontier panel are briefly summarized below, followed by lists of the critical and supporting technical capabilities needed to make progress in this area in the next decade.

SSE-1: How do rotation and magnetic fields affect stars?

In order to understand what drives the evolving internal and surface rotation in stars, the angular-momentum loss must be known, and the internal transport mechanisms understood. Internal transport of angular momentum is intimately coupled to the functioning of the stellar dynamo that maintains an evolving stellar magnetic field, and involves the coupling between the radiative and convective zones, through a pervasive magnetic field, either by way of shear-driven circulations or with deeply penetrating waves.

High-resolution spatial and spectral observations are ranked as critically needed technical capabilities to provide the required detailed insight into the interactions between astrophysical convection, magnetic fields, and mass flows. This includes such observations of the Sun, the sole star for which the loss of angular momentum can be studied by analyzing the solar wind and of the heliospheric magnetic field that is carried within it.

Understanding the Sun's dynamo and the draining of its angular momentum through the solar wind requires an integrated approach that combines full-disk synoptic observations with high-resolution imaging and spectropolarimetric studies with observations of the solar outer atmosphere and of the heliosphere. This requires combining ground-based resources with space-based instrumentation. We thus discuss the needs of solar observations being aware of the instrumentation available now or in the coming years to study the Sun and inner heliosphere from space.

One critical technical capability derived from this perspective is the need to have high-resolution optical spectropolarimetric observations that provide access to photospheric, chromospheric, and coronal diagnostics and synoptic measurement of the Sun's magnetic field (at the surface and at the base of the solar corona) including vector-magnetography for the solar chromosphere (as the foundation of the largely force-free solar corona). From the point of view of society's susceptibility to space weather a national solar synoptic program is critically important.

A related supporting technical capability is the measurement of the dynamics of the solar interior through helioseismology. These observations provide access to internal flows, including their evolution throughout the sunspot cycle, and – for records that are long enough – even changes in flow patterns from cycle to cycle. Only the availability of space-based helioseismology led us to rank this area as supporting – without the space-based assets, helioseismology would be rated a critical technical capability. Full-disk observations of the evolving patterns in the magnetic field at optical and radio wavelengths provide critical information about the dynamo process coupled to the flows below and at the surface. As long as space-based assets remain available to observe the full-disk magnetic field evolution, the ground-based capability is ranked as supporting, but that would change if satellite resources failed or were terminated.

The Sun is but a single star, and its dynamo and evolution run on time scales much longer than what would enable understanding of the impact of stellar rotation on stars from its observations only. Hence, wide-field observations of many distant stars is critically important to provide insight into internal processes via both asteroseismology (such as achieved by the NASA Kepler mission and the European CoRoT project) and spectroscopy and spectropolarimetry of stars that is needed to map their evolving magnetic fields and starspots, and to observe their variability from stellar flaring to cyclic modulation. A critical technical capability derived from this scientific need is access to 4-8 m optical telescopes with medium to high spectral resolution and spectropolarimetric capabilities.

Computational astrophysics involving major 3-D simulations is now a vital complement to theory and observations in many areas. The simulations are key to understanding the complex ways by which stars build variously their persistent or cyclic magnetic fields, and how these influence the mass and angular momentum loss through winds as the stars evolve. The ultimate fate of stars hinges sensitively on such winds, as does the recycling of material into the ISM. A critical technical capability derived from both the stellar and solar fields relevant to SSE1 is therefore the effective use of state-of-the-art supercomputer facilities. This is true also from another perspective: space-based and ground-based observatories are generating terabytes of data per day, and locating, accessing, and processing that data will require a data-driven science infrastructure supported by supercomputer capabilities.

SSE-2 & SSE-3: What are the progenitors of Type Ia Supernovae, and how do they explode? How do the lives of massive stars end?

SSE-2 and 3 focus on different aspects of supernova explosions. Common observational and theoretical/computational capabilities critically underlie progress for both questions.

Type Ia supernova explosions likely result from the collapse and thermonuclear detonation of a carbon-oxygen white dwarf due to accretion from a binary companion taking its mass over the Chandrasekhar limit. Yet, such explosions and their yield may be influenced by the path of evolution to an accreting white dwarf in a binary system, the manner and sites of ignition and subsequent turbulent nuclear burning, and transition from subsonic burning to detonation. Although there may be a common set of characteristics for these explosions, outliers are possible. Finding and characterizing these outliers provides significant leverage on models.

While Type Ia supernova research focuses on the details of a specific class of explosions, endpoints of massive stellar evolution leading to core-collapse supernovae span a range of mass-loss scenarios, and involve a range of core conditions at the time of the explosion. These explosions enrich the ISM and yield compact stellar remnants. Mass loss significantly obscures the connection between initial stellar mass and the resulting stellar remnant. Even with a well-defined final core mass, factors such as rotation, magnetic field and metallicity severely complicate the nature of what is already a complex explosion process. As with Type Ia supernovae, the rare outlying examples may provide the most illuminating constraints on model behavior.

NWNH highlighted the need for discovery of tens of thousands of examples of both Type Ia and core-collapse supernovae to identify the rare out-of-family cases that may provide the most insight into the details of the explosion process. Thus, the critical technical capability needed to find supernovae in such large quantities is deep multi-epoch imaging of a significant fraction of the sky. These flux levels are reachable only by telescopes several meters in diameter if coverage must be several steradians. Simultaneously, computational capabilities have matured to the point to enable 3-D simulations of the ignition/combustion process that are timely and complementary critical technical capability to the emerging observational capabilities. As the decade proceeds, the expected scaling of computational capability will enable the inclusion of magnetic fields and rotation in these computational models.

Ultimately, spectroscopy will probe the detailed structure of the developing supernova remnant, and, in the case of core-collapse supernovae, illuminate the structure of the pre-supernova envelope resulting from prior mass loss. Given the faintness of the most interesting objects, spectroscopy (and spectropolarimetry) of the full population will require a critical spectroscopic and spectropolarametric capability on telescope apertures significant larger than those currently available. At the same time, a variety of workhorse capabilities on modest-aperture telescopes will be critical for target-of-opportunity observations characterizing supernova light curves in the optical and near-infrared part of the spectrum and providing spectroscopy for brighter/nearby supernovae.

SSE4: What controls the mass, radius & spin of compact stellar remnants?

Compact stellar remnants are unique laboratories for studying the behavior of matter under conditions generally not accessible in the laboratory. As with supernovae, discovering remnants with extreme properties, such as neutron stars with extremely short rotation periods, provides the most potential for insight into the interior physics at play.

For neutron stars, the challenge is to identify those for which mass and radius can be measured. New Galactic surveys for pulsars are particularly important in this context, as they are likely to yield new binary millisecond pulsars, thereby increasing the size of the currently small number of neutron stars for which mass measurements can be made. Neutron stars in these systems with unusually high or low masses are especially interesting, as they set strong constraints on the theoretical equations of state of ultra-dense matter. As a result, a critical technical capability for answering this question is cm wide-bandwidth observations with large collecting areas to detect and time faint pulsars. This capability is also essential for following-up interesting neutron stars uncovered at other wavelengths, e.g., gamma-ray pulsars found by the Fermi mission. This is a new and simpler way of identifying millisecond pulsars, and neutron stars characterized in this fashion provide important insight into the structure of their magnetic fields. Furthermore, the new millisecond pulsars found in this manner are an important addition to the sample whose long-term monitoring may allow for the detection of gravitational waves.

Uncertainties about the mass-loss processes during the late stages of stellar evolution significantly limit our understanding of the initial-final mass relation for white dwarfs. Much of the work required to address these uncertainties is theoretical, as it involves improvements to e.g., models of asymptotic giant branch star evolution. Observationally, constraints can come from infrared and interferometric observations of mass-losing stars, and in the next decade, the ability to measure mass-loss rates in evolved stars will be critical in this context. Finally, large optical surveys to identify more white dwarfs—and in particular exotic ones, such as those with masses $<0.2\ M_{\mathrm{sun}}$—are essential to improving our understanding of formation channels beyond that leading to a standard carbon-oxygen remnant.

In parallel, maturing computational capabilities and laboratory experiments are critical to interpreting these observations and to modeling the physics of ultra-dense matter. In addition, on the observational side, high-end computation and specialized processing enables e.g., searches for pulsar signals in the vast volumes of data that are produced by modern wide-bandwidth receivers.

SSE-D1: Discovery Area: Time-domain surveys

Time-domain studies naturally underlie all of the science questions outlined above; the next generation of surveys will push them forward. Synoptic observations of the Sun on timescales of minutes up through the decades spanning multiple solar cycles will allow us to measure and model the behavior of its magnetic field on both short and long timescales, and perhaps to uncover the processes linking the two. Wide-field time-domain optical surveys will uncover large numbers of supernovae and other stellar transients via nightly/weekly observations of a significant fraction of the entire sky, enhancing our understanding of stellar death and extending our ability to use these explosions to measure the expansion of the Universe. Finally, long-term observations of binary pulsar systems and of individual pulsars will allow us to probe both gravitational physics and the internal properties of neutron stars and their magnetic fields.

The critical technical capabilities for this discovery area are high-angular-resolution solar magnetometry and spectroscopy, wide-field optical/infrared imaging and spectroscopy, cm-wave broadband continuum observations using large collecting area, and supercomputer support.

Critical SSE Technical Capabilities

Below we list the rank-ordered capabilities in AST-supported areas that are needed to address the highest-ranked SSE scientific priorities from *NWNH*. Each technical capability is mapped to Table 5.1, the List of Technical Capabilities, in Section 5.5.

1. **Wide-field optical imaging, including time domain (TC-N):** supernova discovery requires synoptic imaging of large areas of the sky. The volume of the Universe addressed scales linearly with solid angle but increases as a significant power of the survey depth. Although wide-area surveys with modest (2-4 m) telescopes will provide (and have been providing) a census of supernovae in the local Universe, significant progress in discovering new and rare deviations from the norm will only progress if this synoptic capability exists on 8m-class survey telescopes. Time-domain wide-angle imaging with precision photometry has the potential to monitor stellar activity and magnetic stellar cycles for a large sample of objects, with extremely-high-precision, high-cadence observations providing asteroseismological data for the brightest stars. Wide-field imaging can also reveal exotic white dwarfs, which constrain pathways for stellar evolution. (SSE-1,2,3,4, D1)
2. **Supercomputing to support suites of 3-D simulations (TC-B):** computing ranks highly, not only because of its maturity and universal application in all of the science areas outlined above, but more importantly because of the timeliness of the maturation of 3-D codes and necessary processing power. Computing support is required for simulations of ignition, combustion, and explosion of supernovae that can be tested against the observed supernova light curves, as well as for simulations of nonlinear dynamics in stellar interiors and magnetized atmospheres. The synergy between computation and wide-field imaging is striking in its timeliness and reinforces the highest ranking of these capabilities. (SSE-1,2,3,4, D1)
3. **High-angular-resolution solar magnetometry and spectroscopy (TC-A)**: the

Sun will remain the one fully resolvable example of a star for the foreseeable future. Information about the small-scale processes of flow-field coupling, magnetic reconnection, and the transfer of mass, energy, and field from the solar interior into the solar outer atmosphere, along with the conversion processes that occur in the transition zone between the plasma-dominated interior and the field-dominated corona will lead to a deeper physical understanding of this star. (SSE-1, D1)

4. **Target-of-Opportunity optical imaging, spectroscopy, and spectro-polarimetry on large telescopes, including supernovae follow-up (TC-Q):** wide-field synoptic observations are sufficient to discover and provide initial light curves for supernovae. Details of the time and spatial evolution of the most interesting explosions are accessible via precise broadband light curves and high-resolution spectroscopy and spectropolarimetry. The largest telescopes will be required for the rarest and potentially most interesting objects, since they will inevitably be among the photometrically faintest discoveries. (SSE-1,2,3)
5. **Centimeter-wave broadband continuum observations using large collecting area and pulsar timing backends (TC-L):** combined with ultra-fast processors to de-disperse and search for periodicity in immense data streams, broad area surveys using this capability will expand the population of millisecond pulsars and pulsar binaries that provide the best constraints on the behavior of matter at nuclear density. (SSE-4, D1)
6. **Workhorse instruments on mid-size telescopes (modest-field optical & near infrared imaging and spectroscopy), including synoptic monitoring., but not including high-stability high-resolution spectroscopy, or AO wide-field/high-multiplex instruments (TC-R)**: this is complementary to the large telescope target of opportunity supernova follow-up observations enumerated above, and the spectroscopy and spectropolarimetry of stars, but enlists modest-sized telescopes in the construction of light curves and in moderate-resolution spectral and spectropolarimetric observations of the brighter/nearer examples of stars and supernovae. (SSE-1,2,3, D1)
7. **High-spectral-resolution optical spectroscopy (TC-S):** high-resolution spectroscopy (and spectropolarimetry) will ultimately illuminate the 3-D structure of expanding supernova envelopes. Mapping of complex spatial and compositional structures, and of expansion velocities, will require extremely-large-aperture telescopes. (SSE-2,3)
8. **Data-driven science infrastructure (TC-C):** exploiting the vast volume of data from synoptic wide-field surveys, for example to extract supernova candidates, will require management and manipulation of large databases and tools for doing so effectively. Similarly, vast amounts of solar observations from space and ground require a dedicated infrastructure in order to be fully exploited. (SSE-1,2,3, D1)
9. **Moderate- to high-angular-resolution (sub-arcsecond to arcsecond) cm continuum follow-up observations of pulsar candidates and other**

unidentified sources detected at other wavelengths (TC-M): large area, blind surveys at all wavelengths are expected to yield numerous candidates to follow. The localization of pulsar candidates to sub-arcsecond precision is most easily performed at cm wavelengths and would enable the detailed proper motion and distance measurements needed to constrain equations of state. (SSE-4, D1)

Summarized Ranking of SSE Critical Technical Capabilities

Stars present a diverse range of astrophysical puzzles. The Sun reveals increasing complexity as expanding capabilities probe it atmosphere, magnetic fields, and interior in increasing detail. The endpoints of stellar evolution, Type Ia supernovae in particular, are important cosmological tools while also intrinsically astrophysically interesting given the complexity of the explosion process. In addition, understanding the nature of post-main sequence mass loss connects initial stellar masses to stellar remnants. Stellar remnants, and neutron stars in particular, are prime laboratories for exploring the physics of ultra-dense matter. Connecting all of these topics are the critical technical capabilities of wide-field optical/infrared imaging and advanced computation. More importantly, these two critical technical capabilities are interrelated. Extensive surveys identify the unusual systems that can make or break a particular theory. Computational modeling is the key to making these evaluations. As a result, these two capabilities naturally lead the list of SSE critical technical capabilities. The maturation of computational codes to include 3-D physics and soon the inclusion of rotation and magnetic fields further reinforces the top ranking of these capabilities.

High-angular-resolution solar magnetometry and spectroscopy appears next in the ranking of critical technical capabilities. Of all of the stars in the sky, the Sun is the one upon which we are completely dependent and has the potential to do our technologically fragile society significant harm. It is also the only star that can be examined in spatial detail.

The next highly-ranked technical capabilities for SSE focus on the ability to conduct photometric, spectroscopic, and spectropolarimetric follow-up observations of transients discovered by wide-field surveys. Doing so requires exploiting these capabilities on the existing largest available telescopes in a target-of-opportunity mode. Similar workhorse capabilities on moderate-aperture telescopes provide critical observations of the brighter transients, which are naturally discovered via synoptic imaging of large portions of the sky.

Supporting SSE Technical Capabilities

The following have been identified as supporting technical capabilities:

- **Moderate-multiplex, R~few thousand spectral resolution optical spectroscopy of faint targets (TC-P):** using multi-slit spectrographs on 8m-class telescopes. (SSE-1,2,3, D1)
- **Diffraction-limited imaging and integral field spectroscopy on large OIR telescopes with adaptive optics (TC-V):** allows for detailed studies of the SNe

host galaxies and circumstellar environments, thereby testing whether and how variations in stellar populations and environments impact the observed SNe properties. (SSE-2,3)

- **Target-of-Opportunity infrared imaging and spectroscopy on large telescopes (e.g., supernovae follow-up):** provide insight into dust formation in core-collapse supernovae and rest-frame visible-wavelength characterization of supernovae at cosmological distance. (SSE-2,3, D1)
- **Near-infrared seeing-limited time-domain imaging over wide field of view:** provides the potential for discovery and characterization of rare supernova explosions not necessarily accessible to visible wavelength surveys. (SSE-2,3, D1)
- **Long-term synoptic magnetometry and seismology:** measurement of evolving dynamics within the solar interior enabled by helioseismology must be continued as the activity cycles proceed, along with full-disk spectropolarimetric measurement of magnetic fields at the solar surface and in the chromosphere. These are critically needed observations, but ranked supporting subject to the availability of high-quality space-based observations. (SSE-1, D1)
- **Ground-based asteroseismology:** complements space-based stellar oscillation observations, which are necessarily limited to small fields. (SSE-1)
- **High-angular-resolution (sub-arcsecond to arcsecond) mm/cm imaging and kinematics (interferometric arrays) (TC-G)**: for characterizing the local environments into which stars explode, as well as for examining mass loss in evolved stars in order to constrain the initial-final mass relation for white dwarfs. (SSE-2,3)

5.4 Planetary Systems and Star Formation

For most of recorded history, humans have wondered about their origins. The discovery of planets orbiting other stars (exoplanets) has launched a lively new subfield of astronomy, intriguing to both scientists and the public. Exoplanet discoveries have been accompanied by great strides in our understanding of star and planet formation. In the past decade, we have imaged the birth sites of stars and planets, from embedded protostars to the latest stages, where planets sculpt and begin to clear the protoplanetary disks of their host stars, and discovered thousands of small bodies that are the remnants of the formation of our own solar system.

To help guide this exploration, the Planetary Systems and Star Formation science frontier panel highlighted four questions and one discovery area for the coming decade. We summarize here the nature of these science priorities, and the technical capabilities within the realm of AST that are critical to answering questions that will have enormous impact on broad areas of science and the public. Where possible, we have dovetailed the recommendations of *NWNH* with those of the *V&V* Planetary Decadal Survey that impact ground-based astronomy and the related areas of theory and laboratory astrophysics.

PSSF-1: How do stars form?

The collapse of dense phases of the interstellar medium to form stars operates over an enormous range of spatial and temporal scales. An understanding of star formation, the impact of environment, and the resulting initial mass function (IMF) is a common priority for both the PSSF and GAN sections in the *NWNH* report. However, it is within the Galaxy that the full spatial dynamic range of star formation can best be explored, and therefore a priority is the ability to image molecular clouds and stellar clusters on spatial scales spanning from less than 0.1 pc to more than 100 pc and at distances of the Galactic Center and beyond. Observations from cm to optical wavelength are required, so no single telescope or array can obtain the needed data. Ascertaining the role of magnetic fields is also critical and demands polarization-sensitive observations that can resolve the full velocity field of the dense and diffuse phases of the ISM in a variety of tracers. Development of theory and simulations is needed to interpret the observations.

Significant advances in these technical capabilities are coming on-line in the radio through submillimeter region; however, new capabilities in both wide-field imaging and wide-field adaptive optics observations on 10m- to 30m-class OIR telescopes are also needed to fully address the science goals. Work on laboratory astrophysics of atoms, molecules, and dust grain analogs will be required to support the observations and data analysis from these facilities

Critical technical capabilities needed in support of this research question include moderate- to high-angular-resolution (sub)mm and mid-infrared imaging spectroscopy, laboratory astrophysics in support of spectroscopic needs, and near-infrared spectroscopy on faint targets in complex regions.

PSSF-2: How do circumstellar disks evolve & form planetary systems? (*V&V* theme "Building New Worlds")

Circumstellar disks transport mass and angular momentum, providing a critical link between star and planet formation. The general properties of the disks and their evolutionary time scales have been fairly well constrained by observations, yet we know little about the internal structure of the disk. This has left gaps in our understanding about the underlying physics and chemistry that mediate planet formation. A top science priority for the coming decade is extremely-high-spatial-resolution observation of the primordial matter in young, gas-rich circumstellar disks, down to scales of at least 1-10 astronomical units (AU). Gas and dust tracers must both be studied, and submillimeter to radio observations are required to image the wide range of temperatures from the outer disk to its innermost zones. For systems that show considerable radial structure, additional searches for nascent planets are paramount. Complementary observations to characterize atmospheres and energy loss are best carried out at near- to mid-infrared wavelengths.

For more evolved debris disks, the connection between the structures induced in (now second generation) dust and planetary bodies is especially exciting. Investigation of these systems requires a combination of optical/IR imaging in scattered light and thermal imaging at millimeter wavelengths. Here the links to our own Solar System are strong. Primitive Solar System bodies provide unique information about the origin and early history of our Solar System and inform observations of debris disks around other stars. The study of primitive bodies in our Solar System is aided by ground-based telescopes and radar observations because there are too many asteroids, comets, and Kuiper Belt Objects (KBOs) to explore individually by spacecraft. Determining the orbits of vast numbers of KBOs presents an unprecedented opportunity to reconstruct the early dynamical history of the Solar System. Orbital surveys coupled with determination of physical characteristics, can constrain physical conditions in the nebula. A vastly improved understanding of the Kuiper and asteroid belts would be achieved by deep, whole-sky synoptic campaigns and follow up imaging/ spectroscopy.

Theory and laboratory work are also critical efforts. At present no analytically tractable model of circumstellar disk viscosity (and thus transport) is available, nor do we understand how the gas and dust transport might vary with position, evolutionary state, chemical composition, temperature of the host star, etc. Numerical simulations are extraordinarily challenging in this regime, and will require a combination of innovative theory and massive advances in computational throughput for progress to be made.

The critical technical capabilities needed in support of this research question include moderate- and high-angular-resolution submillimeter/mm and mid-infrared imaging spectroscopy, laboratory astrophysics in support of spectroscopic needs, near-infrared spectroscopy, wide-field imaging, synoptic optical/infrared monitoring, radar observations of solar-system bodies, and advanced supercomputing support.

PSSF-3: How diverse are planetary systems? (*V&V* theme "Workings of solar systems")

Of the hundreds of exoplanets known, most are wholly unlike those in our own Solar System. The great majority are gas and ice giants with orbits that are much smaller than the orbit of Jupiter, although the first "super-Earths" are being announced at an increasing pace. Radial-velocity (RV) surveys are the province of ground-based astronomy, and continued improvements in precision offer the opportunity to detect smaller amplitude systems, including the detection of Jupiter-like planets out to about 5 AU over the coming decade. At intermediate orbital radii (a few to about 10 AU) ground-based microlensing observations are providing statistical information about cold gas giants, analogous to Jupiter, Saturn or Neptune. Beyond 10 AU, high-contrast direct imaging using adaptive optics is taking the first census of Jovian companions to main sequence stars in wide orbits.

The NASA Kepler mission has discovered nearly three thousand transiting exoplanet candidates, and ground based transit surveys of bright, nearby stars are providing superb targets for follow up. Such transiting systems are of special interest because they present a rare opportunity to understand the interior composition of exoplanets and to observe their atmospheres, either in transmission (primary transit) or emission (secondary eclipse).

Both the Doppler detections and the Kepler results show that the ice giants and super-Earths greatly outnumber the gas giant population. To make further progress, *NWNH* recommends the development of new spectrometers capable of achieving 0.1-0.2 m/s precision, and adequate allocation of observing time on 4-m to 10-m telescopes. This is a challenging goal, and one that will likely require investment in technology development. Near-infrared spectrometers may be advantageous for stars cooler than spectral type M4V, which emit their peak flux in the near-infrared.

Critically needed technical capabilities to address this research question are high precision (≤1 m/s) radial velocity programs for Doppler planet detection and Kepler follow-up (of larger, higher mass planets), high resolution spectroscopy to characterize the properties of host stars, small-to-moderate telescopes for photometric follow-up of microlensing events/ground-based transit surveys, and instrument development for extreme-precision optical spectrometers (to reach 10 cm/s) and high-resolution near-IR spectrographs to detect planets orbiting cool stars (later than M4V).

PSSF-4: Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet? (*V&V* theme "Planetary Habitats")

Astronomers are closing in on the detection of potentially habitable worlds. The Kepler mission has found that about 13% of Sun-like stars harbor sub-Neptune-size planets (radii between 2 and 4 times that of the Earth); in the next few years, Kepler should provide a statistical assessment for the occurrence rate of Earth-sized planets orbiting at habitable zone distances from their host stars. Meanwhile, the prospect of ground-based detections of Earth-mass planets orbiting close to low-mass stars is quite good.

The telltale signs of life may well reside in the atmospheric chemistry of exoplanets. To assess whether imaging of habitable planet atmospheres is feasible, a detailed understanding of the zodiacal dust environment must be carried out. Ultimately this discovery may require mid-infrared interferometers in space, but modest limits for nearby stars can be obtained from the ground with submillimeter or infrared interferometers that incorporate modest spectroscopic capabilities in order to study the chemical nature of the dust. Ground-based thermal infrared interferometers should be able to detect dust from reprocessing disks generated by collisions of small rocky bodies.

The critical technical capabilities needed to address this research question include precision optical and near-infrared photometry, high-resolution spectroscopy with mid- to large-aperture optical/infrared telescopes, and moderate-spectral-resolution mid-infrared interferometers.

PSSF-D1: Discovery potential - Identification and characterization of nearby extrasolar habitable planets

The combined improvement of RV and transit techniques, along with the possibility of the characterization of exoplanet atmospheres via spectroscopy, led the PSSF panel of *NWNH* to conclude that the possible detection of large, rocky planets orbiting low mass stars formed “the single greatest area for unusual discovery potential.” The report noted that it was critical that the necessary resources be made available, both in instrument and technique development and in the substantial investment in telescope time that would be required.

To carry out such a program, it will be necessary to design optical or near-infrared spectrometers that produce a factor of ten improvement over current instruments. Working in the near infrared may be an attractive option for stars later than about M4V in spectral type since these stars emit their peak flux in the near-infrared. Higher-precision optical or near-infrared Doppler surveys could serve to discover new potentially habitable systems and will provide critical follow-up characterization of planetary systems discovered by transit surveys. Transiting rocky planets around low-mass stars are also excellent candidates for ground-based characterization of their atmospheres in the near infrared using multi-object spectrographs. Over the longer term, such programs, if started promptly, would yield many high priority targets for early science with JWST.

The critically needed technical capabilities to address this research question are precision optical and near-infrared photometry, spectroscopy at mid- to large-sized OIR telescopes, high-contrast near-infrared imaging, and moderate-spectral-resolution mid-IR interferometers.

Critical PSSF Technical Capabilities

Below we list the rank-ordered technical capabilities in AST-supported areas that are needed to address the highest-ranked PSSF scientific priorities from *NWNH*. Each technical capability is mapped to Table 5.1, the List of Technical Capabilities, in Section 5.5.

1. **Extreme-precision OIR Doppler spectroscopy (TC-T):** The detection of Earth-mass planets in habitable zone orbits requires radial-velocity (Doppler shift) precision of 0.1-0.2 m/s at optical wavelengths and somewhat lesser precision for NIR studies of cool, low-mass stars. While shot-noise statistics provide a fundamental limit, coupling of light to the instrument, opto-mechanical stability and optimal wavelength calibration are all areas that still merit work. Thus, substantial instrument and analysis development will likely be needed, over the course of several years. Once an understanding of extreme-precision Doppler techniques is in hand, substantial observational resources would be required to carry out the requisite surveys. (PSSF-3,4, D1)
2. **High-angular-resolution (milliarcsecond to arcsecond) mm/submillimeter imaging spectroscopy (TC-E):** Molecular cloud imaging down to the dissipation scale length is needed to make progress on scientific questions about star formation. To better understand planet-disk interactions and volatile transport

higher resolution is required for imaging at AU scales. Arrays with baselines of at least one kilometer, excellent phase performance and correction for atmospheric fluctuations are needed for this work. Large collecting areas are required to provide sensitivity to spectral line tracers that can probe the gas velocity structure, with <km/s resolution. (PSSF-1,2)

3. **High-angular-resolution R ~ 200 near- through mid-infrared imaging spectroscopy (TC-U):** Probes of the dust evolution that match spectral line image cubes provided by aperture synthesis arrays are needed to examine the earliest steps of planetesimal formation. Here, moderate-spectral-resolution instruments operating in the mid-infrared at high angular resolution are best suited to the modifications of dust chemistry, such as can be achieved with an interferometer or a GSMT. At longer wavelengths, spatially resolved submillimeter to radio data provide more stringent constraints on dust grain growth, at least into mm and cm diameters. (PSSF-2,4, D1)
4. **Direct exoplanet detection via near-infrared high-contrast imaging and coronography (TC-Y):** Doppler sensitivity to planets in wide orbits is poor because of the smaller reflex stellar velocity and the very long time baselines required to map out one orbit. Microlensing studies help to bridge the parameter space for orbital radii of a few to about ten AU. High-contrast imaging, especially of young (and therefore bright) exoplanetary systems provides a complementary capability. Extreme-adaptive-optics instruments on 8m-class telescopes will begin to detect planets at distances beyond 10 AU around nearby stars. However, the detection parameter space for near-term AO instruments will not overlap with the detection regime for Doppler surveys for stars beyond about 10 parsecs. In order to provide uniform sampling of planet occurrence versus distance, high-contrast AO imaging will need to be developed for extremely large optical/infrared telescopes. (PSSF-3)
5. **Wide-field optical imaging, including the time domain (TC-N):** placing our Solar System into the context of debris disks, and examining the predictions of emerging models of early Solar System dynamics, requires a much improved understanding of the Kuiper Belt – especially at distances beyond those probed by current surveys. For this work, deep whole-sky synoptic surveys to $R \sim 24^{\text{th}}$ magnitude (or deeper) are required. (PSSF-2)
6. **Moderate-angular-resolution (few arcsecond) mm/submillimeter imaging spectroscopic imaging over wide (~degree) fields (TC-H)**: the nearest star-forming molecular clouds span several degrees on the sky. In order to understand the process of star formation and feedback globally, it is necessary to examine cloud structure over a wide range of spatial scales. Large interferometric arrays are well suited for probing the underlying velocity structure through spectral lines. However, heterodyne arrays provide the enabling technology for observations of large-scale structure. (PSSF-1,2)
7. **Moderate-angular-resolution (~arcsecond) mm/submillimeter imaging continuum imaging over wide (~degree) fields (TC-K)**: the goal is to image the dust continuum emission over wide scales, using the latest generation of large format submillimeter cameras. Polarization capabilities are essential, in both continuum and spectral lines, in order to assess the role of magnetic fields.

(PSSF-1,2)

8. **Workhorse instruments on mid-sized optical/infrared telescopes, including synoptic monitoring (TC-R):** the science drivers are exoplanet transit observations and dedicated high-resolution imaging (to search for companions). Low-resolution spectroscopy is needed to characterize the surfaces of KBO's discovered in synoptic surveys. (PSSF-2,3.4, D1)
9. **Laboratory astrophysics, to measure key atomic and molecular line frequencies and collisional cross sections (TC-D):** the newly available capabilities of large radio through submillimeter interferometers will create a compelling need for laboratory astrophysics measurements of the spectra of complex, prebiotic species. For both mm/radio observations and those in the infrared, line formation is not likely to be in local thermodynamic equilibrium, and so there is also an urgent need for better measurements (or predictions) of atomic and molecular collisional cross sections. Finally, measurements of dust optical constants across the full range of temperatures experienced in the ISM are needed to properly interpret the expected flood of data from RMS arrays and infrared spectrographs. (PSSF-1,2)
10. **Low to moderate spectral resolution near-infrared spectroscopy of faint targets (TC-X):** the most urgent need will be for small Solar System body characterization, especially those objects discovered in deep, wide field surveys. These observations will require the largest possible telescopes – objects in the outer Solar System have low albedos and are thus faint. (PSSF-2)
11. **Radar characterization of primitive Solar System bodies (TC-I):** Near Earth Objects (NEOs) are the main objects of interest here. Radar measurements have provided surprising results on the composition of such bodies, more so than can be provided by spectroscopy of main belt objects alone. If the NEOs come too close, bistatic operation, where the broadcast and receive stations are different, is essential.(PSSF-2)
12. **Supercomputing to support 3-D simulations (TC-B):** Studies of the fundamental physics involved with disk-protoplanet interactions are an area of active research and numerical experiments play an important role here. Theoretical development is important, especially in the area of magnetohydrodynamics. (PSSF-1,2)

Summarized Ranking of PSSF Critical Technical Capabilities

The discovery and initial characterization of thousands of extrasolar planets and potentially planet-forming environments over the past decade(s) has highlighted the deep connections between (exo)planetary science and astronomy. Moving forward, the discovery of rocky, habitable worlds around nearby stars would complete the Copernican revolution. Though such discoveries will ultimately require a combination of ground-based and space-borne facilities, substantial progress can be made by RV techniques and precision transit surveys over the coming decade. The development of extreme-precision RV measurements will require sustained development effort followed by significant investments in observing time, and forms our highest rated critical technical capability.

A second broad area of discovery concerns the investigation of the internal structure of protoplanetary disks and debris disks as planet-formation laboratories, an understanding of which will illuminate the diversity of known extrasolar planetary systems. The critical technical capabilities here – especially the high-resolution imaging of gas and dust signatures in circumstellar disks at cm through infrared wavelengths along with the high-contrast optical/infrared imaging of young and mature planetary systems – will soon be deployed on the latest generation of interferometric arrays and coronographic instrumentation.

Over wider spatial scales, extensive surveys of Solar System objects and star-forming regions from optical through radio wavelengths are needed to address the questions posed by *NWNH*, and will require the development or augmentation of large-field-of-view telescopes/interferometers and large-format focal-plane arrays. Finally, underpinning all of these developments will be follow-up observations of selected objects using workhorse instrumentation (including cm-wavelength radar) and especially fundamental research in laboratory astrophysics and theory.

Supporting PSSF Technical Capabilities

The following have been identified as supporting capabilities:

- **VLBI at cm frequencies:** the major drivers are astrometric observations of protostellar clusters, in order to provide distance measurements and probes of maser activity. (PSSF-1)
- **High-resolution cm-wave imaging of gas/dust in massive star forming clouds (TC-J):** the relationship of ionized and neutral gas is key to the evolution of massive star forming clusters. For the ionized component such observations are best carried out at cm wavelengths, especially when they are combined with multi-conjugate AO imaging over wide fields (in the near-IR) to study the nascent stellar population. (PSSF-1)
- **High-resolution infrared spectroscopy:** high-dispersion infrared spectroscopy of small molecules (carbon monoxide, water, HCN) can study the critical zone of disks from 1 to 5 AU, where many of the known extrasolar planets have been discovered. At wavelengths beyond 5 microns, extremely large telescopes are needed to collect enough photons to study typical T Tauri star disks, and to enable spectro-astrometric observations at <0.1 AU spatial resolution. (PSSF-2)
- **Optical monitoring of gas-giant planets:** spacecraft cannot continuously monitor the planets in the Solar System, or their satellites with atmospheres (especially Titan). Thus, as is the case with the Sun, long-term monitoring of the weather on these bodies from the ground form important data sets that drive both Solar System science and have applications to our understanding of extrasolar planetary atmospheres. (PSSF-D1)
- **Data-driven science infrastructure (TC-C):** to provide high-performance community access to increasingly large observational and simulational datasets, especially those produced by aperture synthesis arrays, as well as ongoing stewardship of heavily-used astronomical data archives. (PSSF-1,2)

5.5 Summary of Critical Technical Capabilities

The technical capabilities rated as critical by the Committee formed the basis for evaluating the roles of existing and future facilities in meeting the science objectives of *NWNH*. Here we summarize the critical technical capabilities, categorized by their type of technology. The letters given are intended solely for identification, and do not signify any ranking within the critical priorities. The Table does, however, list the priority rankings assigned to each capability for each science frontier (Cosmology & Fundamental Physics [CFP], The Galactic Neighborhood [GAN], Galaxies Across Cosmic Time [GCT], Stars & Stellar Evolution [SSE] and Planetary Systems & Star Formation [PSSF]). An empty entry means that the technical capability was not considered critical for that science frontier. For example: CMB polarization experiments were ranked as the 3rd most important of 6 critical technical capabilities for CFP, but were not considered critical to other science frontiers.

Table 5.1: Summary of Critical Technical Capabilities. The ranking of these capabilities within each science panel is listed. We stress that the lettering is solely for identification and does not signify an overall ranking.

Critical Technical Capability	**CFP**	**GAN/GCT**	**SSE**	**PSF**
Solar Capabilities				
TC-A. Subarcsecond solar magnetometry and spectroscopy			3/9	
Lab, Theory and Computational Capabilities				
TC-B. Supercomputing to support suites of 3-D simulations	4/6	3/9	2/9	12/12
TC- C. Data-driven science infrastructure			8/9	
TC-D. Laboratory astrophysics, to measure key atomic and molecular line frequencies and collisional cross sections				9/12
RMS Capabilities (cm, mm, and submillimeter)				
TC-E. High-angular-resolution (milliarcsecond to arcsecond) submillimeter/mm imaging spectroscopy (interferometric arrays)		2/9		2/12

TC-F. CMB polarization experiments (arcminute scale cm/mm polarimetry)	3/6			
TC-G. High-angular-resolution (sub-arcsecond to arcsecond) mm/cm imaging and kinematics (interferometric arrays)		6/9		
TC-H. Moderate-angular-resolution (few arcsecond) submillimeter/mm imaging spectroscopy over wide fields (degree) with polarimetry (single dish)				6/12
TC-I. Radar characterization (cm wavelengths) of primitive bodies (single dish)				11/12
TC-J. High-angular-resolution (sub-arcsecond to arcsecond) mm/cm continuum observations with polarimetry (interferometric arrays)		9/9		
TC-K. Moderate-angular-resolution (few arcsecond) mm/submillimeter continuum observations over wide-field (degree) with large-format detector arrays (single dish)				7/12
TC-L. Centimeter-wave broadband continuum observations using large collecting area and pulsar timing backends			5/9	
TC-M. Moderate- to high-angular-resolution (sub-arcsecond to arcsecond) cm continuum follow-up observations			9/9	
Optical and Infrared (OIR) Capabilities				
TC-N. Wide-field optical imaging, including time domain	1/6	1/9	1/9	5/12
TC-O. High-multiplex, R~few thousand spectral resolution optical spectroscopy	2/6	5/9		
TC-P. Moderate-multiplex, R~few thousand spectral resolution optical spectroscopy of faint targets	5/6	4/9		
TC-Q. Target-of-Opportunity optical imaging and spectroscopy on large telescopes	6/6		4/9	
TC-R. Workhorse instruments on mid-size telescopes (modest-field optical & NIR imaging and spectroscopy), including synoptic monitoring.			6/9	8/12

TC-S. High-spectral-resolution optical spectroscopy, leading to GSMT implementations			7/9	1/12
TC-T. Extreme-precision optical (10 cm/s) and NIR (1 m/s) Doppler spectroscopy				1/12
TC-U. NIR/MIR R~few hundred spectral resolution high-angular-resolution spectroscopy (AO)				3/12
TC-V. Diffraction-limited imaging and integral-field spectroscopy on large OIR telescopes with adaptive optics.		7/9		
TC-W. Moderate-multiplex, R~few thousand spectral resolution NIR spectroscopy of faint targets		8/9		
TC-X. Low- to moderate-spectral-resolution NIR spectroscopy of faint targets				10/12
TC-Y. NIR high-contrast imaging and coronography for direct detection of planets				4/12

6 Capabilities for the Health of the Profession

6.1 Introduction: U.S. Leadership in Astronomy

A vital U.S. astronomical workforce is essential to achieving the ambitious goals of *NWNH* and maintaining U.S. leadership in astronomy. Sustaining the health of the profession requires concerted effort in the current restricted funding environment. Required for leadership are the abilities to open new observational windows on the Universe, create advanced forefront instrumentation, complete complex theoretical calculations, perform advanced computational modeling, undertake essential laboratory experiments and make optimum competitive use of existing and future facilities. Leadership also requires training and mentoring of students and postdoctoral fellows, suitable career progression for soft-money workers, and greater diversity throughout the workforce. *Adequate funding and access to facilities and resources for individual investigators are critically important for safeguarding the forefront research and innovation that have been hallmarks of U.S. astronomy.*

U.S. science leadership cultivates national pride, attracts some of the best and brightest individuals into the field, and provides crucial motivation to STEM education. However, in an era of constrained budgets, it is not realistic to expect that the U.S. can dominate in every single area of astronomy and astrophysics. The growing strength of Europe and Asia in astronomical research accelerates scientific progress and benefits the overall field. Due to this increased competition, U.S. astronomy must make informed decisions so as not to inadvertently cede leadership in chosen strategic areas. As an example of scientific leadership, U.S. universities and research institutes provide excellent education and employment opportunities for astronomers, and so students and researchers from other countries continue to flock here to study and work. Many of these researchers then settle here permanently and become part of the U.S. astronomy system. The health of the profession depends on maintaining this preeminence in education and employment opportunities.

In astronomy and astrophysics, leadership is generally achieved by the ability to make scientific discoveries that involve being “first” or by establishing dominance in a particular field. Such moments often arise when insight drives new investigations or when a new instrument or technology allows us to see some aspect of the Universe in a new way. The ATST and ALMA were highly ranked projects in previous astronomy and astrophysics decadal surveys. These exceptional new facilities will enable U.S. scientific breakthroughs that assure our continued scientific leadership. To optimize the U.S. scientific exploitation of ATST, ALMA, and other major facilities for both observation and theory, it will be critical to maintain a first-rate educational environment for astronomy graduate students and postdoctoral researchers, an active research-grants program, and a steady stream of talented and creative instrumentalists.

The overall health of the astronomical profession is affected by the actions of multiple Federal agencies. In total funding for individual investigators and astronomical facilities, NASA's funding for astronomical science is substantially larger than AST's – almost a factor of ten larger if NASA's entire astrophysics, planetary science, and heliophysics science divisions are taken into account. In addition, the DOE funds astronomical experiments in the Office of High Energy Physics, with a current amount about one-fifth of AST's budget. Therefore, the influence of NSF on the status of the profession is only partial. However, the actions of other government agencies to alter the health of the profession are beyond the scope of this report, and we will focus on AST's contributions to the health of the field.

The following sections highlight the various areas that are vital to the health of the profession and outline the critical capabilities that are required to keep these areas strong so that U.S. astronomers can remain at the forefront of astronomical research. Challenges to each area are also listed within each section and highlighted in italicized lettering. The finalized capabilities for the health of the profession are then denoted with a letter code beginning with "HP." A summary is given in Table 6.1. No ranking should be assumed by the order of the capabilities.

6.2 Access to Facilities and Resources

Much of modern astronomy requires facilities that are largely beyond the capacity of single institutions to provide. A goal of publicly funded astronomical research is to give as broad and diverse a set of researchers as possible access to state-of-the-art facilities and resources in order to provide the rapid realization of new ideas. This goal serves the National Science Foundation's two review criteria: Intellectual Merit and Broader Impacts. In the U.S., determination of Intellectual Merit is accomplished primarily via peer review. The most essential capabilities are those that cannot be easily provided on a small scale. Broad access to such resources benefits the professional development of astronomers at all levels, from undergraduate students to highly experienced researchers. Such access also increases the diversity of the field by allowing astronomers and students from many different backgrounds and types of institutions to participate in the scientific enterprise. This wide access promotes the criteria of Broader Impacts.

However, there are a number of challenges facing astronomers for access to facilities and resources:

Many state-of-the-art OIR facilities are privately operated. The result is that these facilities have limited access to the general research community for both the observing time and the archival data.

A large fraction of the time on world-leading RMS facilities is provided to non-U.S. scientists, without commensurate open access to non-U.S. OIR facilities. This lack of reciprocity can become an issue when funding is scarce.

Inadequate reward to scientists who devote a large portion of their time to building instruments and infrastructure for the benefit of other scientists. These types of scientists include instrument builders, astronomical software developers, planners and operators of astronomical surveys, and astronomers involved in laboratory measurement. These activities are indispensable and will become even more so as astronomy shifts towards larger and more complex projects and in particular, surveys. Such activities are not always rewarded appropriately by employers or the larger astronomical community, and by funding panels in particular.

The PRC identified five categories of resources for which access is deemed vital for the health of the profession and they are described in the following sections (they are not listed in any priority order).

6.2.1 Archival astronomical data

One of the greatest strengths of modern astronomical research is the enormous amount of archival data that is freely accessible to anyone. In the last decade, significant high-impact research has been carried out solely using data archives such as the Mikulski Archive for Space Telescopes (MAST) and the SDSS. The Virtual Astronomical Observatory (VAO) project, according to their mission statement at http://www.usvao.org/about-vao/, is focused on the "…integration of astronomy data, tools, and services on a global scale in a manner that provides easy access by individuals around the world…" This effort, although beneficial to the U.S. astronomical community, is not the same as an archive of ground-based astronomical data.

Many of the national observatories and facilities (NOAO, Gemini, NRAO, Arecibo, and NSO) have made significant efforts to save and process data taken with their telescopes*. However, the archival data coverage is uneven and does not include most of the large amount of data produced by non-federal observatories.* Use of archival data provides a very cost-effective way to achieve cutting edge scientific research, and it optimizes the scientific yield on a data set. As such, open access archival data qualifies as a critical resource for the astronomical community.

6.2.2 Telescopes, Facilities, and Laboratories

For U.S. observational astronomy to be a dynamic and creative enterprise, astronomers need to be able to compete regularly for new telescope observations. The ability to collect new data is paramount to an observational astronomer's scientific output. Large astronomical data products yield an increasing fraction of scientific discoveries, and smaller-scale observational opportunities also remain essential to science breakthroughs in the coming decade.

There is a striking difference between access to telescopes in the ground-based astronomical community and the space-based astronomical community. For most NASA missions, once the guaranteed time reserved for the project team is expended, any qualified researcher can apply for telescope time to carry out the observations they are interested in. In contrast, ground-based astronomy has a variety of access models. In the RMS component of ground-based astronomy, full merit-based access has been part of that community from the beginning of federal funding, and the UROs have provided community access as a requirement of their funding.

The OIR community in the United States has seen a mixture of open-access telescope time, provided by the federal OIR observatories, and institutionally based access, as provided by the non-federal OIR observatories. Future major OIR projects have notably different models: the LSST has a model of near complete open access, with the imaging data becoming public immediately. In contrast, open access to both proposed U.S. GSMT projects may depend upon the amount of funds provided by the NSF.

In the last decade, the Telescope System Instrumentation Program (TSIP) has enabled limited open-access to non-federal OIR observatories in exchange for funding to build new scientific instruments, or to upgrade infrastructure. There is broad consensus within the astronomical community and the PRC that the goals of the TSIP program are desirable and the results are largely beneficial. Creative solutions to promote cost-effective allocation of resources shared across federal and non-federal elements of the OIR system would benefit all stakeholders, and are especially welcome in a tight budget environment.

Current budget pressures make it highly likely that there will be a reduction in the amount of open access time to telescopes in the OIR, Solar, and RMS systems. Given that nearly 50% of OIR astronomers have access to telescopes only through the open-access system and the vast majority of RMS astronomers exclusively use federal radio telescopes, this is a critical issue for the health of our profession. The federal OIR observatories support scientists from non-federal observatories as well; in fact documentation from NOAO and the Ground-based O/IR System Roadmap Committee show that astronomers with non-federal observatory access are the largest group of users of the federal system. The AST portfolio for this decade must be designed to mitigate this loss in open-access time, and to insure that first-class facilities and instruments are available for open access into the next decade.

Access to observing opportunities need not always take the form of allocated telescope time. For example, a highly multiplexed optical spectrograph may have some optical fibers that are not being used for the primary science objectives, and could be used for unrelated science. In the radio, commensal observations are often possible with telescopes, allowing two different research groups to use the radio telescope at the same time.

In addition to observing facilities and opportunities, many astronomers participate in the field of laboratory astrophysics. Obtaining physical parameters in atomic, molecular, solid matter, nuclear, particle, and plasma physics is a crucial foundational activity that underlies the entire field of astrophysics. Historically, much of the NSF funding of this research area came from the Divisions of Physics and Chemistry. According to the White Paper by the American Astronomical Society Working Group on Laboratory Astrophysics, the interests of these two divisions have moved away from astrophysical laboratory work.

6.2.3 Astronomical Software

Astronomy has evolved into a highly complex computational discipline, and the amount of software used in astronomical research is substantial. Here we make a distinction between software that is used to reduce astronomical data to calibrated form and software that is used to analyze reduced data or is used to carry out theoretical calculations or simulations. For the former category, the data obtained are useless without high quality software to reduce it; hence open access to the tools to access and calibrate the data is also a critical resource to the science community. Observatories, instrument teams, and research groups have developed many large and complex software packages to aid in the reduction and analysis of astronomical data. Packages such as IRAF, AIPS, CASA, and SolarSoft are widely used throughout the astronomical community and have been a valuable asset to astronomers at all institutions. *However, the growing complexity of instrumentation and the declining resources of observatories pose an ongoing challenge to the development and support of public data reduction packages.*

Astronomy also has a long history of analysis and theory software that emerges from individual investigators or small research groups that becomes the "standard" package for a particular technique or sub-field. Software packages such as CLOUDY, GADGET, GALFIT, DAOPHOT, and DOPHOT are examples of codes that have been widely used and well cited. The development of such public packages is crucial for the collaborative advancement of the field. *Developing and supporting public software requires substantial effort, and metrics for rewarding it need to be improved, particularly in academia.*

6.2.4 Supercomputing Resources and Resources Dedicated to Theory

Overall, astronomy has been well served by the supercomputing networks developed by the National Science Foundation. Specifically, the Extreme Science and Engineering Digital Environment (XSEDE, formerly TeraGrid) has provided about 10% of its computing time to astronomy and astrophysics computations. However, there is no compelling reason to treat the results of a complex supercomputing calculation any differently than a large astronomical survey. Eventually, both should be public, after a reasonable proprietary period. Many results of complex supercomputing calculations can be used for other scientific projects not envisioned by the original users. For example, the Millennium series of N-body simulations have enabled many theoretical and observational projects.

In addition to large-scale computational work, a large amount of theoretical work is supported by AST. This work on fundamental astrophysics and its relation to observational results is essential to the field. *Adequate support of theoretical research can be overlooked because the dominant costs are for people rather than facilities or hardware.* These fields depend heavily on the small-grants programs.

6.2.5 Grants Funding

Research grants are at the heart of the scientific enterprise, and because they are usually decoupled from the application for telescope time, robust grants funding is essential in any portfolio that seeks to support broad, merit-based access to astronomical resources. *Without sufficient grants funding, access to the other resources would be rendered moot. Access to this capability is thus critical to the astronomical profession.* The issue of small-grants funding is discussed in Chapter 7 and the funding enabled by the proposed mid-scale program will be discussed in Chapter 8.

6.2.6 Critical Capabilities for Access to Facilities and Resources

HP-A: The ability to compete regularly for access to telescopes, instruments, and observing opportunities to carry out innovative astronomical research.

HP-B: Cost-effective allocation and sharing of resources through federal and non-federal elements of the OIR and RMS systems.

HP-C: Access to surveys and archival astronomical data, reduced to a usable form, after a reasonable proprietary period.

HP-D: Access to the software necessary for basic reductions of astronomical data and the generation of catalogs in the case of surveys.

HP-E: The ability to regularly compete for access to world-leading computational facilities to carry out innovative numerical simulations and calculations.

HP-F: The ability to complete innovative theoretical calculations, including pure theory and phenomenology.

HP-G: The ability to carry out innovative experiments in laboratory astrophysics.

HP-H: The funding support for both scientific groups and individual investigators to engage in creative and innovative astronomical research.

6.3 Instrumentation

Innovation in astronomical instrumentation is essential for opening new avenues of discovery as well as enhancing existing ones. The U.S. astronomical community must maintain the ability to design, develop and build the advanced instrumentation that is necessary to pursue forefront research. Doing so requires well-equipped facilities and highly trained and creative scientists interested in instrumentation. Opportunities for funding at many scales, from technology development to instrument fabrication supports the objective of maintaining a healthy instrumentation community while enabling compelling scientific opportunities. Advancing the state of the art in fundamental technologies is central to progress in the field. Technological advances enable the design, construction and exploitation, via sophisticated innovative instrumentation, of the largest aperture telescopes. Research in instrumentation-associated technology (e.g., new optical coatings and materials, optical and IR detectors and gratings) has been limited in the astronomical community, which tends to rely on industry or the military. The needs of astronomers are often very specialized, and the astronomy market is too small for most industrial concerns. For example, there are extremely few places in the world where one can purchase astronomy-grade CCD or IR detectors, and OIR astronomers have been constrained by what industry is able or willing to provide. RMS instrumentation does not rely on industry as heavily but requires well-funded instrument groups to advance the field (e.g., wideband feed horn development or large submillimeter continuum arrays). Technology development for the sake of long-term advancement of the field not tied to a specific instrument (i.e., "blue sky" instrumentation) is an essential aspect of a healthy instrumentation program.

The U.S. astronomy community faces a number of challenges in maintaining its world-class instrumentation capabilities:

Complex astronomical instrumentation can be very expensive and building instrumentation often involves detailed management. Excellent focal-plane instrumentation is crucial for the most effective operation of any telescope. Designing and building the best instrumentation has become increasingly complex and expensive, and the challenge (and cost) increases with telescope size. Affording the very expensive instruments will be an enormous challenge. Next-generation AO systems with cost estimates of $50M, and focal-plane instruments that cost $25M or more are part of the landscape of extremely large OIR telescopes. In addition, future RMS filled-aperture telescopes will be coupled with large-format cameras and/or spectrometers, while interferometers will have large numbers of elements (thousands or more). The single-dish instrumentation for large apertures can cost as much as $10-20M. For all such applications highly sophisticated digital electronics will need to be developed along with exquisitely sensitive detectors, which are likely to be expensive. Due to the large cost and the longer times for development, management of instrumentation projects has become a major challenge.

A wide diversity of instrumentation groups may not be able to remain active and engaged under an increasingly tight budget. Large instrumentation projects require large and complex instrumentation fabrication facilities and large teams with diverse talents that have continuity, requiring appropriate funding over long timescales. In the past, when smaller instrumentation projects were the norm, maintaining first-rate instrumentation, and thus training, capabilities was possible for a number of non-federal observatories and universities. As instruments inevitably become larger in scale it will become more challenging to sustain these instrumentation programs, particularly ones of more modest scope. Capabilities and accumulated instrumentation wisdom and prowess are in danger. The *NWNH* white paper by Elias *et al.* states the importance of having a broad range of instrumentation opportunities throughout the entire OIR system. In the RMS community, much of the instrumentation work takes place at the NRAO Coordinated Development Lab as well as at individual facility sites (NRAO-Socorro, NRAO-Green Bank). Radio instrumentation groups at universities also have long made important advances in instrumentation and it is important for the health of the community to have instrumentation groups working outside of national observatories. As with the OIR community, funding for programs like the University Radio Observatories has been declining and it is unclear that such programs can be supported going forward. The *NWNH* white paper by O'Neil underlines the importance of university/NRAO cooperation in radio instrumentation.

It will be difficult to attract and retain the next generation of instrument builders. Highly effective new instrumentation for astronomy requires highly creative people knowledgeable about both forefront astronomical research and advanced technology. They must both be attracted to the endeavor and then suitably trained. Recruitment of instrumentally inclined and capable students to graduate programs can be difficult. *NWNH* stated: "…the opportunities for training students in instrumentation have declined precipitously over the past 20 years. Training for the next generation of instrumentalists is most efficient when there is a steady-state hierarchy of project sizes, so that people can progress from relatively smaller, simpler, and faster projects to responsibilities in larger and more complex activities…" (p. 149) Instrumentally talented students sometimes seek other, often more lucrative, professions, or, if they apply to an astronomy program, can rank lower in the admissions process than those with a strong astrophysics emphasis. Furthermore, there are fewer opportunities for students to get trained in instrumentation at national facilities.

6.3.1 Critical Capabilities for Instrumentation

HP-I: The ability to design, develop and build instrumentation that is necessary to pursue forefront astronomical research.

HP-J: Grants opportunities at small, medium and large scales to encourage the continuity, longevity, and advancement of existing instrumentation groups (including continuity of soft-money technical staff) and support the development of new instrumentation groups.

HP-K: The ability to pursue research on innovative "blue-sky instrumentation" to make important advances on technological fronts.

HP-L: The ability to afford and construct the most complex instruments that the next generation of large telescopes across the electromagnetic spectrum will require.

6.4 Career support and progression

Astronomical facilities and programs depend absolutely on the dedicated efforts of people at all career levels. Traditionally, most astronomers progress through a number of stages in a scientific career: undergraduate education, graduate education, postdoctoral training, and eventually professional long-term employment, which include faculty positions, research positions, and research support positions. However, a significant number enter the astronomical workforce through non-traditional paths, such as engineering, computer science, and education, and make major contributions to the field.

NSF/AST provides funding for astronomers throughout the career path. Undergraduate students involved in astronomical research are often funded through the REU program and the Astronomy and AAG program. Graduate students' work in astronomical research can be funded by NSF Graduate Research Fellowships program (GRF) and through the AAG program. Postdoctoral fellows can be funded directly through the AAPF program and the AAG program. Additionally, NSF astronomical facilities have their own postdoctoral fellowship programs, such as the Jansky Fellowship Program (NRAO) and the Leo Goldberg Fellowship (NOAO). Many professional astronomers are in positions where the bulk of their salaries come from time-limited grants rather than a permanent funding stream. These astronomers, referred to as soft-money astronomers, can be funded through the AAG program. The AAG program also funds summer salary for faculty; junior faculty also have the option of proposing to the CAREER program for summer salary support. A large number of professional astronomers are employed through the national facilities, which provide observing support and long-term stewardship of the OIR and RMS systems. Astronomers who are involved with the development and construction of state-of-the art instrumentation can be funded through the ATI program. There are also numerous NSF programs that fund some astronomers.

Each stage of the career path provides opportunities for astronomical research and each stage is vital to the health of the profession. Undergraduate and graduate students are the astronomers of the future – *NWNH* reported that about 13% of all AAS members are junior, and the number of junior members has increased roughly twice as fast as full members. Postdoctoral fellows and soft-money researchers are exceptionally valuable to the astronomical community, performing many critical tasks that would be difficult for students or people in permanent positions to accomplish. Postdoctoral positions are a critical training opportunity for future independent researchers. Astronomers in permanent positions have the capability to undertake longer-term research projects more easily than students or postdoctoral fellows and have the long-term job security that makes it more feasible to lead collaborations of scientists to complete large scientific projects.

There are significant opportunities and challenges throughout the entire astronomy career cycle. In the undergraduate and graduate stages, training the next generation of astronomers is fundamental to the health of the profession. Today, students can study and be mentored at a larger number of diverse institutions than ever before. Students have relatively easy access to high-performance computing, through campus clusters or state and national supercomputing centers. Students can conceive, propose, and carry out publishable and dissertation-scale projects using national facilities and/or a variety of archival datasets.

However, *NWNH* recognized two major challenges to the current student training model:

Academic mentors often have a narrow focus on academic careers. Academic mentors often fail to make their students aware of non-academic career opportunities.

A majority of the students who are trained to be astronomers will require additional education and training not commonly provided in astronomy Ph.D. programs, regardless of their final career path. NWNH stated: "Professional training should accommodate the career paths taken by graduate and postdoctoral alumni, giving attention to: (1) the full range of activities in academic faculty work, including teaching, advising, and performing institutional and national service; (2) the non-research skills needed by all researchers, including communicating to the non-specialist and public at large, writing and administering grants, and project management; (3) necessary high-level training in communication and in the increasingly important areas of computation and instrumentation; and (4) career options both within and outside academia." (p. 125)

For postdoctoral fellows, there is a broad range of experiences and concerns. The number of astronomy postdoctoral fellows has increased dramatically over the last decade, by about a factor of two (Figure 4.13, *NWNH*). Most postdoctoral fellows who are NSF funded are supported through AAG grants from principal investigators (PIs). The NSF requires a mentoring plan for postdocs on PI-led grants, which is aimed at providing some accountability from the PI and some structure for the postdoctoral fellow. A significant number of postdoctoral fellows are "prize postdocs" allowing the awardee to undertake completely independent research, but having no formal mentoring requirement. The overall situation of postdoctoral fellows in astronomy and throughout STEM is dynamic and still not fully understood: the National Research Council is currently preparing a study entitled *The State of the Postdoctoral Experience for Scientists and Engineers Revisited* to investigate these issues. Within astronomy, there are aspects of the postdoctoral situation that are unhealthy and unstable. Current challenges to the postdoctoral experience include:

Many postdocs find it difficult to obtain a permanent position. There are not enough permanent positions or long-term positions to absorb the flow of scientists through the graduate school and postdoctoral pipeline. This has the potential of leaving individuals stranded after two or more postdoctoral positions. Furthermore, the volatility of temporary positions means that the individuals in the postdoctoral phase inevitably bear a disproportionate fraction of budget reductions.

Postdocs have limited time for professional development. Postdoctoral fellows often have a limited time to obtain the necessary skills and research results required to be competitive for many permanent or long-term positions. Small disruptions in their research productivity can have a substantial negative impact on their long-term career prospects.

Frequent relocation does not lead to family-friendly environments. The *Women in Astronomy and Space Science 2009* conference and several *NWNH* white papers stated that the frequent relocation generally required of postdocs does not lead to family-friendly environments and note this as a major source of attrition for female astronomers.

There is a persistent mismatch between the production rate of Ph.D.s and the number of tenure-track faculty or long-term astronomy positions. *NWNH* estimated the surplus to be at least a factor of three. Therefore, many astronomers are forced to accept soft-money positions to continue their career in astronomy. Soft-money astronomers perform many of the critical infrastructure tasks such as instrumentation development, software development, survey planning, and calibration that all other astronomers rely on. In practice, there are many types of soft-money astronomers, and their work environments are extremely varied. Some soft-money astronomers align themselves with non-profit research and education organizations that administer grants that the soft-money astronomer is awarded. Other soft-money astronomers work within universities as research faculty and observatories as research astronomers, but raise their entire salary through grants. Still others are hired by other astronomers to complete a specific portion of a scientific project. There are a number of challenges regarding soft-money astronomers in addition to those faced by postdoctoral fellows:

Employment benefits for soft-money positions are not always included with salary. Although temporary or soft-money positions supply salary, they often do not supply employment and retirement benefits equivalent to long-term positions.

Soft-money astronomers may frequently be caught in the "two-body problem." Many astronomers have difficulty obtaining employment in the same region as their partner. This issue, known as the "two-body problem," leads many astronomers to take soft-money positions. In addition, the flexibility of temporary positions means that they inevitably bear a disproportionate fraction of budget reductions.

Soft-money astronomers may feel the lack of professional respect. Soft-money astronomers often face the perception that because they do not have a long-term position they must be second-rate. As Cardelli (1994) stated: "…There is a general consensus among soft money astronomers that they are often perceived as lesser quality and importance than their faculty counterparts…" There is no evidence that this has changed in recent years, despite the steadily increasing fraction of astronomers in soft-money positions.

6.4.1 Critical Capabilities for Career support and progression

HP-M: Opportunities to participate in creative and innovative research at all stages of a career, including undergraduate and graduate education, postdoctoral fellows, soft-money science positions, research positions, and tenure-track faculty.

HP-N: The ability to receive training and mentoring to prepare for differing astronomical specialties, including education, instrumentation, theory, laboratory work, data-mining, and computation. The ability to receive advanced training in non-research skills such as communication and management needed for scientific activities.

HP-O: Opportunities to progress through different stages of a scientific career and to have a long-term career in astronomy.

HP-P: Opportunities to contribute to stewardship activities that benefit the entire community, including, but not limited to, software development, instrumentation development, educational materials, lab measurement, and calibration activities.

6.5 Diversity of the Workforce

Diversity in the astronomical workforce is in the best interest of the health of the profession and society as a whole. As *NWNH* stated, lack of diversity leads to squandering valuable human resources, and sends a negative message to young people that careers in science and engineering are not for them. *NWNH* states: "improving the involvement of minority Americans and women is a matter of the highest priority." (p. 30)

The challenges in this area are well documented and represent a substantial blemish on our profession:

The U.S. astronomical workforce continues to suffer from low rates of participation by women, ethnic minorities, and first-generation college students. NWNH stated that African Americans, Hispanic Americans, and Native Americans are underrepresented by factors of at least six relative to their fraction of the U.S. population. Women are underrepresented in astronomy by factors of 1.5 in graduate school, and by factors of at least four in senior positions.

This underrepresentation of minorities is substantial and persistent. While there has been significant progress in increasing the participation of women at all career levels, but particularly at the undergraduate and graduate levels, the lack of progress on minority recruitment and retention at any level suggests that additional innovations and resources are required to make progress.

6.5.1 Critical Capabilities for Increasing Diversity

HP-Q: Opportunities for all those interested and capable of doing astronomical work to do so.

HP-R: New groundbreaking programs to significantly increase the involvement and numbers of underrepresented minorities in the field.

6.6 Astronomy Education and Public Outreach

Astronomy has an impact far beyond its scientific discoveries. *NWNH* noted that "Astronomy stirs the public imagination and the human spirit," and astronomers have a long history of EPO to K-12 students, non-science college students, and the general public. Many astronomers at all career levels devote a significant portion of their time to EPO activities. It is estimated that over 250,000 students take introductory astronomy courses at colleges and universities and many of these students are taught by professional astronomers. Astronomers often work with K-12 schools, museums and planetariums to present astronomical discoveries to the public. Professional astronomers are often interviewed on national television and there are many television programs that focus on astronomy. An exciting recent innovation of astronomy EPO is "citizen science" projects, which take advantage of the digital nature of astronomical data and the World Wide Web to enable non-scientists to participate in astronomy. Programs such as Galaxy Zoo, Planet Hunters, and Moon Mappers attract thousands of people who contribute to scientific projects and gain a larger appreciation of astronomy. These EPO activities not only benefit astronomy, but the larger cause of STEM education.

AST provides funding for EPO through the Broader-Impact criterion that is a requirement of all NSF grants, and many astronomers undertake creative outreach efforts with K-12 students, non-science college students, and the general public. In particular, the AAPF program and the NSF-wide CAREER program have an expectation for educational activities that often take the form of EPO activities. In addition to EPO undertaken by small groups of scientists, many of the federal and non-federal observatories have visitor centers open to the general public. Many of these visitor centers host tens of thousands of visitors per year and provide astronomical outreach to people of all ages, but have a particular impact on adult citizens interested in life-long learning.

Some challenges in this area include:

The difficulty in obtaining continuous EPO funding. Many outreach activities are long-term in nature. Yet, after the first successful funding cycle it can become substantially more difficult to find funding to continue a successful EPO project.

The need for continued improvement in EPO program evaluation and dissemination. For an EPO activity to be broadly useful, it must first be evaluated professionally for its educational impact. The lessons learned from undertaking the activity must then be broadcast to the larger EPO community. Both of these require resources. The astronomy EPO community has increased its overall professionalism dramatically in the past decade, leading to better evaluation and dissemination, but more work in these areas is needed to maximize the educational impact of EPO activities.

6.6.1 Critical Capabilities for Education and Public Outreach

HP-S: The ability to deliver effective and innovative astronomy education and outreach programs to K-12 students, college students, and the general public through activities at small and large scales.

6.7 Summary of the Critical Capabilities for Health of the Profession

Having reviewed the broad areas related to the health of the profession and identifying challenges, we summarize the critical capabilities for the health of the profession below. As in Chapter 5, these critical capabilities are given a letter code for reference, but with the prefix “HP”. No ranking should be attributed to the order of the critical capabilities.

Table 6.1: A summary of all of the critical capabilities for the health of the profession. The lettering is for identification only; no ranking of these capabilities is implied.

Health of the Profession Capabilities	
HP-A	The ability to compete regularly for access to telescopes, instruments, and observing opportunities to carry out innovative astronomical research.
HP-B	Cost-effective allocation and sharing of resources through the federal and non-federal elements of the OIR and RMS systems.
HP-C	Access to surveys and archival astronomical data, reduced to a usable form, after a reasonable proprietary period.
HP-D	Access to the software necessary for basic reductions of astronomical data and the generation of catalogs in the case of surveys.
HP-E	The ability to regularly compete for access to world-leading computational facilities to carry out innovative numerical simulations and calculations.
HP-F	The ability to complete innovative theoretical calculations, including pure theory and phenomenology.
HP-G	The ability to carry out innovative experiments in laboratory astrophysics.
HP-H	The funding support for both scientific groups and individual investigators to engage in creative and innovative astronomical research.
HP-I	The ability to design, develop and build instrumentation that is necessary to pursue forefront astronomical research.
HP-J	Grants opportunities at small, medium and large scales to encourage the continuity, longevity, and advancement of existing instrumentation groups (including continuity of soft-money technical staff) and support the development of new instrumentation groups.
HP-K	The ability to pursue research on innovative "blue-sky instrumentation" to make important advances on technological fronts.
HP-L	The ability to afford and construct the most complex instruments that the next generation of large telescopes across the electromagnetic spectrum will require.
HP-M	Opportunities to participate in creative and innovative research at all stages of a career, including undergraduate and graduate education, postdoctoral fellows, soft-money science positions, research positions, and tenure-track faculty.
HP-N	The ability to receive training and mentoring to prepare for differing astronomical specialties, including education, instrumentation, theory, laboratory work, data-mining, and computation. The ability to receive advanced training in non-research skills such as communication and

	management needed for scientific activities.
HP-O	Opportunities to progress through different stages of a scientific career and to have a long-term career in astronomy.
HP-P	Opportunities to contribute to stewardship activities that benefit the entire community, including, but not limited to: software development, instrument development, educational materials, lab measurement, and calibration activities.
HP-Q	Opportunities for all those interested and capable of doing astronomical work to do so.
HP-R	New groundbreaking programs to significantly increase the involvement and numbers of underrepresented minorities in the field.
HP-S	The ability to deliver effective and innovative astronomy education and outreach programs to K-12 students, college students, and the general public through activities at small and large scales.

7 Small-Grants Programs

Having developed lists of critical technical and health of the profession capabilities, we now consider how the AST portfolio can be balanced, starting with the small-grants programs. Many astronomers, whether they are students, senior staff, or postdoctoral researchers, are supported by AST individual-investigator research grants. These grants programs thereby sustain the entire field. Grant support of observational and theoretical work is essential for any of the science goals of Chapter 5 to be successfully addressed; all of the technical capabilities **TC-A** through **TC-Y** depend on the individual investigator programs to translate the technical facility or the capability into cutting-edge research. The small-grants programs are also the most flexible and rapid way to develop new ideas and respond to new scientific opportunities; along with telescope time allocation, this is the primary way that peer review steers the scientific enterprise. Similarly, grants undergird all of the health-of-the-profession capabilities (**HP-A** through **HP-S**). From providing the capacity needed to train the next generation of astronomers, to developing the newest generation of instruments, theories, and observations, to broadly engaging the public, the grants programs are essential in delivering the critical capabilities outlined in Chapter 5. NSF plays a unique role in supporting astronomy research; while NASA supports many astronomers through research grants, they are mostly mission-driven and cannot provide funding for the full diversity of new opportunities and ideas.

During the past decade, and despite doubled funding, increasing proposal pressure saw the overall AAG proposal success rate fall below 20%. This pressure is likely to grow. *NWNH* articulates clearly and unequivocally the need to increase support to the small-grants programs in order to propel astronomy forward. *NWNH* states that "In the committee's judgment, it is absolutely necessary for the health of the whole astronomy and astrophysics enterprise to increase the support of individual investigators: those who write the papers, who train the students and other junior researchers, and who in the end produce the results to drive the field forward and ignite the public's imagination. Reallocation of resources may have to come at the expense of support of existing missions/facilities and new projects." (p. 134)

As in Chapter 3, we define small-grants programs as the set of peer-reviewed programs that support small research projects without scientific restrictions. Currently, individual investigators are supported primarily through the AAG and ATI programs. During the three-year period FY10-12, these were funded at an average of \$47M and \$10.5M respectively, so represent 20% and 4.4% of the AST portfolio. AAG awards offer the most flexible means of addressing *NWNH* goals in all sub-fields of astronomy, while ATI focuses on the development and construction of state-of-the-art detectors and instruments. AST additionally provides other small grants averaging \$15M in FY10-12, or 6.4% of the portfolio. Some of these programs are specific to AST, such as support for young investigators provided through the

AAPF program or support for career development of underrepresented minorities provided through the PAARE program. High over-subscription rates for these programs and the stringent peer review of proposals make for efficient delivery of the best science. AST also supports a set of smaller programs that are agency-wide. These grants encourage workforce development (CAREER, ADVANCE), fund cyberinformatics (CDI and others), and further other targeted goals of the NSF.

7.1 Research Grants

NWNH recommended an increase of $8M (FY10) per year for AAG (bringing it to $54M per year) and of $5M (FY10) per year for ATI (bringing it to $15M per year). It also recommended that AST create a new small-grants program, "Theory and Computation Networks," to be supported at the $2.5M per year level.

Conclusion: **The Astronomy & Astrophysics Research Grants (AAG) and Advanced Technologies & Instrumentation (ATI) programs remain top priorities within the AST portfolio and should be aggressively funded.**

ATI should remain focused on novel instrumentation, blue skies research, and small upgrades and instruments. The funding level for individual programs should be below about $2M; larger-scale programs should be competed under the Mid-Scale program described in Chapter 8 (some would also be appropriate for support under the Foundation-wide Major Research Instrumentation [MRI] program). The AAG aspect of the recommendation enhances a core capability that safeguards the health of the profession (particularly **HP-H** but also **HP-M**, **HP-N**, and **HP-O**) and the ATI aspect impacts a number of capabilities relating to the technical vitality of the profession (**HP-I**, **HP-J**, **HP-K**, **HP-L**).

Recommendation 7.1: **We recommend adding a "Theory and Computation Networks" program to the small-grants portfolio at a funding level of at least $1M/year.**

Theoretical and computational work remains a core component of astronomical research. Our committee ranks high-performance computing as a critical component of all four of the science themes. Much of this work will be supported through the AAG program; however, *NWNH* also recommended a new program of Theory and Computation Networks (TCN) to fund coordinated longer-term research. We prioritize the TCN below the AAG and ATI program, and in the more restricted funding environment than *NWNH*, such networks would necessarily be modest. Larger programs, of fixed duration, are candidates for support under the Mid-Scale program (Chapter 8). Given the pivotal role of theory and computation in all high priority science areas of *NWNH*, the enhancement of support for this activity affects the health of the profession via critical capabilities **HP-E**, **HP-F**, and **HP-H**.

While laboratory astrophysics also has broad reach (**HP-G**), we do not recommend a dedicated funding opportunity, but rather continued reliance on AAG and ATI. Larger scale efforts in this area would also be eligible for mid-scale support (Chapter 8).

7.2 Student and Postdoctoral Training

Management of the grants programs is also the primary way in which the NSF can impact the training of students and postdoctoral fellows.

***Recommendation 7.2:* We recommend that the NSF and AST continue to support the Research Experiences for Undergraduates (REU) program, both through site awards and REU supplements to AAG awards.**

Astronomy remains well suited to connect undergraduates to cutting-edge research projects. This capability is crucial for recruiting the best talent of the next generation into the field. Undergraduate research happens in many venues, often without federal support, but REU programs have been particularly successful.

With modest growth in REU support, applications could be solicited from universities or observatories to provide specialized training in computation, instrumentation, and other areas where growth is needed. This recommendation contributes to the diversity of training and career paths and so impact the health of the profession in several aspects (**HP-M**, **HP-N**). REU programs also are a method for increasing the participation of underrepresented groups (supporting **HP-Q** and **HP-R**)

***Recommendation 7.3*: The Astronomy and Astrophysics Postdoctoral Fellowships (AAPF) program should be continued.**

AAPF's intent is to recognize early-career investigators of significant potential and to provide them with experience in research and education that will establish them in positions of distinction in the community. The legacy of this fellowship has been to encourage and advance leaders in the field who are passionate about their research and about sharing that passion with students and the public. Compared to other national prize postdoctoral programs, the AAPF program is sufficiently unique to be preserved in all budget situations. The AAPF program impacts the health of the profession by providing critical capabilities **HP-N**, **HP-O**, and **HP-S**.

***Recommendation 7.4*: We recommend that the national observatory prize fellowships be combined into a single program that would fund postdoctoral fellows with strong research ties to one or more of the AST-funded observatories: NRAO/ALMA, NOAO, Gemini, NSO, and Arecibo.**

The goal of this recommendation is to create more uniformity of purpose and funding for this important component of professional development. A possible implementation would be for the selection committee to be drawn from the science staffs of the observatories, or community appointments made by the observatories. Funding for the selected individuals could be via the observatories, and some amount of observatory residency for the recipients would be expected. The names of the resulting positions might vary with the host observatory, so as to preserve the historical associations.

We will refer to this program as the AST Observatories Postdoctoral Fellowship program in this report. We recommend 5 to 7 positions per year and have budgeted $1.5M in budget scenario B and $2.0M in budget scenario A. By supporting fellows with strong ties to the national observatories, the AST Observatories Postdoctoral Fellowship program would impact the health of the profession by enhancing capabilities **HP-M**, **HP-N**, **HP-O**, and **HP-P**.

7.3 Workforce Diversity

Demographic studies show that the U.S. astronomical workforce continues to suffer from low rates of participation by women, ethnic minorities, and first-generation college students relative to the population at large and to some other fields of science. *NWNH* recommends that "…Agencies, astronomy departments, and the community as a whole need to refocus their efforts on attracting members of underrepresented minorities to the field…" (p. 30).

***Recommendation 7.5:* AST should broaden and sustain or increase funding for the Partnerships in Astronomy & Astrophysics Research and Education (PAARE) program: (1) to allow proposals to be led by any institution that can present a compelling plan for increasing minority participation, with strong preference for minority-serving institutions (MSIs), and (2) to develop a mechanism for funding small grants for exploratory projects that initiate programs between MSIs, community colleges, and other research institutions.**

PAARE successfully promotes partnerships of community colleges and MSIs with research universities, national centers, and laboratories. Increased funding beyond present levels would only be warranted by corresponding pressure from high quality proposals. These changes would increase the opportunities for initiating new programs. Continuing and broadening the PAARE program benefits the profession via critical capabilities **HP-Q** and **HP-R**.

***Recommendation 7.6:* AST should increase funding by $1M/year for grants programs or projects that directly seek to improve recruitment and retention of underrepresented minorities in astrophysics.**

This would increase the community's ability to propose creative responses, beyond PAARE-style partnerships, to address the underrepresentation of minorities in the field. Given persistent and substantial problem of equal opportunity and participation in astronomy, the critical capabilities **HP-Q** and **HP-R** are directly addressed by this recommendation.

8 Mid-Scale Projects and Strategic Investments

NWNH named a vigorous "mid-scale innovations" program (MSIP) as a high priority for large ground-based initiatives, ranking it behind only the LSST. In particular: "A major recommendation of this report, directed to both the ground and the space programs, is that more support should be directed toward activities of intermediate scale… Medium-scale programs and experiments offer excellent return for the investment and are essential to the capability for responding flexibly to new scientific opportunities, for demonstrating novel techniques and instruments, and for training the experimental scientists, engineers, and managers who will execute the major missions and observatories of tomorrow." (p. 148). There is a large monetary gap between traditional AAG, ATI, or MRI awards and major construction and operations funding, but important, innovative, and revolutionary research and development projects require funding in this gap. Mid-scale projects (broadly defined) offer superb opportunities to address the full spectrum of *NWNH* science goals, encourage innovation, and respond to new technical capabilities and science opportunities, while maintaining "free energy" in a constrained budget environment. Mid-scale projects often produce world-leading science and generate the ideas and development for future large projects. Some recent examples of projects enabled by mid-scale AST funding are listed below; some of these were funded through dedicated lines with separate solicitations, while others were unsolicited "mid-scale" proposals:

- The **Sloan Digital Sky Survey (SDSS)** and its successor projects, which are perhaps the most scientifically productive astronomy project of the past 15 years.
- The **University Radio Observatories (URO)** program, which helped to pioneer the development of submillimeter interferometry and other RMS technologies.
- The **Atacama Cosmology Telescope (ACT)**, and its impending polarization-sensitive successor ACTPol, which are designed to measure small-scale CMB fluctuations and the Sunyaev-Zeldovich effect in galaxy clusters.
- The **Telescope System Instrumentation Program (TSIP)**, which funded the development of 10-12 advanced instruments on private OIR telescopes and opened >400 nights of large telescope time to public access.
- Development funds for the **Large Synoptic Survey Telescope (LSST**, a dedicated wide-field optical imaging facility. The high level of preparedness of LSST contributed to it being the highest priority large ground-based activity in *NWNH*.

- **Precision Array for Probing the Epoch of Reionization (PAPER)**, aimed at constructing arrays to detect highly redshifted 21 cm neutral hydrogan emission.
- The **Dark Energy Survey (DES)**, which is turning NOAO's Blanco 4-meter telescope into the world's most powerful imager in optical wavelengths and will spend the next five years surveying 1/8 of the sky several magnitudes deeper than SDSS.

Looking to the critical technical capabilities from Chapter 5, we see plausible implementations as mid-scale projects for the majority of them, including at least **TC-A TC-F, TC-H, TC-K, TC-L, TC-N, TC-O, TC-P, TC-Q, TC-R, TC-S, TC-T, TC-U, TC-V, TC-W, TC-X,** and **TC-Y**. This is not surprising, as virtually any state-of-the-art instrument for a large telescope or telescope array will fall in this price range. Furthermore, projects that unite large collaborations of scientists, such as large surveys and key projects, similarly fall into this scale.

NWNH framed this category to span costs from a few million dollars to over $100M, bracketing everything from upgrades for existing instruments to major new facilities, with substantial design and development (D&D), construction, and operating costs. The past five years have seen roughly $30-40M per year spent on (broadly defined) mid-scale activities, adding up to 13-17% of the AST portfolio. Typical amounts for the largest components are URO ($9M), NOAO/Gemini/NRAO instrumentation ($8M), mid-scale projects ($7M), and varying amounts of up to $5M per year each for D&D related to large projects such as CCAT, LSST, and GSMT.

Unfortunately, AST spending on mid-scale projects has been dropping, as the budget for many major facilities has expanded and the relative flexibility of the mid-scale program has been exploited to keep the budget balanced. We emphasize that *strategic investment in mid-scale projects is an essential component in a plan to maintain the long-term health of U.S. astronomical capabilities.* We therefore offer recommendations below to configure and sustain a vigorous mid-scale program even if this requires painful decisions elsewhere in the portfolio. NWNH was unequivocal that this item should get increased investment: "…the committee recommends the establishment of a formally competed mid-scale instrumentation and facilities line within NSF/AST with additional funding beyond that currently being provided." (p. 153). This is a forward-looking and scientifically productive strategy for many reasons:

- The mid-scale program will fund instrumentation upgrades for existing AST facilities, keeping them able to provide cutting-edge capabilities for *NWNH* science goals. Several of the existing facilities will struggle to remain competitive by 2020 without ongoing instrumentation upgrades.
- A mid-scale "Open Access Capabilities" program would generalize TSIP as a means of improving the capabilities available to the general astronomical community while enabling new instrumental capabilities on non-AST facilities.
- New mid-scale experiments with fixed-duration lifetimes (such as ACT and PAPER) and surveys (such as DES and SDSS) are highly effective

paths to new science initiatives in this decade. Mid-scale projects can be more nimble and responsive than large projects. Since LSST will not be operational before 2020, it is very likely that there will be no new large NSF nighttime OIR astronomy facilities in the remainder of this decade, during which time new capabilities can come from mid-scale projects.

- Mid-scale projects could include other coordinated efforts, such as a large laboratory astrophysics project. This would impact capability **HP-G**.
- Mid-scale projects are the development and proving grounds for new technologies and techniques for astronomy. Research and development at the UROs reduced much of the risk for (and enhanced the science case for) ALMA, and there would be no viable LSST proposal without the development of mosaic CCD cameras on smaller telescopes. Mid-scale projects will help generate the ideas for the exciting new large projects to be ranked at the next Decadal Survey.
- Mid-scale projects are essential for the health of the profession. The Open Access component (described below) directly impacts critical health-of-the-profession capabilities **HP-A, HP-B,** and **HP-C**; while mid-scale projects in theory would impact **HP-E** and **HP-F**. Furthermore, they are the often the community's primary training ground for instrumentalists. Without mid-scale instrumentation opportunities, the pool of skilled astronomical instrumentalists with project experience may shrink in the U.S., potentially leaving insufficient talent to design and build the future large facilities. This aspect of the mid-scale program impacts critical instrumentation capabilities, particularly **HP-J** and **HP-L**.

NWNH strongly supported a commitment to the MSIP concept: "The principal rationale for the committee's ranking of the Mid-Scale Innovations Program is the compelling number of highly promising projects with costs between the MRI and MREFC boundaries, plus the diversity and timeliness of the science they could achieve." (p. 227).

Recommendation 8.1: **Funding of projects beyond the scale of the AAG and ATI programs, but below the major facilities scale, should be provided through a Mid-scale Innovations Program (MSIP) and a Strategic Investments Program (SIP).**

The key difference between these two programs is the duration of the funding commitment. The committee sees a substantial difference between project investments that can be freely re-competed every five years as compared to longer-term commitments. The MSIP should remain flexible, while the SIP should fund activities aimed at providing major new capabilities for the AST portfolio. This division is illustrated in Figure 8.1.

Examples of SIP-style projects include the construction and operations agreements for WIYN and SOAR, which span nearly 20 years. Other examples include design and development funding for MREFC candidates such as ATST or

LSST, where the funding of a short-term grants is clearly inspired by the interest of the NSF in the long-term project, or a long-term data archive.

We believe that it is important to separate these two funding classes, so that the amount of money available for frequent re-competition can be monitored. Such funding provides several critical capabilities for the health of the profession, including the ability to build complex instrumentation (**HP-I,HP-J, HP-K, and HP-L**), the ability to fund research groups for innovative research (**HP-H**), and the ability to facilitate technical and scientific career progression through major projects (**HP-J** and **HP-M**). We note that the examples listed from *NWNH* for its mid-scale line have cases from both classes. Of course, a given project might be able to adjust which program it applies to, e.g., by adjusting how its long-term operations would be funded.

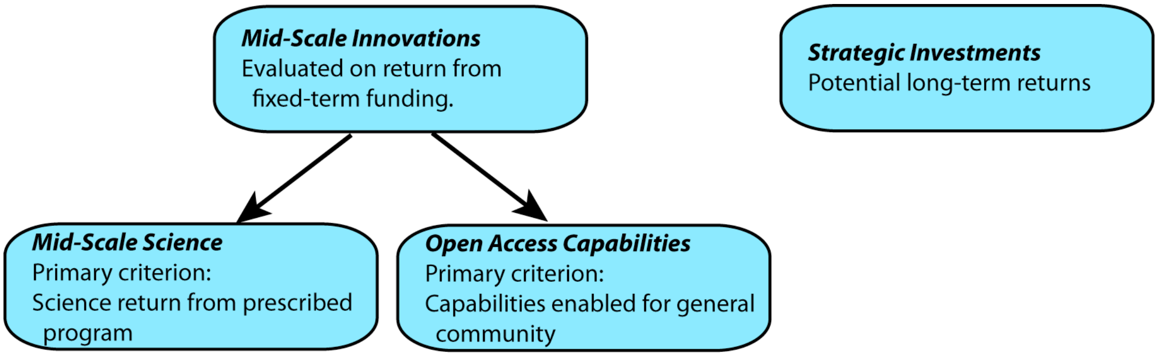

Figure 8.1: Recommended structure of mid-scale AST programs.

Recommendation 8.2: **All MSIP projects should be competitively selected by peer review. Projects are envisioned to cost $3-50M total over no more than five years. MSIP funds should not be used for continuing commitments to any project for longer than five years without re-competition.**

As with all NSF proposals, merit review criteria are based on Intellectual Merit and Broader Impacts. However, additional program-specific review criteria should be the scientific return from the proposed fixed-term funding, and also the substantial or new capabilities made available to the astronomical community. Examples of the latter would include open-access data products, newly available telescope time, better instruments on public facilities, or fiber allocations on a massive-multiplex spectroscopic survey.

Large projects (over $50M) are not excluded from funding through the MSIP. However, they would have to either seek partnerships for funding or provide access and data to a broad community and to fit within NSF budget constraints.

We affirm the *NWNH* perspective on MSIP: “It is important that the Mid-Scale Innovations Program maintain a balance between large and small projects. Indeed, such a program in NSF/AST could take on some of the larger Advanced Technology and Instrumentation (ATI) projects, so that ATI would emphasize advanced technology development together with instrumentation below about 2$M.” (p. 226).

Recommendation 8.3**: MSIP would subsume projects historically included in the TSIP, ReSTAR, and URO programs, as well as fixed-term experiments such as ACT, SDSS, and PAPER that have previously had no defined funding line. Proposals that include a component of observatory operations, while providing a compelling scientific result or a resource (observing time and/or data) to the community, are also appropriate for MSIP. We recommend that major new instrumentation at NOAO, Gemini, NSO, Arecibo, and NRAO be included in this same competition, as well as laboratory astrophysics and fixed-term numerical simulation initiatives above the ATI or the new Theory and Computation Networks program scale.**

For all of the diverse components of mid-scale, awards would be peer reviewed without fixed allocations among the types of project or wavelength. Generally, selections would be governed by scientific impact and cost-effectiveness, with AST retaining the discretion to focus the scope of the MSIP competition in a given year. We believe this will lead to the most nimble and scientifically powerful investment of the mid-scale funding line.

We note that because of the importance of a free re-competition of funding every five years, with the corresponding cycling among projects supported, long-term arrangements for ongoing support for observatory operations is not envisioned as part of this program. Such arrangements would fall into the Strategic Investments Program.

We believe that directly competing proposals for new instrumentation on national facilities and on other major telescopes is advantageous for the field, as it produces more open competition and encourages a broader view of the U.S. system of telescopes. However, we note that we intend this to apply only to significant new initiatives, not routine upgrades, optimizations, and maintenance.

Recommendation 8.4: **The national facilities should continue to have sufficient resources built into their budgets to maintain their critical core competencies, handle instrument upgrades, initiate small new experiments, and deal with occasional instrumentation failures.**

Stewardship of activities at the national facilities that benefit the health of the entire community will address the critical capability **HP-P**, and an ongoing source of instrumentation and maintenance support will impact critical capability **HP-J**.

Mid-scale projects offer tremendous opportunity for innovative science, but these opportunities come in two forms: in some cases, there is a well-defined science program to be executed, while in others, progress comes from creating a new capability and placing it in the hands of the open-access community for creative and unanticipated uses. Both kinds of advances are essential but can be difficult for reviewers to consistently rank if they were part of the same competition.

Recommendation 8.5**: MSIP should have two strands, Mid-scale Science and Open Access Capabilities, the former having as its primary selection criterion the quality of science returned by the proposers, and the latter having as its primary criterion the quality and quantity of science capabilities**

made available to the full U.S. astronomy community. Proposers would choose which of these criteria is best matched to their project.

In addition to standard NSF review criteria, proposals to the Mid-Scale Science strand will be judged primarily on the science return from the fixed-term projects, with open access science as a secondary criterion. New facilities, instruments, or surveys with well-determined science programs would be best considered in this strand. Previous projects serving as good examples might be the HETDEX, ACT, and PAPER experiments. Development of high-resolution Doppler spectrographs and a dedicated exoplanet survey could fit in this strand, as could proposals for new instruments for private OIR or RMS telescopes that promote dedicated observing programs rather than open access science. The two MSIP strands should be subject to separate competitions. This sub-division of MSIP is illustrated in Figure 8.1.

In the Open Access Capabilities strand, the capabilities made available to the community become the *primary* program-specific criterion for selection. Examples of projects appropriate to the Open Access Capabilities program would include (but are not limited to):

- Instrumentation and/or operations support for non-AST funded telescopes in exchange for open access, with the goal of delivering access to substantial amount of time on private facilities to the general astronomical community while providing enhanced capabilities for private users;
- Major instrumentation upgrades on AST-funded OIR, RMS, and solar facilities;
- New public databases and data-mining tools.

The Open Access Capabilities competition would subsume the TSIP program, but be open to a much broader range of proposals. We suggest that no particular rate of exchange of telescope time for funds be specified. Given the diversity of possible proposals, a selection panel needs the flexibility to judge the quality and form of capabilities that would be returned to the open access pool. Over time, past successful proposals set the community standard. We note the experience relayed in the Access to Large Telescopes for Astronomical Instruction and Research (ALTAIR) report, that smaller TSIP grants lead to amounts of open access time that are too small to build robust open-access user communities. In this context, we advocate that substantial allocations, e.g., at least of order 100 nights per grant in the OIR context, or 100 days of observing per grant for a URO, are more desirable. Such allocations would increase telescope access by the community, and thus address critical capabilities **HP-A** and **HP-B**.

***Recommendation 8.6*: Open access to data reduction pipelines and data access tools should be judged as an essential part of open access capabilities proposals.**

As recommended by NWNH: “NSF, NASA, and DOE should plan for effective long-term curation of, and access to, large astronomical data sets after completion of the missions or projects that produced these data, given the likely future scientific benefit of the data.” (p. 31). The ability to reduce data to a usable scientific form is a prerequisite for meaningful open access. Excellent software can lead to sharply improved scientific return from a facility. Proposals will necessarily need to confront on an individual basis the balance of software investment versus science return, but MSIP selection should give heavy weight to the overall development of the user capability, not simply the hardware implementation. Provision of open access data and processing tools is central to the health of the profession, providing the community with critical capabilities **HP-C** and **HP-D**.

Recommendation 8.7: **To remain vibrant, the MSIP should support at least two new project starts per year in each strand.**

Given the wide range of past activities that are being combined into the MSIP, considerable funding will be required as well as many more new starts than the *NWNH* recommendation of at least 7 per decade. Moreover, it is essential that the funding not be compressed into only a few activities, as that will imply that many other fields will make little progress.

This recommendation will constrain the scale of projects to track the overall funding of the MSIP line. It will necessarily make projects at the high end of the cost range rare, e.g., one new start every 3 years in the best circumstances. NSF could consider emulating the NASA Explorer model for projects at the upper end of mid-scale, i.e., select the most promising incoming proposals for design studies followed by a down-select process to fund implementation. This could provide NSF with much greater control over the disbursement of large chunks of funding and a fair and competitive environment for selecting the biggest enterprises.

Recommendation 8.8: **Following *NWNH*, we recommend the funding of one or more Data Stewardship projects to address the need for the long-term curation of astronomical data sets of enduring value and benefit to the community. This should be funded at a minimum level of $1M per year.**

Access to surveys and archival astronomical data, reduced to a usable form, is deemed a critical capability for the health of the profession (**HP-C**). Online interactive digital archives with search and data analysis capabilities are a critical technical capability (**TC-C**), and support the growing importance of archival astronomy and an element of open access. NASA has embraced the creation of such archives and continues to support them far beyond the end of the mission (e.g., MAST). Similarly valuable online archives have now been created with NSF funding (e.g., SDSS) but these archives have no means of support beyond the end of the project. Archives of increasing size, scope, and value will be created by new mid-scale projects in the coming decade (e.g., DES). Given the high priority given by this committee to mid-scale projects that have leaner budgets and shorter durations that major AST facilities that can support permanent archives, it is essential that AST devote some resources to the long-term stewardship of the most widely used and scientifically valuable archives arising from these projects. Once selected, the project(s) should be subjected to data life-cycle management best practices.

The Strategic Investments Program is appropriate for projects that will require decade-scale commitment from AST to shepherd through the design, construction, and operations phases. At present, CCAT and GSMT are the two highest ranked

NWNH telescope projects that involve funding models appropriate to the SIP. A data archive, while much smaller in funding scope, requires a similarly long-term view. We will address CCAT and GSMT in Chapters 9 & 10. Additional SIP opportunities may arise, e.g., for design and development in advance of the next decadal survey, but in a declining budget environment, we believe that AST should be conservative in making further commitments to construction,

We expect that because SIP projects necessarily require a strategic commitment from NSF, their funding proposals may continue to be handled on an *ad-hoc* basis as they emerge from the community, but it is assumed that they will be subjected to the same level of peer review as MSIP proposals.

9 AST Facilities

AST directly funds the operations of a diverse set of astronomical facilities, and the astronomical community aspires to add additional facilities to this mix. As discussed in Chapter 3, the combination of *NWNH* recommendations and the current budget situation will necessarily put significant pressure on AST-funded facilities. The PRC therefore developed a detailed priority ranking of these facilities.

For all AST facilities, we carefully reviewed the present and planned capabilities of each, including the mapping to our technical and health-of-the-profession capabilities. We also considered the budget impacts and interactions with other projects.

In this Chapter, we will describe the critical technical capabilities **(TC)** individually for each facility, since these capabilities differ greatly between facilities. However, the critical health-of-the-profession capabilities **(HP)** map more uniformly to the facilities. In fact, national observing facilities are crucial for the entire group of health-of-the-profession critical capabilities **(HP-A, HP-B, HP-C, HP-D, HP-H, HP-I, HP-J, HP-K, HP-L, HP-N, HP-Q, HP-R).** National facilities certainly play an important role for **HP-A**, the ability to compete regularly for access to telescopes, instruments, and observing opportunities. In addition, many institutions depend on this open-access telescope time for their training and research programs **(HP-N)** and have, at times, led the production of data reduction software **(HP-D)**. National facilities provide a site for new instrumentation and instrument groups **(HP-H, HP-I, HP-K, HP-L, HP-N, HP-R),** and of course, they provide long-term jobs in astronomy **(HP-M and HP-O)** and opportunities for outreach to underserved communities **(HP-Q and HP-R)**. These are just a few examples of the critical nature of national facilities for enabling the HP capabilities.

We will present the individual facilities in four groups—OIR, RMS, Solar, and High-Energy—and present conclusions and recommendations within each group. We then present the merged rankings and recommendations in Section 9.5.

9.1 Optical & Infrared Facilities

NSF/AST funds a substantial complement of OIR facilities. First, there are the two 8.2-meter telescopes of the international Gemini Observatory. Currently the United States partnership in the facility is 50.7%, a share that will rise to 64.1% on January 1, 2013. Second, there are telescopes operated by the National Optical Astronomy Observatory (NOAO). At the Kitt Peak National Observatory (KPNO), NOAO operates the Mayall 4-meter and the 2.1-meter telescopes; in the Southern Hemisphere, NOAO operates the Blanco 4-meter at the Cerro Tololo Interamerican Observatory (CTIO). NOAO provides additional facility access for U.S. astronomers by collaborating with a number of private institutions, sharing in operation costs for the WIYN (Wisconsin-Indiana-Yale-NOAO) 3.5-meter telescope, the SOAR (SOuthern

Astrophysical Research) 4.1-meter telescope, and the Small and Moderate Aperture Research Telescope System (SMARTS) consortium. In addition, NOAO brokers access to premier private facilities through the Telescope System Instrumentation Program (TSIP).

The top recommendation of *NWNH* for large-scale ground-based initiatives is the Large Synoptic Survey Telescope (LSST), which would join the NSF OIR facility portfolio. The second-highest *NWNH* ground-based priority is a strong Mid-Scale Innovations Program (MSIP); some components of MSIP would include OIR telescope surveys, instrumentation, and expanded TSIP-like access to private facilities (see Chapter 8). NSF support for one of the Giant Segmented Mirror Telescope (GSMT) candidates was the third-ranked *NWNH* priority for large ground-based initiatives.

AST OIR facilities exist within the context of a substantial network of telescopes operated by foreign and private U.S. institutions. In the 8-meter class, the Southern Hemisphere hosts the private Magellan telescopes (2*x*6.5-meter) and the four 8-meter Very Large Telescopes (VLTs) run by the European Southern Observatory (ESO). In the North, U.S. institutions operate the two 10-meter Keck telescopes, the 2*x*8-meter Large Binocular Telescope (LBT), and the 6.5-meter MMT, with the Japanese 8-meter Subaru telescope being the most capable foreign-owned Northern observatory. U.S. institutions are also partners in the twin 10-meter Hobby-Eberly and South African Large Telescopes in opposite hemispheres, which operate with poorer image quality over limited ranges of declination and hour angle. Most of the capabilities of the Gemini telescopes and smaller AST assets are replicated or replicable on one or more of these private or foreign facilities. But the U.S. user base and science needs for these capabilities are very large, and access to these alternative facilities by the general U.S. astronomy community is very limited. It is therefore of high priority to arrange for access to these capabilities through AST portfolio elements.

9.1.1 Overview of OIR Facilities

Gemini-North Telescope

Gemini-North (Gemini-N) 8-meter telescope is located on Mauna Kea and is the highest-altitude publicly accessible 8-meter facility for the U.S. community. The principal Gemini-N instruments are the Gemini Multi-Object Spectrograph (GMOS), an optical long-slit, multi-object, and integral-field spectrograph with recently upgraded red-sensitive CCDs, and the Gemini Near-Infrared Spectrograph (GNIRS), a 1-5 micron versatile IR spectrograph with low to medium resolution (R~1700 up to ~18,000) spectrographic modes. There is also a NIR integral field spectrograph (NIFS), an NIR Imager (NIRI), and a mid-IR imager and spectrograph (Michelle). Under development is an optical high-resolution spectroscopic capability (GRACES, R~50,000), which is a fiber link to the Canada-France-Hawaii Telescope (CFHT) ESPaDonS echelle spectrograph. Adaptive optics (AO) is provided by the Altitude Conjugage Adaptive Optics for the InfraRed (ALTAIR) system, which can feed several instruments, including GNIRS, NIFS, and NIRI.

Capabilities: Gemini-North provides 140 nights/year of 8-meter time for the U.S. community in the Northern Hemisphere, which is about 40% of all publicly available 8-meter time (**HP-A**). The current Gemini-North instrumentation provides critical capabilities **TC-P, TC-Q, TC-S, TC-U, TC-V,** and **TC-X**. These include moderate-multiplex optical spectroscopy for measuring redshifts of faint sources (**TC-P**). The queue scheduling offers unique and rapid follow up for targets of opportunity, such as supernovae, with both optical and IR imaging and spectroscopy (**TC-Q**). High spectral resolution with GRACES will permit investigations of metallicity gradients in the Milky Way and abundance analysis of extremely low-metallicity stars (**TC-S**). Instruments also provide diffraction-limited imaging and integral field spectroscopy, and NIR spectroscopy is available for small body characterization (**TC-U, TC-V, TC-X**). With future instrumentation investments, these capabilities could be enhanced, and critical technical capabilities **TC-T** and **TC-Y** (extreme precision OIR Doppler spectroscopy, high-contrast NIR direct imaging of planets) could potentially be implemented at Gemini-N. Instrumentation development opportunities at Gemini-North provide capabilities **HP-I** and **HP-L**. Gemini-N can also perform the science for critical technical capability **TC-R**, workhorse OIR observations on mid-size telescopes, if it could offer time-sensitive and cost-efficient short observing programs, although the Gemini telescopes cannot offer a wide field of view (FOV). For example, GNIRS and GRACES are or soon will be the most powerful of their type on AST facilities.

Gemini-South Telescope

The Gemini-South (Gemini-S) 8-meter telescope is located on Cerro Pachon in Chile, near CTIO. The three principal instruments on Gemini-S are GMOS, a copy of the spectrograph on Gemini-N, NICI, a coronographic imager and Flamingos-2, a 6'-FOV IR imager and Multi-Object IR Spectrograph. The last of these is due to come back online in the near future. The instrumentation for Gemini-S has been a major issue, due to a failure of GNIRS, extensive delays in Flamingos-2, and delays in bringing the Gemini Multi-conjugate Adaptive Optics System (GeMS) online. The situation should substantially improve in the near future when both Flamingos-2 and the Gemini Planet Imager (GPI) will be on the telescope, as well as an upgraded Gemini Multi-Object Spectrograph (GMOS). One current use of Gemini-S is a dedicated planet search with the NICI coronagraphic imager; this will be succeeded by GPI. Long-term plans for GPI may include moving it to Gemini-N. Gemini-S is the first 8m-class facility in the world with a working multi-conjugate AO capability (GeMS) that offers adaptive optics over a wide FOV (1’ to 2'). GeMS has been demonstrated with its Gemini-South Adaptive Optics Imager (GSAOI) and with GMOS imaging.

Capabilities: Gemini-S provides 140 nights/year of 8-meter time for the U.S. community to have open access to observing time in the Southern Hemisphere, which is about 40% of all publicly available 8-meter time (**HP-A**). Gemini-S provides critical technical capabilities **TC-P, TC-Q, TC-U, TC-V, TC-W, TC-X,** and **TC-Y.** GMOS offers moderate multiplex optical spectroscopy, important for redshift surveys of faint galaxies (**TC-P**). The facility also offers the opportunity for target-of-opportunity optical imaging and spectroscopy and moderate multiplex R~3000 NIR spectroscopy of faint targets (**TC-Q** and **TC-X**). The GeMS instrument should soon provide world-class AO capabilities for diffraction-limited imaging and multi-object NIR spectroscopy, e.g. for small body characterization (**TC-U** and **TC-V**). The GPI instrument (with a world-class AO system) will provide world-leading high-contrast NIR imaging and coronography for direct detection of planets (**TC-Y**). A new spectrograph is under development, the Gemini High-resolution Optical Spectrograph (GHOS), which will be available for abundance analysis, exoplanet searches, and supernovae follow-up, providing critical technical capability **TC-S**. GHOS is likely destined for Gemini-S but could go on Gemini-N as well. Future instrumentation investments on Gemini-S could provide critical technical capability **TC-T** (extreme precision OIR Doppler spectroscopy for planet detection), and Gemini-S is also capable of providing workhorse OIR observations (**TC-R**), if short observing programs can be efficiently executed. Gemini-S provides access to observing the Southern sky (i.e., for detailed studies of the Galactic Bulge and Magellanic Clouds in the Local Group) and will play a role for LSST follow-up if LSST is constructed. As with Gemini-N, Gemini-S offers HP critical capabilities for instrument development (**HP-I**, **HP-L**).

Nicholas U. Mayall Telescope

The Mayall 4-meter telescope is the largest telescope at KPNO. The telescope specializes in wide-field imaging, with the Mosaic camera in the optical and the NOAO Extremely Wide Field Infrared Mosaic (NEWFIRM) camera (shared with Blanco) in the near-IR. The Mayall also provides open-access spectroscopic observations with several instruments, including the new Kitt Peak Ohio State Multi-Object Spectrograph (KOSMOS). The Mayall and Blanco are excellent platforms for optical imaging and spectroscopic surveys. The Mosaic and NEWFIRM cameras are the highest-throughput visible and near-IR imagers available for U.S. public access in the Northern Hemisphere, and the proposed Big Baryon Oscillation Spectroscopic Survey (BigBOSS) project would implement a 3-degree-FOV multi-fiber spectrograph on the Mayall to provide a significantly enhanced ground-based facility for wide-field redshift surveys of faint galaxies. The combination of Mayall plus the KPNO 2.1-meter provides the majority of the open-access nights in the U.S.

Capabilities: The Mayall provides critical technical capability **TC-R**, workhorse OIR imaging and spectroscopy, via the NEWFIRM, Mosaic, and, soon, KOSMOS instruments. The Mosaic camera is currently the most sensitive implementation of critical technical capability **TC-N**, wide-field optical imaging, that is publicly available to U.S. astronomers in the Northern Hemisphere. However, Mosaic capabilities are inferior to DECam in the Southern Hemisphere, and there are several other comparable or superior Northern facilities to which public access might be negotiated. The Mayall and Blanco telescopes are uniquely well-suited among all the world’s 4m-class telescopes to providing high-multiplex wide-field optical spectroscopy, critical technical capability **TC-B**. The BigBOSS project has proposed this for the Mayall. The Mayall can provide Target of Opportunity imaging and spectroscopy, although cannot switch instruments rapidly. Combined with the

KPNO 2.1-meter, the Mayall provides ~700 open-access nights/year to the astronomical community and one of the most powerful open-access visible and NIR survey capabilities in the North (**HP-A**). Support of a major facility at KPNO enables other tenant observatories to continue operations; these tenant observatories provide many of the critical HP capabilities (**HP-A, HP-H, HP-J, HP-N, and HP-P**). Finally, the Mayall provides support for the KPNO Visitor Center, which is one of the most popular astronomical visitor centers in the continental U.S. (**HP-S**).

Victor M. Blanco Telescope

The Blanco 4-meter telescope at CTIO in Chile is a twin to the Mayall on Kitt Peak. For national access to Southern skies it is second in size only to Gemini South. It is equipped with four major instruments: the Dark Energy Camera (DECam), a three-square-degree CCD imager currently being commissioned; the Infrared Side-Port Imager (ISPI), a near-infrared imager with a 10' field; Hydra, a 138-fiber visible spectrograph covering a 40' field (not now considered state-of-the-art); and Cerro Tololo Ohio State Multi-Object Spectrograph (COSMOS), a low-resolution multi-slit spectrograph covering a 10' field. TripleSpec is due to be delivered near end of FY13, adding moderate resolution (R~3,500) near-IR (0.85-2.5 microns) spectroscopy. While all instruments can be used to address important scientific problems in the South, it is DECam that is unique. The Blanco is also a potential site for a state-of-the-art high-multiplex fiber spectrograph, such as the Dark Energy Spectrograph (DESpec) concept.

Capabilities: Blanco provides open access for more than 200 nights/year of U.S. community access to Southern skies with a moderate-sized telescope (**HP-A**). The Blanco provides critical technical capabilities **TC-N** and **TC-R**. With DECam, the Blanco provides a forefront implementation of wide-field optical imaging, including in the time domain (**TC-N**), the only capability deemed critical to all science themes. DECam has six times the field of view and hence survey speed of Mosaic on the Mayall telescope; there is nothing of equivalent power anywhere in the U.S. system. The broad scientific capabilities of DECam alone may be sufficient reason to keep the Blanco operating for a number of years; indeed there is a 5-year commitment of 105 nights/year to the *Dark Energy Survey* collaboration of DOE, private, and international institutions, which will produce a powerful survey (**HP-C**). The Blanco also joins Mayall as the largest contributors to workhorse OIR observations (**TC-R**) in the U.S. open access system. The COSMOS spectrograph offers increased efficiency for workhorse moderate-resolution optical spectroscopy in the South, and will provide spectroscopic follow-up of LSST sources. The Mayall and Blanco telescopes are uniquely well-suited among all the world’s 4m-class telescopes to providing high-multiplex wide-field optical spectroscopy (**TC-O**). DESpec and BigBOSS have proposed such instruments to be built with DOE contributions, although the wide-field spectrograph and DECam cannot be operated on the Blanco at the same time.

Southern Astrophysical Research Telescope (SOAR)

The SOAR telescope is a modern 4-meter telescope in Chile funded as a partnership by NOAO, the Ministerio da Ciencia e Tecnologia of the Federal Republic of Brazil, the University of North Carolina at Chapel Hill, and Michigan State University. The U.S. community (through AST) gets 30% of the time through 2018 in exchange for funding 70% of operations; the higher operations and maintenance (O&M) fraction is because NSF did not contribute construction funds. The telescope specializes in narrow-field (~3' to 5') optical and near-IR instrumentation, including cameras (SOAR Optical Imager, Spartan), moderate-resolution spectrographs (Goodman High-Throughput Spectrograph, Ohio State Infrared Imager/Spectro–graph), a tip-tilt system, and the optical SOAR Integral Field Spectrograph. A laser-based ground-layer AO system is being commissioned.

Capabilities: SOAR provides open access to about 100 nights/year of U.S. community access to Southern skies with a moderate-sized telescope (**HP-A**), along with critical technical capability (**TC-R**), workhorse OIR imaging and spectroscopy. It is a useful facility for target-of-opportunity observations, albeit from a mid-sized aperture, particularly for future open-access optical/NIR spectroscopy and higher-resolution imaging of objects to be discovered by DECam and/or LSST. SOAR is commissioning AO-fed imaging and IFU spectroscopy, but those will not operate near the diffraction limit. We note these capabilities are not unique; SOAR is not yet "best in the U.S. system" at anything and NOAO has only a 30% share. SOAR also provides training and career development opportunities.

Wisconsin-Indiana-Yale-NOAO (WIYN) Telescope

Commissioned in 1994, WIYN is a 3.5-meter telescope at KPNO. The three university partners contributed the $14M capital construction cost of the facility. NSF contributes $1.1M to annual mountain operation costs of WIYN in return for 40% of the telescope time. The telescope provides a one-degree-diameter FOV with better image quality than the Mayall. The current major scientific capabilities focus on time-domain spectroscopy, narrowband imaging in the optical/near-infrared, and integral-field spectroscopy of low surface brightness objects. The most popular instrument is the Hydra multi-object feed to the recently overhauled Bench Spectrograph. The One-Degree Imager (ODI) would, if completed, provide wide-field/time-domain optical imaging superior to the Mayall Mosaic camera, although with capabilities well below DECam and LSST.

Capabilities: WIYN provides open access ~130 nights/year of open access to a 3.5 meter "workhorse" telescope (**HP-A**), and is well configured for target of opportunity capabilities requiring mid-sized telescope. WIYN thus contributes to critical technical capability (**TC-R**), workhorse OIR imaging and spectroscopy.

Large Synoptic Survey Telescope (LSST)

Proposed for construction under the MREFC line before the end of the decade, the LSST will be a dedicated wide-field CCD imaging facility with several times larger survey figure of merit (telescope area × FOV × time devoted to imaging) than any predecessor. LSST will have a clear aperture equivalent to a 6.5-meter-diameter mirror, and a 10-square-degree FOV. Proposed operation is for nearly full-time survey mode with a very open data model including rapid dissemination of transient alerts. LSST was given highest priority for large ground-based astronomy projects by *NWNH*, which is mirrored in our assessment by the high ranking given to wide-field optical imaging in all four science areas (and *the* highest ranked capability in 3 of 4). Science impact of the LSST deep summed images should include: obtaining visible colors needed to obtain photometric redshifts of the target galaxies in the large-scale structure surveys from NASA's WFIRST spacecraft and the European Space Agency's Euclid spacecraft; greatly improved maps of Milky Way and Local Group stellar populations, including variability information; and parallax and proper motion for stars fainter than Gaia flux limits. Variability and transients detected by LSST will greatly improve statistics and follow-up opportunities for all known and unknown forms of stellar explosions and AGN variability, will firmly constrain optical counterparts of gamma-ray bursts, and will provide a high-completeness census of near-Earth asteroids and the Southern outer solar system population to several magnitudes fainter than current limits.

Capabilities: If built, LSST will provide an order-of-magnitude advance in wide-field optical imaging, including the time domain, that is, critical technical capability **TC-N**. The data will be provided to the community almost immediately and will facilitate a wide range of scientific investigations that lie well beyond existing capabilities. This rapid and open access to LSST data will boost the health of the profession through critical capabilities **HP-A**, **HP-B**, **HP-C**, **HP-D**, and **HP-M**. In the absence of LSST, these science opportunities could be pursued at lower efficiency and significantly compromised time cadence by DECam/Blanco in the South (4m telescope/3 square degrees FOV). In the North, the best current AST facility is Mosaic/Mayall (4m/0.5 square degrees) but time could potentially be purchased/traded at Megacam/CFHT (4m/1 square degree), ODI/WIYN (3.5m/1 square degree), or PanSTARRS (1.8m/6.5 square degrees). These less-capable facilities would achieve only a small fraction of the LSST science goals.

Giant Segmented Mirror Telescope (GSMT)

A Giant Segmented Mirror Telescope (GSMT) of 20-30m aperture would be the next great leap in the collecting power and angular resolution of OIR astronomy. *NWNH* placed 25% federal participation in a GSMT project as a high priority for large ground-based initiatives, behind LSST and a MSIP, with a projected federal capital cost of $250M-350M, and operations costs in the 2020's of $9M-14M/yr. With three GSMT projects in development through private and government funding worldwide, *NWNH* considered that "federal investment in a GSMT is vital to U.S. competitiveness in ground-based optical astronomy over the next two decades." Capital investments at the full scale proposed by *NWNH* would severely stress the AST budget envelopes being considered by this panel for this decade, and would almost certainly require funding through the MREFC line. We consider operations and/or instrumentation funding in our AST portfolios, with the assumption that AST participation in the project would lead to concomitant access to GSMT capabilities by the general U.S. astronomy community.

Capabilities: A GSMT with a full instrumentation and adaptive-optics suite would enable substantial advances beyond the current state of the art for critical technical capabilities **TC-P**, **TC-S**, **TC-U**, **TC-V**, **TC-W**, **TC-X**, and **TC-Y**. A GSMT could extend the reach for Target of Opportunity Optical Imaging and Spectroscopy (**TC-Q**) if its instrumentation and scheduling were sufficiently flexible and could host extreme-precision OIR Doppler spectroscopy (**TC-T**) capable of detecting planets around fainter stars than existing telescopes. The positive impact on the health of the profession would also be considerable, should NSF investment in a GSMT prove feasible, principally through open access (**HP-A**) to the largest telescopes in the 20+-meter era of OIR astronomy.

9.1.2 Optical and Infrared Facility Recommendations

The panel makes a number of recommendations regarding the OIR system. We first present the recommendations for new OIR facilities before turning to a consideration of existing OIR telescopes.

Recommendation 9.1: **We recommend that the Large Synoptic Survey Telescope (LSST) begin construction with an MREFC start in FY14 or as soon as possible thereafter, so as to maintain an expected start of operations in late 2021 or early 2022.**

LSST is the highest ground-based astronomy priority of *NWNH*; it should have enormous scientific impact and enable science from comets to cosmology for astronomers from many different communities, including the open-access community. LSST operations will affect the AST budget toward the end of the portfolio window, but currently envisioned NSF costs can be borne in both budget scenarios given the high scientific priority on this capability.

Recommendation 9.2**: We recommend that the federal government (NSF and DOE), as the majority LSST partner, avoid any contractual structure that prevents it from unilaterally reviewing and setting the federal operations support level.**

Past experience with other projects have shown the difficulty in controlling operating costs with projects that are large in scope, have international partners, and have complex management agreements. It is reasonable to be concerned that increases in LSST operation costs could produce unwanted pressure on other parts of the AST portfolio. While we expect that the planned LSST operations costs will be affordable for AST, we think that the federal government should retain the ability to set its operations support level separately from contractual obligations to other partners. This will also aid AST in exerting pressure on the LSST project to identify cost savings as survey operations mature and computational costs decrease.

Recommendation 9.3**: Following *NWNH*, we place major funding for the Giant Segmented Mirror Telescope (GSMT) projects at lower priority than executing LSST and maintaining a vigorous MSIP.**

Major AST contributions to construction and/or operation of a GSMT would be a huge boon to U.S. OIR science goals, but these will be expensive ventures. Within the budget scenarios we consider, significant GSMT construction funding by AST this decade would engender catastrophic cuts to other facilities, and mid-scale and/or small-grants programs, so a federal share of GSMT construction would require MREFC funding. Within the AST portfolios we recommend, GSMT instrumentation and/or fixed-term operations could compete within the MSIP line, and in our more optimistic Scenario A, AST could consider creating a stable GSMT funding partnership in the Strategic Investments line described in Chapter 8 late in the decade. If funding permits, this particular recommendation would have a large and enduring positive impact on the health of the profession in terms of research, instrumentation, and training, by enabling critical capabilities **HP-A, HP-C, HP-H, HP-I, HP-J, HP-K, HP-L, HP-M.**

We now turn to existing facilities.

***Conclusion*: We rank a continued AST partnership in Gemini-South as the highest priority in the current OIR open-access system, with instrumentation to include both advanced adaptive-optics capabilities and workhorse seeing-limited OIR instrumentation.**

Gemini-South is on an excellent dark site in the same hemisphere as ALMA, Blanco/DECam, and LSST. The high-angular-resolution near-infrared coverage of the GeMS multi-conjugate AO system and the high-performance AO system of GPI are superb matches for the opportunities ALMA provides in star formation, exoplanet systems, proto-planetary disks, and high-redshift galaxy evolution. The workhorse NIR spectroscopy of Flamingos-2 and optical spectroscopy of GMOS, combined with Gemini's flexible observing model, match well to time-domain astronomy with Blanco/DECam and LSST. Gemini's large aperture will allow investigations of faint, static objects from these two large imagers.

***Conclusion*: We rank continued operation of the Blanco telescope as our next AST OIR priority, at least through the commissioning of the LSST, due to its world-leading imaging capabilities of the Dark Energy Camera (DECam) and additional workhorse instrumentation.**

The new DECam will be the most powerful optical imager in the U.S. system by a large margin; only the Subaru HyperSuprimeCam has a comparable etendue (telescope area times imaging field of view) with good image quality, and DECam will provide more nights at lower operating cost. DECam will allow a strong build-up to LSST science. The Blanco will also field workhorse instruments for multi-slit optical spectroscopy and for single-object infrared spectroscopy. In principle, the wide-field NIR imager NEWFIRM could be returned to Blanco; this instrument has the highest etendue for a NIR imager in the U.S. system.

***Conclusion:* We place higher priority on Gemini-North than on continued operation of the Mayall as a user facility.**

The committee carefully considered the relative ranking of the Mayall and Gemini-North. The Mayall 4-meter telescope is the anchor of the Kitt Peak National Observatory. It serves the critical needs for workhorse OIR instrumentation and for health of the profession as the largest Northern OIR facility offering full-time U.S. open access. The Mosaic camera is under high demand and is the best open-access optical imager in the Northern Hemisphere. The NEWFIRM NIR camera is the best wide-field NIR imager in the U.S. system. The new KOSMOS multi-slit spectrograph will be a workhorse instrument for optical spectroscopy. In the future, Mayall and

Blanco are by far the strongest candidate sites for providing the critical technical capability of high-multiplex optical spectroscopy.

Gemini-North is, however, a larger, more modern telescope on a better site. We judge that Gemini-North offers a somewhat lower cost per square meter of aperture, and its better site renders it the more effective choice for narrow-field OIR observations. Mayall instrumentation is strong, but the Mosaic and KOSMOS instruments are not best-in-class. Looking forward, we conclude that strengthening the Gemini-N workhorse instrumentation, plus provision of significant open-access time through a vigorous Open-Access Capabilities program, offers a stronger option for a full-sky open-access OIR program than operating the Mayall. The Mayall wide-field imaging capabilities could also be provided by other telescopes made available through the Open Access Capabilities program.

The committee recognizes that such a path, one that is reliant on a multi-national partnership and peer-review for major instrumentation decisions, is not without risk; a concern for the Gemini Observatory has been its instrumentation program. One requirement of the current international agreement is that "any work arising out of expenditures from the Instrument and Facility Development Funds shall be subject to an equitable sharing of responsibilities and benefits between the parties." While this is a valuable goal, in practice, it does not seem the most flexible avenue towards rapid and low-cost development of new instrumentation. We add further discussion of Gemini within the U.S. OIR system context in Chapter 11.

Recommendation 9.4**: We recommend that the U.S. retain at least a 50% share of the Gemini telescopes. However, we also recommend a cost cap on the U.S. share of $17M (FY17), excluding major instruments, which will be competed through the mid-scale program. We further recommend that the U.S. negotiate a Gemini partnership so that the instrumentation investments can be more entrepreneurial between partner countries, e.g., with investments to be compensated from transfer of nights from partners that have not invested in instruments.**

The Gemini international agreement ends in 2015, and the negotiation of a new partnership agreement will begin soon. This is a significant opportunity for changes in governance that will improve the responsiveness of the facility to all partners, but in particular to the U.S. interests. With the recent withdrawal of the U.K., the U.S. is now funding about 2/3 of the Gemini partnership.

Recommendation 9.5**: The U.S. should aim to continue to lower the Gemini operations cost per night by focusing on simpler operations at Gemini-N and maturing instrumentation at Gemini-S. We recommend that Gemini end next-generation AO development for the Gemini-N and that the observatory prepare capabilities for both telescopes toward the end of the decade that will emphasize the synergy with LSST.**

The committee believes that Gemini-North, a modern 8-meter telescope on an excellent site, offers the most forward-looking, cost-effective opportunity to maintain open access to the critical technical capability of workhorse OIR instrumentation, such as optical mid- and high-resolution spectroscopy and NIR mid-resolution spectroscopy, especially in the North, thus continuing Gemini's capabilities for time-critical observations.

We see the adaptive optics system on Gemini-North as low priority: it is less advanced than the system on Gemini-South, and the U.S. private telescope system has ambitious AO systems in the Northern Hemisphere. Simplification of the Gemini-N instrument suite should reduce its operating costs.

The Gemini telescopes should also enable remote observation from sites in the continental U.S. Current NOAO telescopes promote the health of the profession as an avenue for projects that are too small to merit a full night of 8-meter time, and as opportunities for hands-on operation of OIR instruments. This is particularly true of the most geographically accessible site, Kitt Peak. As the scientific capabilities become more concentrated in 8m-class telescopes in Hawaii and Chile, it is important to maintain the capability for users to execute small projects, and become familiar with observing techniques. Remote observing makes this possible on large telescopes without incurring travel expenses, and reduces observatory costs for the care and feeding of observers, as well as the need for running all short programs in queue.

Recommendation 9.6**: We recommend that AST continue its agreement for Southern Astrophysical Research Telescope (SOAR) operations support through 2018.**

SOAR provides open-access OIR telescope nights and synergy with ALMA. AST currently has a partnership agreement in place to fund SOAR operations through 2018. We recommend that AST not break this partnership agreement; this would be a poor precedent in any situation, but particularly in this case because the open-access community has enjoyed full project membership despite a back-loaded AST contribution. Beyond 2018, a new agreement will be required, and AST should reconsider its partnership. SOAR's scientific value and priority to the U.S. community may increase in the LSST era, if it has capable and cost-effective instrumentation for spectroscopic and targeted-imaging follow-up of LSST discoveries.

Conclusion**: We rank the AST share of the WIYN telescope as our lowest OIR priority.**

The One-Degree Imager may eventually be a stronger capability than the Mayall with Mosaic, but it is not yet completed and it will not be as strong as Blanco/DECam. The existing instruments are useful but not extraordinary. NOAO is only a fractional partner, so the impact on the number of open access nights is less severe than the divestiture of the Mayall telescope.

9.2 Radio, Millimeter, and Submillimeter Facilities

NSF/AST currently supports several of the world's premier RMS facilities through the National Radio Astronomy Observatory (NRAO). NRAO operates the Robert C. Byrd Green Bank Telescope (GBT), the Karl G. Jansky Very Large Array (VLA), and the Very Long Baseline Array (VLBA). NRAO is also responsible for

North American participation in ALMA, including user support at the North American ALMA Science Center and Chilean operations via the Joint ALMA Observatory. Beyond NRAO, AST has supported the University Radio Observatories (URO) program. The URO program has contributed significantly to the development of RMS capabilities though its support of university groups that build, design, and operate state-of-the-art radio instruments that often complement the suite of NRAO facilities. AST also supports operation of the Arecibo Observatory, the world's largest single-dish telescope.

The coming decade will be an exciting one for U.S. RMS astronomers: the recently upgraded VLA is showing order-of-magnitude improvements in sensitivity in existing and new observing windows, ALMA is on track to be completed during the next few years and is already the world's premier submillimeter/mm interferometer, and *NWNH* ranked CCAT as one of its priorities for ground-based astronomy in the next ten years.

9.2.1 Overview of RMS Facilities

Atacama Large Millimeter/submillimeter Array (ALMA)

ALMA is an aperture synthesis instrument located at an altitude of 5000m on the Chajnantor plain in northern Chile. When completed, ALMA will consist of an array of 12-meter antennas separated by baselines of up to 16 km. The dishes are routinely reconfigured to form arrays with different distributions of baseline lengths. An additional compact array of 7-meter and 12-meter antennas will enhance ALMA's ability to image (somewhat) extended targets. Initially, ALMA will be sensitive to wavelengths ranging from 400 μm to 3 mm.

Capabilities: ALMA provides critical technical capabilities **TC-E, TC-G,** and **TC-J.** ALMA is already the world's premier submillimeter/mm interferometer and will soon provide a sensitivity and angular resolution far surpassing that of any existing instrument (**TC-E** and **TC-G**). Once completed, ALMA will produce milliarcsecond to arcsecond resolution imaging spectroscopy of molecular gas, including dust and highly excited molecules. It is also capable of subarcsecond continuum observations of thermal (principally dust) and non-thermal emission with polarimetry for galaxies at medium to high redshifts (**TC-J**). ALMA will make important discoveries in many key science areas, spanning the galactic (star and planet formation) and the extragalactic (high-redshift galaxies and AGN). As ALMA is a newly constructed U.S. and international flagship facility for radio and submillimeter/mm astronomy, it largely impacts and provides all of the HP critical capabilities (**HP-A** through **HP-S**).

Karl G. Jansky Very Large Array (VLA)

The VLA is an array of 27 identical 25-meter antennae located on the high desert plains of St. Augustin, near Socorro, NM. The EVLA upgrade of the VLA is nearing completion, and the telescope now provides continuous wavelength coverage between 0.6 to 30 cm with up to 8 GHz of bandwidth per polarization and subarcsecond angular resolution. In addition to improvements in continuum sensitivities by factors of up to 10 and improvements in dynamic range and polarimetric imaging, the spectroscopic capabilities of the VLA have also become incredibly powerful. Observers can flexibly adjust the number of channels (from 10,000 to 4 million) and the frequency resolution (over seven orders of magnitude) to meet a very broad range of science needs.

Capabilities: The VLA provides critical technical capabilities **TC-G, TC-J,** and **TC-M.** It uniquely delivers high-angular-resolution and high-sensitivity spectral line (**TC-G**) and continuum (**TC-J**) imaging over a large range of wavelengths, including polarization. In addition, the VLA can be used in a phased-array mode for large-collecting-area cm-wave observations for sensitive pulsar discovery (in pointed follow-up mode) and timing, (critical technical capability **TC-L**) or as a receiving element for radar characterization of primitive bodies (critical technical capability **TC-I**), or as an additional, high-sensitivity element of the VLBA, once additional correlator software modes are implemented. As a newly upgraded U.S. and international facility, the VLA provides and impacts all of the HP critical capabilities (**HP-A** through **HP-S**).

Robert C. Byrd Green Bank Telescope (GBT)

The GBT is the largest fully steerable telescope in the world. With a diameter of 100 meters and an unblocked aperture, it provides excellent sensitivity and polarization performance across the instrumented wavelength range of 3 mm to 3 m. The GBT is located in the National Radio Quiet Zone, which helps to mitigate the rapidly increasing effects of radio frequency interference. The GBT instrumentation consists of single pixel or small arrays of heterodyne instruments at cm/mm wavelengths and a 3 mm bolometer array (MUSTANG). Novel backend technology includes the Green Bank Ultimate Pulsar Processing Instrument (GUPPI) for pulsar timing, Zpectrometer (high-frequency spectrometer for high-redshift surveys), the Caltech Continuum Backend (CCB) for continuum observations at 0.7 to 1 cm, and the currently shared-risk Versatile GBT Astronomical Spectrometer (VEGAS).

Capabilities: The GBT provides access to the most flexible, fully-steerable, and unblocked aperture single dish radio telescope in the U.S. (**HP-A, HP-C**). The GBT provides critical technical capability **TC-L,** cm continuum observations using large collecting area and pulsar timing backends, and is an important part of the recent efforts to discover and time pulsars in both blind surveys and pointed follow-up observations. The GBT has been efficient at following up Fermi point sources, for example, to reveal a population of millisecond pulsars outside the Galactic plane (it has better sky coverage than Arecibo). The GBT can be configured as a radar receiving station, enhancing critical technical capability **TC-I** with Arecibo – especially for near-Earth objects. The GBT may be able to address technical capabilities **TC-H** and **TC-K** for wide-field submillimeter/mm line and continuum surveys (at 3 mm or longer), with upgrades to array cameras. The GBT serves as a very sensitive element for the supporting technical capability of very-long baseline interferometry and is used often to fill in flux on scales that are missed by higher resolution interferometers. It also provides steerable Northern Hemisphere access to imaging of diffuse HI emission from the neutral ISM in the nearby Universe.

Although the GBT is currently well instrumented across its operating range, many of the GBT's capabilities are duplicated by other single dishes: at the longest wavelengths (> 10-60 cm) Arecibo has similar capabilities and larger effective collecting area over a more restrictive portion of the sky. At the shorter wavelength ends of the GBT's operational range (< 40 cm), the Effelsberg 100m telescope has similar receivers, including a 7-beam array at 1 cm, and 2-beam receiver at 3 mm (see: http://www.mpifr.de/div/effelsberg/receivers/receiver.html). However, the sensitivity of Effelsberg is typically poorer, by factors of 3-4 at the shortest wavelengths.

The GBT also provides critical health-of-the-profession capabilities for access to data archives and software (**HP-C, HP-D**) and the development of instrumentation for single dish radio telescopes (**HP-I, HP-J, HP-K, HP-L**), along with student training (**HP-O, HP-Q**). In addition, the Green Bank site provides many opportunities for science education and education in West Virginia with 45,000 annual visitors. The GBT runs a pulsar-discovery collaboration with high schools around the country, as part of which students have recently discovered at least one new millisecond pulsar (**HP-S**).

Very Long Baseline Array (VLBA)

The VLBA includes 10 identical antennae with baselines up to 8000 km. The facility is unique in its ability to do extremely high-angular-resolution imaging and spectroscopy in the wavelength range of 3 mm to 30 cm. Perhaps the outstanding unique aspect of the VLBA is its ability to carry out astrometry with precision (~10 microarcseconds) that is ~2 times better than the European Gaia spacecraft will achieve for stars. Other VLBI networks exist (e.g., the European VLBI Network, or EVN), but these connect existing single-dish telescopes and are much more heterogeneous. In addition, the EVN observes only in campaigns rather than year-round. Following the recommendation of the 2006 Senior Review that AST reduce its support for the VLBA, the operational costs are now shared or planned to be shared among AST and a number of partners (Shanghai Astronomical Observatory, Academia Sinica Institute of Astronomy and Astrophysics, and the U.S. Naval Observatory and others). Large increases in sensitivity have been made possible both by hardware/software increases in bandwidth and by adding larger aperture single dishes through the High Sensitivity Array (HSA). The HSA mode is used for spectroscopic (maser) VLBI observations, where the VLBA bandwidth extension cannot be utilized, but is important for continuum observations as well. The VLBA is currently spending much of its time on several large key science projects.

Capabilities: The VLBA can provide subarcsecond cm continuum follow-up to sources detected at other wavelengths (**TC-M**), in cases where the radio emission is bright enough to be observed. The role of the VLBA in parallax distances and super-massive black hole mass determination is a supporting technical capability. The VLBA provides an order of magnitude gain in angular resolution, allowing us to determine a high-precision distance scale in the Milky Way and low-redshift Universe. Gaia will be a revolution in mapping of the Milky Way, but it cannot see through the dusty disk to survey the other side of the Galaxy. In addition, the VLBA provides the ability to do high-angular-resolution imaging and spectroscopy of sources like AGN jets. The VLBA provides critical health-of-the-profession capabilities **HP-A** and **HP-C** and furthers certain areas of RMS-related instrumentation.

Arecibo Observatory

The Arecibo Observatory, located in Puerto Rico, is home to the world's largest single dish radio telescope (with a diameter of 305 meters) with observations possible at wavelengths between 3 and 92 cm. The scientific goals of Arecibo are broad: radio astronomy, study of the atmosphere, and characterization of Solar System and Near-Earth Objects. Following the recommendation of the 2006 Senior Review that AST reduce its support for Arecibo, it is now supported cooperatively among NSF/AGS, NASA, and NSF/AST. The single dish is fixed, but with a steerable secondary reflector, and observations can be made for objects with declinations -1 to +38. Arecibo also has a 7-beam receiver used for sensitive, wide-field imaging at 21 cm in both spectral line and continuum known as the Arecibo L-band Feed Array (ALFA). In the near future, the Puerto Rican Ultimate Pulsar Processing Instrument (PUPPI), a pulsar-timing instrument identical to the Green Bank Ultimate Pulsar Processing Instrument backend (GUPPI), will be deployed. On longer timescales, AO40 is planned to be a 40-element focal plane array replacement for ALFA.

Capabilities: Arecibo provides critical technical capabilities **TC-I** and **TC-L** for progress in several highly-ranked *NWNH* and *V&V* science areas: pulsar discovery and timing observations soon to be enhanced by PUPPI (critical technical capability **TC-L**) and radar characterization of primitive bodies (supported principally by NASA funding, capability **TC-I**), which increases our ability to assess asteroid impact risk. In addition, wide-field observations for transient detection (Discovery Area: Transients) and wide-field, sensitive surveys in HI and in continuum using ALFA are supporting technical capabilities that Arecibo offers. Arecibo can also be included as a very sensitive element for the supporting technical capability of very-long baseline interferometry (VLBI). Arecibo provides access to the world's largest single dish telescope for the U.S. Community **(HP-A, HP-C)**. Arecibo has an active education and public outreach program: a large number of workshops and student research training programs **(HP-Q, HP-R)** are carried out at Arecibo and the bilingual Visitor Center attracts up to 100,000 visitors annually **(HP-S)**.

Cerro Chajnantor Atacama Telescope (CCAT)

CCAT is a proposed wide-field-of-view, 25-meter submillimeter telescope to be sited adjacent to ALMA in Chile, which will observe at wavelengths of 0.35 to 2.1 mm. Its major role is as a submillimeter survey instrument with an etendue substantially in excess of ALMA. The telescope design is driven by the desire to spatially resolve the submillimeter extragalactic background at the shortest wavelengths and thereby move past the confusion limit to dramatically improve the detectability of faint submillimeter sources. Recommended as the only specific medium-scale project by *NWNH*, the first light instruments include short- and long-wavelength continuum array cameras, a direct detection multi-object spectrograph, and a modest heterodyne receiver array operating at 0.3-0.6 mm. The design phase is nearing completion, with partial support by AST.

Capabilities: If constructed, CCAT would provide critical technical capabilities **TC-H** and **TC-K**: submillimeter/mm continuum imaging and submillimeter/mm imaging spectroscopy, both over wide fields of view. In particular, the submillimeter wide-field surveys are a critical technical capability to enable U.S. science return with ALMA (**HP-A**). Wide-field ALMA surveys are inefficient, so CCAT would be important for identifying galactic and extragalactic targets for detailed characterization by ALMA. The deep, large-area surveys that would be enabled by CCAT should yield new Galactic, extragalactic and Solar System science, especially in combination with deep optical and infrared imaging. As with the GSMT, the construction and operation of this next-generation facility would have a significant positive impact on the health of the profession in terms of research, instrumentation, and training, by enabling the critical health of the profession capabilities **HP-A, HP-C, HP-H, HP-I, HP-J, HP-K, HP-L, HP-M, HP-N, and HP-O**.

9.2.2 Radio, Millimeter and Submillimeter Facility Recommendations

Recommendation 9.7: **We recommend that the NSF support Atacama Large Millimeter/submillimeter Array (ALMA) operations and development over the next decade but cap the U.S. share of operations at ~$40M/year over this time period in Scenario B.**

As a newly constructed international RMS flagship facility, ALMA is already the world's premier submillimeter/mm interferometer. The committee strongly recommends continued NSF support for ALMA, albeit with a push for cost containment. The committee is aware that this will result in a slight decrease in purchasing power, but believe that as the facility matures, operations can be optimized. A non-advocate review of ALMA operations in 2015 with the charge of itemizing and prioritizing costs within the project could allow the partners to make cost-informed decisions about on-going project scope.

Recommendation 9.8: **We recommend that NSF continue to fund the Karl G. Jansky Very Large Array (VLA) at its current scope.**

Recently upgraded, the VLA is one of the world's most sensitive and flexible instruments for cm continuum and imaging spectroscopy over a very large range of wavelength (0.6 to 30 cm). When properly phased, its collecting area can also be used as a sensitive single dish element with important science drivers. The next decade should see many new scientific results in the areas of the *NWNH* recommendations from the VLA.

Conclusion: **The committee ranks the remaining RMS facilities in the order (1) Arecibo, (2) VLBA, and (3) GBT.**

The committee carefully evaluated the relative capabilities of Arecibo, the VLBA, and the GBT relative to other RMS facilities and their relevance to carrying out *NWNH* and *V&V* science priorities. Given that the highly constrained budget in any scenario may not allow for support of all RMS facilities, we place a higher priority on supporting Arecibo than the VLBA or the GBT. Although the VLBA offers a unique high angular-resolution capability that supports *NWNH* science priorities, and the GBT offers many flexible and sensitive observing modes, these facilities do not provide highly-ranked critical technical capabilities for addressing *NWNH* and *V&V* science questions. The unmatched collecting area of Arecibo at low frequencies is a strong complement to the high angular resolution of very sensitive interferometers such as ALMA and VLA for making progress in critical science areas – although Arecibo covers a smaller portion of the sky than does the GBT. New and planned Arecibo instrumentation (PUPPI and AO40) will enhance Arecibo's ability to address *NWNH* science goals. AST divestment from Arecibo might also cripple the radar characterization of small bodies in the Solar System, which was one of the most highly ranked *V&V* priorities for ground-based observations for the next decade. Continued instrumentation development and training programs will be important in mitigating negative impact to the health-of-the-profession capabilities lost when RMS facilities close.

The VLBA provides the highest angular resolution available from the ground, a unique capability and important follow up capability. Through operational consolidation with the VLA and cost-sharing with non-NSF partners, the VLBA operating cost to AST is now of order $4M/year. The possible extension of the distance ladder through high precision astrometry over the coming decade is especially noteworthy (though expanded maser distance measurements would likely require the HSA). Nonetheless, these distance-ladder improvements were not deemed critical to the *NWNH* science program, reducing the priority of the VLBA.

Finally, the committee places a lower priority on supporting operations of the GBT than either the VLBA or Arecibo. With operations costs of order $10M/year, the GBT supports a much smaller user community than does the VLA (or will ALMA) and delivers fewer technical capabilities critical to achieving the science goals laid out in *NWNH* or *V&V*. Critical technical capability **TC-L**, for pulsar discovery and timing, typically uses wavelengths below 10-60 cm, where Arecibo surpasses the capabilities of the GBT because of its larger collecting area, though with severe sky coverage constraints. GBT is a potential site for array cameras providing the >3mm portion of critical technical capabilities **TC-H** and **TC-K**, submillimeter/mm spectroscopy and continuum observations (respectively) over wide fields. The cost of continued operation and instrumentation development of GBT to provide these capabilities must be balanced against, e.g., acquiring broader capabilities in the submillimeter/mm via CCAT or extended operation of existing smaller-aperture mm survey facilities such as ACT and South Pole Telescope. The GBT's contribution to critical technical capability **TC-I**, small-body radar observations, can be largely replicated by phased-array operation of the VLA.

To obtain the supporting capabilities for *NWNH* science that currently use the short-wavelength instruments on the GBT, the U.S. community would need to turn to the similarly-instrumented German 100m Effelsberg telescope, with lower sensitivity but with 40% open access to external astronomers based on scientific merit. Although not a single dish, the VLA offers imaging spectroscopic capabilities flexibly for wavelengths as short as 6 mm with favorable sensitivities that can be observed over a wide range of spatial scales.

The committee recognizes that the capabilities provided by the short-wavelength and pulsar-timing instrumentation on the GBT, as well as the spectroscopic capabilities for characterizing complex molecules and the potential for large-format heterodyne arrays and mm continuum imagers, will be significant losses to the community if the GBT cannot remain open, and that the future of other projects at Green Bank and the continued existence of the National Radio Quiet Zone might be placed at risk. Scientifically, the phased-array mode of the VLA (currently under development) can mitigate some of these losses, and we therefore suggest that its development should be made a priority by NRAO. Health-of-the-profession impacts will occur in both access and instrumentation, as outlined above.

Recommendation 9.9: **We recommend that AST discontinue the University Radio Observatory (URO) program. To provide an opportunity to preserve the valuable contributions from university-based radio instrumentation groups, we recommend that these groups compete in the MSIP for fixed-term, science-driven projects.**

The wavelength-based approach to the dedicated support of university-led facilities has been central to the development of the U.S. RMS community and has led to major contributions to non-university projects such as ALMA. However, as we go forward into the next decade, a wavelength-based approach to such projects may not provide the best capabilities for addressing *NWNH* science. In addition, the URO model of funding facilities at the level of $3-6M/year in return for community access is no longer sustainable over 7-10 year periods of time in any realistic budget environment. Instead, fixed-term science and/or instrumentation projects can be competed in the Mid-Scale Innovations Program (MSIP, see Chapter 8). We recognize this carries real risk to the sustainability of RMS instrumentation programs at the universities, and the associated health of the profession, especially in challenging budget environments. However, this challenge is true at other wavelengths as well, and we argue that a broader competition among mid-scale projects will allow peer-review selection of the strongest proposals.

Recommendation 9.10: **We recommend that AST provide partial funding to the construction and/or operations of CCAT through the Strategic Investments Program later in the decade, if and when funding for the Mid-Scale Innovations Program exceeds $30M per year.**

The *NWNH* description of the CCAT project calls for AST funding of $7.5M/year of ongoing operations costs, in addition to a substantial construction contribution. This does not fit the 5-year fixed-term requirement of a MSIP project under our definition for this program. Rather, CCAT would be considered a mid-scale *facility* and should be considered as part of the SIP as described in Chapter 8. We judge CCAT to be a very valuable opportunity but one that must not preempt the frequent funding opportunities of a vigorous MSIP program. Fixed-term proposals for CCAT instruments could compete in the MSIP program if CCAT were able to secure construction and operations funds by other means.

9.3 Solar Facilities

The solar optical and infrared facilities supported by NSF are predominantly the National Solar Observatory (NSO; within NSF/AST) and the High Altitude Observatory (HAO; within NSF/AGS). They are joined by five public/private solar observatories, of which the Big Bear Solar Observatory (operated by New Jersey Institute of Technology) possesses the largest telescope (the New Solar Telescope, or NST, a 1.6-meter off-axis clear aperture telescope with adaptive optics). These independent observatories have somewhat fragile funding streams, with significant prior reductions in support for them by the Office of Naval Research and the Air Force Office of Scientific Research. They also have close collaborative links with both NSO and HAO.

The national ground-based solar OIR facilities are currently based at two sites: Kitt Peak, AZ and Sacramento Peak, NM. These facilities are planned to be closed once the Advanced Technology Solar Telescope (ATST), to be built by NSO, is completed and becomes operational in about 2019. The ground-based solar OIR studies are complemented by observations at optical and UV wavelengths from very successful spacecraft like the Solar and Heliospheric Observatory (SOHO), the Transition Region and Coronal Explorer (TRACE), the Solar Terrestrial Relations Observatory (STEREO), and now the Solar Dynamics Observatory (SDO). The NSO Integrated Synoptic Program (NISP) combines two ongoing projects, the Global Oscillation Network Group (GONG), which has distributed sites worldwide, and the Synoptic Optical Long-term Investigations of the Sun (SOLIS).

Solar observations at radio and millimeter wavelengths are being carried out with NRAO facilities such as the VLA and the Green Bank Solar Radio Burst Spectrometer, along with the Owens Valley Solar Array operated by the New Jersey Institute of Technology. ALMA will be capable of probing the lower solar atmosphere.

9.3.1 Overview of Solar Facilities

Advanced Technology Solar Telescope (ATST)

The ATST, to be built on Haleakala on Maui, is an open-air, off-axis all reflective Gregorian telescope with a 4 meter primary mirror. The ATST will have a field of view of up to 180 arcseconds and will resolve down to 0.03 arcseconds in mid-visible light (550 nm) and 0.08 arcseconds at near-infrared wavelengths (1500 nm). This will reveal features as small as 20 to 70 km wide at the solar surface, made feasible with adaptive optics to compensate for atmospheric blurring. ATST will have higher spatial resolution than any OIR solar telescope on the ground or in space. It aims to study the scales at which intense magnetic structures are formed within the highly turbulent convection proceeding just below the solar surface. With Coudé platforms that rotate with the telescope structure, ATST will accommodate an extensive suite of large instruments (such as visible light and NIR polarimeters, tunable visible and IR filters, a broadband filter system). These instruments will exploit the rich diagnostic potential of spectral lines in the visible and NIR parts of the spectrum, such as measuring all four Stokes polarization parameters and generating diffraction-limited vector magnetograms.

Capabilities: ATST will provide critical technical capability **TC-A**, high-angular-resolution solar magnetometry and spectroscopy. ATST will also possess a natural seeing coronographic capability, for the measurement of coronal fields. The ATST will provide transformational technical capabilities in the OIR study of the Sun but also important health-of-the-profession capabilities (**HP-A, HP-C, HP-G, HP-H, HP-I, HP-K, HP-L, HP-M, HP-N, HP-O, and HP-U**).

Dunn Solar Telescope (DST)

The DST at Sacramento Peak is a 76-cm diffraction limited telescope with dual AO paths to instrumentation for spectropolarimetric observations of the solar photosphere and chromosphere, for optical and near-IR observations, supporting a speckle image reconstruction system. The DST is currently the world's most powerful facility available in terms of post-focus instrumentation, and is the only high-resolution solar facility with extensive spectroscopic capabilities open for community access in the U.S.; the new German Gregor telescope is still being completed and offers only part-time access to the U.S. investigators (with a multi-conjugate AO system, developed together with the NSO, being installed this year).

The DST is a development test bed for the high-order AO system needed for ATST, especially for the advanced multi-conjugate AO capabilities of ATST, which includes the development of deformable-mirror systems and their thermal management system. DST's operating mode is as a test bed for ATST "queuing observing mode" to make optimal use of dynamic seeing conditions.

Capabilities: DST provides critical technical capability **TC-A**, high angular-resolution solar magnetometry and spectroscopy. The DST is the world's most capable spectropolarimetric observatory (**HP-A, HP-C**), and provides the ATST testbed for (MC)AO, instrumentation, and dataflow development (**HP-D, HP-I, HP-K, HP-L, HP-N**). DST provides high-resolution, spectropolarimetric observations of the chromosphere in support of NASA/Japanese Hinode and NASA Interface Region Imaging Spectrograph (IRIS) missions (**HP-A**), training of the next generation of ATST researchers and instrumentalists (**HP-O, HP-P**) and experienced staff for ATST testing and operations (**HP-R**).

McMath-Pierce Solar Telescope

The McMath-Pierce telescope at Kitt Peak, AZ has until recently been the largest unobstructed-aperture optical-IR solar telescope in the world, with a diameter of 1.5 m. It has been the only facility worldwide to routinely observe the Sun beyond 2.5 microns in the thermal infrared, which is important for the study of ubiquitous weak magnetic fields and molecular species (CN, CH, CO, H_2O, etc.) It has the unique capability to combine infrared and polarimetric observations, allowing study of the thermal and magnetic structure of the solar atmosphere from the deep photosphere into the upper chromosphere.

Capabilities: The McMath-Pierce provides infrared spectroscopy and polarimetry of the Sun. This telescope currently contributes the only solar observations in the thermal infrared (at wavelengths longer than 2.5 micron) until the IR instruments are deployed at the NST at Big Bear or ATST is on line. The NST 1.6-meter solar telescope is operational and, like ATST, uses an off-axis Gregorian configuration that permits work in the thermal infrared. The McMath-Pierce also provides a test bed for IR instrumentation and data analysis.

NSO Integrated Synoptic Program (NISP)

The NSO Integrated Synoptic Program combines two ongoing projects, the Global Oscillation Network Group (GONG) and the Synoptic Optical Long-term Investigations of the Sun (SOLIS). GONG is a globe-spanning six-site helioseismology and magnetography project, including an H-alpha monitor. To this SOLIS adds full-disk photospheric and chromospheric vector-magnetography (currently at a single site, but the NSO is looking for international partners to expand SOLIS to a network) and spectroscopic observations of the Sun as a star. The main aim of the synoptic program is to observe the solar interior dynamics and the surface/chromospheric (vector-) magnetic fields routinely and systematically in order to collect information on the solar dynamo, while providing context information for high-resolution solar observations and for space-weather purposes.

Capabilities: GONG and SOLIS provide supporting capabilities for *NWNH* (and the Solar decadal report) science goals: (1) Ground-based helioseismology and long-term synoptic magnetometry and seismology. (2) Ground-based astero-seismology, in the sense that the Sun provides an exquisitely detailed seismology data set. These projects also provide the continuity of acoustic interior studies over multiple magnetic cycles (the first full cycle has just been completed with a single facility), which impacts continuity for solar interior records and moderate-resolution full-disk magnetic field data (**HP-A, HP-B, HP-C**). GONG and SOLIS also allow for means to differentiate instrumental or observational artifacts in helioseismic data (**HP-D, HP-P**). For the measurment of the internal solar dynamics through helioseismic analyses, GONG is the only available backup to SDO's Helioseismic and Magnetic Imager (HMI) in case of instrument failure or mission termination. In addition, GONG is capable of providing space weather monitoring data in collaboration with the Air Force Weather Agency. Finally, these projects enable the study of the "Sun as a star."

9.3.2 Recommendations for Solar Facilities

Conclusion: The Advanced Technology Solar Telescope is the top AST priority for solar facilities.

The ATST was a high priority of the astronomy decadal survey in 2000. It has received MREFC funding for construction and should be completed later in the decade, becoming a key part of the AST portfolio. Ensuring high scientific productivity from ATST is of high importance and will require significant operations support as well as support for solar researchers and instrumentation.

***Recommendation 9.11*: AST and NSO should plan for the continued use of the Dunn Solar Telescope (DST) as a world-class scientific observatory, supporting the solar physics community, to within two years of ATST first light, as well as utilize it as a test bed for development of critical ATST instrumentation.**

The top priority among the current solar facilities is the DST, which is currently the world's most powerful facility available in terms of post-focus instrumentation. As the only high-resolution solar facility with extensive spectroscopic capabilities open for community access in the U.S., the operation of the DST is critical to the solar physics community. Moreover, the DST is a development test bed for the advanced adaptive optics system and for the data-flow and observing-mode infrastructures crucial for successful operation of ATST. Maintaining full operational capability of DST until approximately two years prior to ATST coming on-line for scientific observations thus ensures the community's ability to remain at the forefront of international science, positions the community to be ready for exploitation of ATST, and enables the engineering staff to develop and test critical ATST infrastructure. In this context, the NSO should develop an explicit plan for the closure of the DST and the transfer of staff that seeks to minimize the impact of the gap between DST and ATST for the science community and at the same time minimize the cost of the transition in terms of overall staffing for the DST and ATST system during the 2-year transition phase. Should the DST remain scientifically useful as the ATST comes on-line, a privatization plan could be considered.

***Recommendation 9.12*: AST and NSO should develop a plan for the NSO Integrated Synoptic Program (NISP) that includes GONG and SOLIS but that limits AST funding to no more than $2M (FY17) annually. Expanded partnerships for operations should be sought, and the plan should be completed in time for implementation in the FY16 budget. If a partner cannot be found, NISP should be divested entirely.**

The primary aim of the synoptic program is to measure the internal solar dynamics and the surface magnetic field in order to collect information on the solar dynamo, while providing context information for high-resolution solar observations (including NSF's ATST and NASA's space missions including Hinode, SDO, IRIS, Solar Orbiter, and Solar Probe) as well as for space-weather forecasting purposes.

Currently, helioseismic and magnetographic measurements are also being made by SDO's HMI from a stable space-based platform. HMI is funded, at present, through 2015 and its continued existence beyond that time is not assured. Moreover, any major technical problems with HMI or its instrumentation would likely terminate the mission. Given the importance of synoptic solar observations for context studies by high-resolution, small FOV facilities such as ATST and for space weather situational awareness and forecasting, it is unwise to rely on a single data source that might not be funded (or operational) beyond 2015. On the other hand, fiscal constraints limit NSF's ability to support NSIP at its current levels. AST should consult with other federal agencies to determine whether additional support for GONG as a back-up system to currently available space-based observations (especially the Hα monitoring) and SOLIS as a context imaging system for ATST and as a support observatory for solar monitoring in the context of the National Space Weather Program can be obtained. Because NSIP observations are important to multiple agencies and departments, such as NSF, NASA, the Department of Defense, and the National Oceanic and Atmospheric Administration, their joint operation of NSIP is in line with the nation's needs.

***Conclusion*: We rank the McMath-Pierce solar telescope as our lowest priority solar facility.**

The McMath-Pierce solar telescope did not map to any of the critical technical capabilities and will be superseded by ATST. NSO has planned to divest from the McMath-Pierce telescope in its transition to ATST; in the current budget climate, this divestment should happen as soon as possible.

***Recommendation 9.13*: The AST PRC reiterates the importance of the finding of *NWNH* that "NSF should work with the solar, heliospheric, stellar, planetary, and geospace communities to determine the best route to an effective and balanced ground-based solar astronomy program that maintains multidisciplinary ties."**

NWNH continues "Such coordination will be essential in developing funding models for the long-term operation of major solar facilities such as the Advanced Technology Solar Telescope and Frequency-Agile Solar Radio Telescope and in the development of next-generation instrumentation for them along with the funding of associated theory, modeling, and simulation science."

This process should build on the recent decadal surveys by identifying the needs of the nation relating to solar physics and its complementing sciences to study the Sun-Earth connections, should identify gaps and redundancies in existing and planned capabilities, should consider requirements from the astrophysical perspective as well as from the societal impacts of space weather, and should develop a vital research program to maintain world leadership.

The Sun's magnetic activity controls the evolving conditions in space throughout the heliosphere and thus the surroundings of all planets, their moons, and the satellites and – at some future time – manned probes exploring the solar system. As society's reliance on electronic and electrical devices increases – reaching from the ground-based electric power grid to space-based infrastructures for communication, navigation, surveillance, and national security – many sectors of the nation's economic activity and organizations of the national and state governments increasingly require the situational awareness and forecasting of space weather conditions. Solar activity also reaches down into the atmospheric domain, changing upper-atmospheric chemistry and conductivity, and perhaps even modulating weather patterns with the global climate system.

Understanding, modeling, and forecasting solar activity, the resulting space weather, and the societal impact is thus an important field of study for a variety of scientific disciplines and for societal sectors. The needs for solar and inner-heliospheric observations and for environmental and forecasting models for societal impact studies and from the astrophysical perspective frequently overlap but are in many cases fundamentally different.

The diversity of requirements for the range of societal sectors and scientific disciplines make it very difficult for a single division or even agency to make informed decisions about investments being aware of the consequences of any funding decision on the needs of other such sectors and disciplines. Recognizing this problem, magnified in an era of limited financial resources, *NWNH* recommended a national assessment of the needs of solar observations. In the context of the forthcoming 2012 “Solar and Space Physics” decadal survey, this assessment would need to be of even larger scope to encompass the "vision for space weather and climatology" recognized as a National Imperative.

9.4 High Energy AST Facilities

NSF/AST has partnered with NSF/PHY and DOE in the construction of two of the leading ground based high energy astrophysics facilities: the Very Energetic Radiation Imaging Telescope Array System (VERITAS) and the Pierre Auger Observatory. VERITAS is an imaging atmospheric Čerenkov telescope (IACT) array of four 12-meter optical reflectors located at the Fred Lawrence Whipple Observatory in southern Arizona, that observes gamma-rays from astronomical objects in the tera-electronvolt (TeV) energy range. The Pierre Auger Observatory is a 3,000 km^2 array of water Čerenkov detectors overlooked by four fluorescence telescopes built in collaboration with 18 countries in the province of Mendoza, Argentina, to study the origin of ultrahigh energy cosmic rays. The 4th priority *NWNH* recommendation for large ground-based astronomy projects is that NSF partner with DOE to participate in the international effort to build the next generation IACT array, named the Atmospheric Čerenkov Telescope Array (ACTA), described next.

9.4.1 Atmospheric Čerenkov Telescope Array (ACTA):

An international effort is underway to build two large arrays of IACTs that will capitalize on recent scientific advances in our understanding of very high-energy gamma-rays (that is, energies above a few tens of GeV). This next generation γ-ray observatory will significantly increase the sensitivity and energy coverage in gamma-rays to study a wide variety of high-energy astrophysical sources and search for indirect evidence of dark matter annihilation. *NWNH* recommended that the U.S.-led effort, named the Advanced Gamma-ray Imaging System, join the European led effort, the Čerenkov Telescope Array (CTA), in a combined project that includes the best features of each proposed observatory.

The baseline design of the combined CTA project in the Southern Hemisphere calls for three nested arrays of instruments. The low energy array will consist of a few 24m-class telescopes with a FOV of order 4-5 degrees. The next layer in the array will combine a number of 10 to 12m-class telescopes with a FOV of 6-8 degrees reaching an energy range between ~100 GeV to 1 TeV. The third layer of the array will involve a large number of small 4- to 6-meter-diameter telescopes with a FOV of around 10 degrees to operate above 10 TeV. A Northern Hemisphere array is also proposed. CTA will serve as an open observatory to a very broad astrophysics community providing deep insight into the non-thermal high-energy Universe.

Capabilities: ACTA is the international flagship for high energy astrophysics on the ground. It will provide an order-of-magnitude advance in sensitivity to γ-ray sources and will search for dark matter annihilation signals. It is considered a supporting capability (CFP-3), and the likely AST contribution is modest but will provide important U.S. participation in the project (**HP-A**) and can help to ensure project completion and scope.

9.4.2 High-Energy Recommendations

***Recommendation 9.14*: We recommend that support for the Atmospheric Čerenkov Telescope Array (ACTA) be considered by NSF/AST later in the decade through the MSIP or Strategic Initiatives Program, but at lower priority than LSST, CCAT, and GSMT.**

NWNH recommended that U.S. funding for ACTA be shared among DOE, NSF/AST, and NSF/PHY (as in the case of VERITAS), that the U.S. contribution be of the order of $100 million spread between the agencies over the decade, and that the agencies work together to better define the U.S. role in the combined project. A fixed-term proposal for an AST fraction of this ground-breaking instrument could compete in the MSIP program. A longer-term investment via the Strategic Initiatives Program should be considered by AST late in the decade but should be dependent upon sufficient funding that programs ranked higher or equivalently by *NWNH* (LSST, vigorous MSIP, GSMT participation, and CCAT) are well supported. This will likely require budgets at least as strong as Scenario A.

9.5 Inter-wavelength Priorities and Rankings

Having ranked the facilities within each wavelength group, we now consider the full prioritization.

***Recommendation 9.15*: The committee regards ALMA, VLA, ATST, Gemini-South, Blanco, and DST as essential facilities for the AST portfolio.**

ALMA, VLA, and ATST are newly constructed or comprehensively upgraded state-of-the-art facilities. AST should operate all three this decade in any plausible scenario. Gemini-South is the largest U.S. optical telescope in the Southern Hemisphere and has capabilities that are very well matched to ALMA, Blanco/DECam, LSST, CCAT, and JWST. The Blanco hosts a world-leading wide-field imager, which will enable a set of high-profile science applications and which provides a key pathfinder to LSST. The DST is the bridge to ATST; with NSF investing $300M in ATST, it is essential to continue to support and grow this user community in preparation for the large advance that ATST will make possible. AST would divest from the DST as ATST nears completion.

Recommendation 9.16: **Based on their capabilities and current cost, the committee ranks the remaining facilities in the priority order (highest to lowest): Gemini-North, Arecibo, Mayall, VLBA, NISP, GBT, SOAR, WIYN, and McMath-Pierce.**

As discussed above, the committee ranked Gemini-North as the next highest OIR priority, followed by Mayall and then by SOAR and WIYN. The committee ranked Arecibo as the next highest RMS priority, followed by VLBA and GBT. The committee ranked the integrated synoptic solar program as the next solar priority, followed by the McMath-Pierce solar telescope.

The committee ranks Gemini-North as the most important of this set, followed by Arecibo. Gemini-North is the flagship open-access OIR telescope in the U.S. and can address a number of critical technical capabilities and support a large user base. Arecibo is the largest single-dish radio telescope in the world and likely to be the only single-dish radio telescope remaining in the AST portfolio; it can provide world-leading capabilities at wavelengths longer than 10 cm for pulsar timing and 21 cm emission. AST also has an agreement with NSF/AGS that provides substantial cost sharing for Arecibo.

The next priorities are the Mayall, VLBA, and NISP. The Mayall telescope (and the Kitt Peak 2.1-meter telescope, whose operations piggyback on the Mayall) provides a large number of open access nights and access to workhorse OIR instrumentation. The VLBA provides a unique window to sub-milliarcsecond imaging and high precision astrometry. However, the high brightness constraints limit the VLBA's utility and hence the user base. We rate the Mayall higher due to its large user base and workhorse instrumentation.

The committee saw high value in NISP. SOLIS can play an important role to supply context for ATST observations, while GONG supports a long-running helioseismology effort. However, the committee believes that cost sharing is possible, given the large number of other constituencies and nations interested in the Sun. If this cost sharing can be arranged, then we judge that the core capabilities of the NISP and its connection to ATST are important enough and inexpensive enough to preserve; we will return to this in Chapter 10.

The next priorities are the GBT and SOAR. The GBT is the world's most sensitive single-dish radio telescope at wavelengths shorter than 10 cm; however, its capabilities are not as critical to *NWNH* science goals as the higher-ranked facilities. The VLA operates over similarly high frequencies and can be used to access many of the spectral lines at its shortest wavelength (0.6 cm); the German Effelsberg 100m provides another route to the shortest wavelengths, albeit at lower sensitivity. The phased-array mode of the VLA is an option for pulsar timing observations. Low frequency observations (at wavelengths longer than 10 cm) can be done as well or better at Arecibo Observatory in the areas of the sky it can access. The SOAR telescope is a Southern Hemisphere facility, less common in the U.S. system, and hence well positioned for ALMA, DECam, and LSST follow-up. However, AST is only a 30% partner and Gemini-South is a stronger platform for AST investment. The partnership agreement for SOAR runs until 2018 and we recommend that AST evaluate the SOAR capability later in the decade to decide whether to continue, as SOAR might be of more utility in the LSST era.

Finally, the lowest ranked facilities are WIYN and the McMath-Pierce. AST has a 40% share of the WIYN telescope, which has struggled to bring the ODI to completion. We do not see a sufficiently critical technical capability that WIYN is unique in bringing to the AST portfolio. McMath-Pierce is an aging solar facility. While unique in the mid-IR observations of the Sun, we did not see this as a sufficiently important capability to preserve.

10 Recommended AST Portfolios

10.1 Recommendations of Priorities and Budgets

Having discussed the pieces of the AST portfolio, we now combine them into integrated portfolios to match the two budget scenarios given in Chapter 3. Clearly, a wide range of possible implementations can be considered. In constructing the recommended portfolios, we have been guided by the principles outlined in Chapter 2 and the compelling scientific opportunities described in *NWNH*, as translated into critical capabilities in Chapters 5 and 6.

10.1.1 Balance of Grants and Facilities

Maintaining a balance among facilities, grants, and novel experiments and surveys enabled by the latest technologies, such as has been provided in AST portfolios over the past decades, is especially critical. As discussed in Chapter 3, our more pessimistic budget Scenario B represents a large loss of AST purchasing power over the coming decade and a factor-of-two reduction relative to the assumptions of *NWNH*. Maintaining the current set of facilities (assuming 2.5% annual inflation) along with the planned operation ramps on ALMA and ATST would result in an immense reduction of the AST small and mid-scale grants programs and fail to open any funding for *NWNH*-recommended facilities. For example, the strawman status quo budget in Table 3.3 of Chapter 3 would see a 75% reduction in the grants programs by FY17.

In the view of the committee, this would be a disaster for the field. Small-grants support is essential to getting science from the existing facilities, both public and private, and it is essential for training the next generation of astronomers. Mid-scale projects, as described in Chapter 8, figure heavily into a wide range of *NWNH* science goals and our critical capabilities. Further, they are an efficient way to implement new technologies. To maintain a fleet of facilities without adequate grants support or a competitive portfolio for new instruments, surveys, and experiments is a prescription for stagnation. In terms of the health of the profession, this would imply loss of or significant reductions in health-of-the-profession critical capabilities **HP-B**, **HP-H**, **HP-I**, **HP-J**, **HP-K**, **HP-L**, **HP-N**, and **HP-P**.

***Recommendation 10.1*: AST should maintain substantial funding to AAG, ATI, and a mid-scale program as a top priority.**

We see it as highly important to keep the level of "free energy" in the AST portfolio at least comparable to that of today, so that funding can flow to new ideas and new projects. As described in Chapter 3, *NWNH* recommended significant increases in AAG, ATI, TSIP, and mid-scale projects, in addition to new facilities. The resulting *NWNH* portfolio would have a similar grants-to-facilities ratio as the current AST portfolio. *NWNH* further states that "…it is absolutely necessary for the health of the whole astronomy and astrophysics enterprise to increase the support of individual investigators [...]. Reallocation of resources may have to come at the expense of support of existing missions/facilities and new projects." (p. 134)

We do not place a firm lower bound on these programs because it is inevitable that the grants programs, being more flexible, will serve as the capacitor against budget fluctuations. However, we believe that AST should strive to maintain these programs and ideally fund them at the high levels recommended in *NWNH*. However, the strawman status quo scenario (Chapter 3) of extrapolating the current facility operations budgets (Table 3) falls well short of this, and the damage inflicted by this approach in budget Scenario B is so great that our committee believes that AST must take action to reduce this risk.

Recommendation 10.2: **AST should plan its facility portfolio assuming the more pessimistic range of forecasts (e.g., Scenario B), with the result that more optimistic budgets (e.g., Scenario A) can have heavier re-investment in the field through the small-grants and mid-scale programs.**

Facility investments are typically slower to change than funding for grants programs. Divestments will require several years to implement, and partnership agreements can extend even longer. We do not have the luxury of knowing what the FY17 budget will be far enough in advance to adjust the facility choices to match perfectly. The alternative of attempting to stay the course on facilities, hoping for better budgets, such as Scenario A, carries the significant risk of sweeping cuts in all grants programs should those budgets not materialize. This will be particularly important in the next two years, when the budget squeeze is expected to be most severe and in anticipation of the need to identify funds for the ATST operations ramp. Because of this recommendation and the knowledge that facility divestments can take years to perform, our FY17 portfolios for budget Scenarios A and B will contain the same set of current facilities. This implies that despite the high priority we place upon the AAG, ATI, and mid-scale programs, these carry the bulk of the differences between Scenarios A and B.

As with the grants programs, cuts to facilities that are too deep would also damage the health of the profession, especially in critical health-of-the-profession capabilities **HP-A**, **HP-N**, and **HP-O** through the loss of open access time, especially on the largest, most capable platforms. Other observatories, such as those provided by medium-sized OIR telescopes or the independent RMS telescopes of the URO program, often serve as a principal training ground for students, and so changes here can affect critical health-of-the-profession capabilities **HP-I**, **HP-M**, and **HP-N**. Our recommended facility mix is intended to preserve or acquire the critical technical capabilities needed to meet *NWNH* priorities (as outlined in Chapter 5), while leaving room for new science and technology (via the mid-scale program) and protecting the health of the profession through variegated access to telescopes, data archives, and computational tools. Given the challenging budget environment and the compelling need to achieve a balance between observatories and grants, some reduction in access to the current facilities is inevitable—even without any new investments in the projects and programs recommended by *NWNH*.

10.1.2 AST Facilities

We next present our recommended portfolios for Scenarios A and B. Facility recommendations are presented in this subsection, followed by subsections about mid-scale grants and small grants. Budgets for both scenarios are given in Table 10.1. Further discussion is given in section 10.1.5 with visual summaries in Figures 10.1 and 10.2.

Recommendation 10.3: **Our recommended portfolio includes ALMA, ATST, VLA, Gemini, Blanco, DST, Arecibo, NISP, and SOAR.**

This suite of facilities is based on the priority rankings from Chapter 9. SOAR did not rank highly, but as noted in Chapter 9, we do not recommend that AST break the partnership agreement currently in force.

As described in Chapter 9, we recommend that the DST be closed about two years before ATST first light and that AST funding of NISP be capped at $2M (FY17) annually. With the cap on NISP funding, we recommend to preserve NISP ahead of the significantly more expensive Mayall, VLBA, and GBT facilities. NISP will support ATST by supplying the full-disk context of the ATST observations and is important for monitoring of space weather. Although these programs did not rate as highly as others for their *NWNH* technical capabilities, our committee is reluctant to end the monitoring programs of the Sun, particularly as we enter the ATST era. However, we do believe that cost sharing and/or reductions can be found. If no cost sharing or reductions can be found by FY16, then we recommend that AST divest from NISP.

As described in Chapter 9, we recommend a cap of $17M (FY17) on the U.S. share of Gemini, excluding major instrumentation. As described in Chapter 8, we recommend that major instrumentation initiatives at these observatories be competed in the MSIP line, not as fixed instrumentation budgets attached to each facility.

Recommendation (from Chapter 9): **We recommend that LSST begin construction with an MREFC start in FY14 or as soon as possible thereafter, so as to maintain an expected start of operations in late 2021 or early 2022.**

LSST is the top-ranked *NWNH* large project and it connects strongly to many of the *NWNH* science questions and discovery areas. Proceeding on LSST does not impact the FY17 AST budget. The operations budget requirements in FY22 can be accommodated because of the facility reductions that will need to happen to meet the anticipated FY17 budget forecast.

Recommendation (from Chapter 9): **We recommend that AST provide partial funding to the construction and/or operations of CCAT through the Strategic Initiatives Program later in the decade, if and when funding for the Mid-Scale Innovations Program exceeds $30M per year.**

CCAT is the top-ranked medium-sized project from *NWNH*. We recommend that AST pursue CCAT if it can reasonably expect to be able to fund the remainder of the small-grants and mid-scale programs at a level of at least $105M, i.e., half way between Scenarios A and B.

The FY22 portfolios follow directly from the FY17 cases, with the addition of LSST in both cases and CCAT and some GSMT funding in Scenario A. The FY22 Scenario A portfolio contains considerable flexibility for AST to respond to new science and technical opportunities through small grants and mid-scale funding. Scenario B would be more restricted.

Recommendation 10.4: **AST should reevaluate its participation in Arecibo and SOAR later in the decade in light of the science opportunities and budget forecasts at that time.**

If funding remains tight later in the decade, then the scientific need for continued AST funding for Arecibo and SOAR must be weighed against the needs in the grants programs. The AST current agreement with NSF/AGS on the operations of Arecibo runs through 2016, while the partnership agreement with SOAR runs through 2018. Although we have included both facilities in our FY22 Scenario B budget, we believe that the low level of grants funding in this case will demand a critical look at the science opportunities of Arecibo and SOAR late in the decade. From our vantage point today, the science return from pulsar timing on Arecibo and the suitability of SOAR to study LSST and ALMA sources are the most relevant metrics. Of course, these science opportunities may evolve over the next 5 years.

Recommendation 10.5: **In our Scenario A, we recommend that AST contribute of order $20M/year to GSMT late in the decade**.

This could happen either through a formal partnership as a Strategic Investment or through proposal-driven funding of instrumentation and operations through the Open-Access Capabilities component of the MSIP. We have allocated $20M/year to this in our Scenario A FY22 budget. Attaining the *NWNH* goal of a 25% AST share in total GSMT costs would be dependent upon additional construction funding through the MREFC line. Even in the absence of MREFC funds, a SIP or MSIP investment would give all U.S. astronomers some access to a GSMT.

Recommendation 10.6: **We recommend that AST divest from the Mayall, WIYN, and 2.1-meter telescopes at Kitt Peak, the Robert C. Byrd Green Bank Telescope, the Very Long Baseline Array, and the McMath-Pierce solar telescope.**

Our portfolios do not include these facilities. We recognize that these will be painful losses for the astronomical community, as these are well-used and scientifically productive facilities. There is no doubt that these facilities would be highly productive in the coming decade and that they would impact on *NWNH* science goals. Kitt Peak National Observatory, in particular, is a mainstay of U.S. OIR astronomers, with over 800 open-access nights. GBT and VLBA have world-leading capabilities in some aspects of radio astronomy.

However, we must judge these facilities against the rest of the portfolio in the context of a limited budget and in light of possible investments toward future paths for the field. We have concluded that these facilities rank below the ones included in our FY17 portfolio in terms of their science opportunities and cost effectiveness. These facilities have a total annual budget of approximately $20M for operations, plus additional and less easily quantified shares of centralized costs in their parent observatories. Preserving any of them would force a substantial additional reduction in the small-grants and mid-scale programs, which are critically stressed in our portfolios. By decreasing the facility budget and preserving new investments through the grants programs, AST can be prepared to support a new generation of projects when the financial climate does improve.

As discussed in Chapter 9, we recommend that AST divest from the WIYN and McMath-Pierce telescopes in any realistic budget scenario. These facilities were our lowest ranked and we see no plausible scenario in which they could be retained ahead of the Mayall, Very Long Baseline Array, and Green Bank Telescope.

Divestment need not mean the closure of a facility; it simply means the end to AST operations support. We expect that AST will explore many possible divestment implementations. Finding new organizations to fund and operate the facilities is clearly preferable to mothballing or permanent closure. This might, of course, include other NSF divisions or government agencies.

We are aware that these divestments largely affect sites in the continental U.S. However, we believe that the leadership of U.S. astronomy depends on access to the very best astronomical sites, e.g., the high, dry, and clear sites in Hawaii and Chile. Most major new AST facilities constructed in the last two decades (Gemini, ALMA, and ATST, plus LSST in the future) have been sited to take advantage of these conditions and maximize their scientific effectiveness. There remains an extensive network of non-AST telescopes operating in the continental U.S. that preserve an active research and educational mission, often with AST funding for instrumentation and supplemental operations.

Future budgets are never certain, and if realistic AST forecasts prove to exceed our Scenario A, then AST might consider preserving funding to these facilities. Following the rankings of Chapter 9, we recommend a prioritization with the Mayall highest and most important to preserve, followed by the VLBA, and finally the GBT. However, this ranking does not imply a time-ordering of divestments, which may depend on many implementation factors.

Recommendation 10.7: **We recommend that AST divest in a manner that is responsible to its fellow tenants at observatories and to its long-duration user programs**.

Given the heavy budget pressure in the coming years, we expect that facility divestments will need to proceed promptly in order to unburden the FY17 budget. However, facilities operated by other organizations also operate at these sites, and provide valuable astronomical resources. It is important not to create a cascade of closures of non-AST facilities when divesting.

Furthermore, some of these facilities are engaged in long-term monitoring programs. Consideration should be given to maximizing return from these programs, as they leverage past observing time. However, the completion of these programs cannot itself justify delay in the divestiture.

Table 10.1 — Recommended portfolios for Scenarios A and B, along with a comparison to the FY10-12 baseline. All dollar values are in then-year $M. Purchasing power comparisons are relative to the average FY10-12 baseline and assume 2.5% annual inflation. We remind the reader that the budgets for the observatories are only suggestive and are not based on detailed analysis of the budgets required for the revised set of facilities.

Programs (All budget values in $M)		**Scenario A**		**Scenario B**	
	FY10-12	**FY17**	**FY22**	**FY17**	**FY22**
Small Grants					
AAG	47.0	46.3	51.8	37.4	38.1
ATI	10.5	11.0	12.4	9.0	9.0
AAPF	2.4	2.6	2.9	2.0	2.0
AST Observatory Postdocs	0.0	2.0	2.3	1.5	1.5
Theory & Computation Networks	0.5	2.0	2.3	1.0	1.0
New Funding for Workforce Diversity	0.0	1.0	1.1	1.0	1.0
Other small grants	12.3	14.0	14.1	14.0	14.1
Total for Small Grants	**72.7**	**78.9**	**86.9**	**65.9**	**66.7**
Purchasing power: Small Grants	100%	94%	91%	78%	70%
Mid-Scale Grants					
Mid-Scale Projects	18.9	38.0	43.0	20.0	20.0
Strategic Investments D&D	6.8	2.0	5.0	2.0	2.0
Data Stewardship	2.0	1.0	1.1	1.0	1.0
Total for Mid-Scale	**27.7**	**41.0**	**49.1**	**23.0**	**23.0**
Purchasing power: Mid-scale	100%	128%	135%	72%	63%
Total for Small + Medium Grants	**100.4**	**119.9**	**136.1**	**88.9**	**89.7**
Purchasing Power: Small+Medium	100%	103%	103%	76%	68%
National & International Observatories					
NOAO	27.0	14.5	16.4	14.5	16.4
Gemini	20.1	17.0	19.2	17.0	19.2
NRAO	43.1	25.0	28.3	25.0	28.3
EVLA construction	2.5	0.0	0.0	0.0	0.0
ALMA Ops & Development	23.4	40.8	46.2	40.0	40.0
Arecibo	6.7	4.2	4.8	4.2	4.8
NSO sans ATST	9.1	4.8	2.3	4.8	2.3
ATST	1.3	16.0	19.5	16.0	19.5
LSST Ops	0.0	0.0	26.5	0.0	26.5
SIP: CCAT Construction & Ops	0.0	10.0	7.4	0.0	0.0
SIP: GSMT	0.0	0.0	20.0	0.0	0.0
Total for Obeservatories	**133.2**	**132.3**	**190.5**	**121.5**	**156.9**
Purchasing power: Observatories	100%	86%	109%	79%	90%
Non-research expenses	4.7	4.9	4.9	4.9	4.9
EARS	1.0	12.0	12.0	12.0	12.0
Total AST Budget	**239.3**	**269.1**	**343.5**	**227.3**	**263.5**
Purchasing power w/o EARS	100%	93%	106%	78%	80%
Percentage: Small Grants	30%	29%	25%	29%	25%
Percentage: Mid-scale Grants	12%	15%	14%	10%	9%
Percentage: Small+Mid-scale Grants	42%	45%	40%	39%	34%
Percentage: Observatories	56%	49%	55%	53%	60%

Regarding the URO program, as discussed in Chapters 8 and 9, we recommend that AST discontinue the URO program and that these proposals compete in the MSIP for fixed-term, science-driven projects. In Scenario B, however, MSIP will almost certainly be heavily oversubscribed, so this is likely to result in reductions of funding to previous URO recipients.

Estimating budgets for the national observatories, given our large recommended changes in their facility portfolios, is necessarily uncertain. These are complicated organizations with a wide range of interleaved activities and with significant administrative requirements. The budgets listed in Table 10.1 are suggestive, based on reading of the observatory program plans and other AST input, but are not based on detailed analysis of how the observatory would function with a different set of telescope facilities. We have assumed 2.5% annual inflation.

In addition to the changes in the facility portfolio, we are recommending that funding for prize fellowships be moved to the AST Observatories Postdoctoral Fellowship program and that funding for major instrumentation projects be competed in the MSIP.

Our portfolio for NOAO includes running the Blanco and SOAR telescopes as well as system interfaces such as the National Gemini Office. The divestment of KPNO activities is expected to be a significant cost savings. We estimate budgets of $14.5M in FY17 and $16.4M in FY22 for NOAO.

Our portfolio for NRAO includes running the VLA and system interfaces. The divestment of GBT and VLBA is expected to be a significant cost savings. We estimate budgets of $25M in FY17 and $28.3M in FY22.

As described in Chapter 9, we recommend that the ALMA operations budget be held to about $40M through the decade in Scenario B, although we restore the baseline plan supplied by AST in Scenario A.

Our portfolio for NSO includes running the DST and the NISP, as well as ATST. For the non-ATST portion, we estimate a budget of $4.8M in FY17 and $2.3M in FY22 (the DST having closed by then).

Our portfolio includes operations support for Arecibo assuming a continuation of the current level of cost sharing, although the agreement with NSF/AGS runs through 2016. Including inflation, we estimate AST support of $4.2M in FY17 and $4.8M in FY22.

We did not include estimates for divestment costs, as these depend sensitively on implementation. We note that reducing AST costs to zero by FY17 may require ending science operations well before FY17, so that the facility budget can be used to fund divestment activities.

10.1.3 Mid-Scale Grants

Turning to the non-facilities portion of the portfolios, we recommend the implementation of a mid-scale innovation projects and strategic investment lines as described in Chapter 8.

***Recommendation 10.8:* We recommend heavy investment into the Mid-Scale Innovations Program (MSIP), particularly in the more optimistic Scenario A portfolio.**

This line now encompasses several activities that used to be distinct, including URO and TSIP funding of new instruments and open-access time from non-AST facilities, funding of major instrumentation at AST facilities, new surveys and dedicated experiments, laboratory astrophysics projects, and data-related activities such as the VAO.

We have explicitly highlighted the importance of setting up a center to provide stewardship of ground-based data, although our funding level here is only indicative. Following Chapter 8, we include $1M for a data archive, likely through the Strategic Investments Program. Additional funding might come from programs in the NSF Office of Cyberinfrastructure or of course from sources beyond NSF.

***Recommendation 10.9:* In the near term, we recommend only minimal funding of additional strategic investments beyond CCAT, GSMT, and data archive(s)**.

NWNH has set priorities to include LSST, CCAT, and GSMT that are already explicitly in our portfolio, and we do not anticipate the budget capacity to make additional long-term arrangements. If budgets rise toward FY22 (e.g., Scenario A), we would expect the strategic investments to increase as new large facilities are considered, e.g., in the next round of decadal surveys. We include $2M in the SIP for ongoing design work toward major facilities, rising to $5M annually in FY22 Scenario A.

For the total of mid-scale efforts, our Scenario A portfolio contains a total of $41M in FY17 and $49.1M in FY22. This would allow substantial new investments in instruments, system improvements, surveys, and projects. However, Scenario B contains only $23M in FY17 and FY22 for such items, which is a 30% decrease relative to current investment levels. Indeed, the baseline of $27.7M in FY10-12 stated in Table 10.1 does not include major instrumentation funding in national facility budgets, so the drop is underestimated. This outcome would pose a substantial challenge to the field with a lengthy period of underinvestment in mid-scale projects.

10.1.4 Small Grants

Following the recommendations in Chapter 7, we continue the AAPF program at its current level in Scenario A. We reduce it to an annual budget of $2M in Scenario B. We include funding for the AST Observatories Postdoctoral Fellowship program in both scenarios: $2.0M in Scenario A and $1.5M in Scenario B.

We include the Theory and Computation Network in both scenarios, at a level of $2M (FY17) in Scenario A and only $1M in Scenario B. The latter may require less frequent proposal calls.

We include $1M (FY17) for new support of projects that directly seek to improve minority recruitment and retention.

For FY22, we attach 2.5% annual inflation to these funding levels in Scenario A and flat fund in Scenario B.

Beyond this, we have not closely critiqued the various smaller individual investigator programs, many of which are required as NSF-wide mandate and/or support important goals such as diversity and undergraduate research. We have continued these programs as planned. We then divide the remaining money between the AAG and ATI programs at approximately the FY10-12 baseline split. In Scenario A, this yields \$46.3M for AAG and \$11M for ATI for FY17, growing approximately with inflation to FY22. In Scenario B, this yields \$37.4M for AAG and \$9M for ATI in FY17 and essentially no increase to FY22. Scenario A is approximately a 15% drop in AAG and ATI relative to FY10-12 purchasing power, whereas Scenario B is a 30-35% drop.

These decreases in the purchasing power of AAG and ATI are distressing given their central role in AST-funded astronomical research. In particular, we regard the situation for both small and mid-scale grants in Scenario B, despite the considerable recommended reductions in the facility portfolio, as strong motivation for AST to act decisively in its divestments and to recover appropriate centralized costs from the affected observatories.

10.1.5 Quantitative Summary

Figure 10.1 present overviews of our recommended portfolios for these two budget scenarios. The top-level categories of small grants, mid-scale innovation grants, and current facility operations are shown, along with the budget for new facilities and strategic investment design & development funding. These graphs have been scaled by 2.5% annual inflation to FY11 dollars.

In Scenario B, the purchasing power of the small grants is 78% of the FY10-12 funding level in FY17, dropping to 70% in FY22. In Scenario A, the purchasing power is 94% in FY17 and 91% in FY22. Including all small-grants and mid-scale programs, the FY17 spending on grants in Scenario B is 76% of FY10-12 grants' purchasing power, dropping to 68% in FY22. In Scenario A, it is 103% in both FY17 and FY22. In other words, the difference between Scenario A and B is disproportionately in the mid-scale program, which jumps in FY17 from 72% of FY10-12 purchasing power in Scenario B to 128% in Scenario A.

For comparison, total inflation-adjusted AST spending on facilities compared to FY10-12 is 79% in FY17 (90% in FY22) in Scenario B and 86% (109%) in Scenario A. The increases toward FY22 and toward Scenario A are driven by new investments in LSST, CCAT, and GSMT. The fraction of the AST budget spent on facilities stays close to its current level of 56% in FY10-12: 53% in Scenario B FY17 (60% in FY22) and 49% (55%) in Scenario A. This is actually an underestimate because the facilities will compete for instrumentation funding in the MSIP and because the funding for observatory prize postdocs has been moved from the facility lines to the AST Observatory Postdoctoral Fellowship program.

Figure 10.2 shows another view of the same data, this time focusing on the changes between Scenario A and B.

The budget pressure posed by Scenario B will be difficult for all facets of the AST portfolio. We stress that the decisions facing AST and the astronomical community in FY17 Scenario B do not involve new commitments toward major facilities. Figure 10.1 makes clear that simply bringing the existing commitments to ALMA and ATST to enable their efficient and effective scientific use in a constrained budget environment will require significant evolution in the facility portfolio. World-class facilities take many years to build, and successful operations require relatively stable budgets. Despite significant cuts in the facility portfolio, our recommended portfolio for Scenario B decreases grants funding somewhat more than facility funding. In a stronger budget scenario, AST would begin construction on CCAT and more heavily fund the mid-scale program, including the Open-Access Capabilities program.

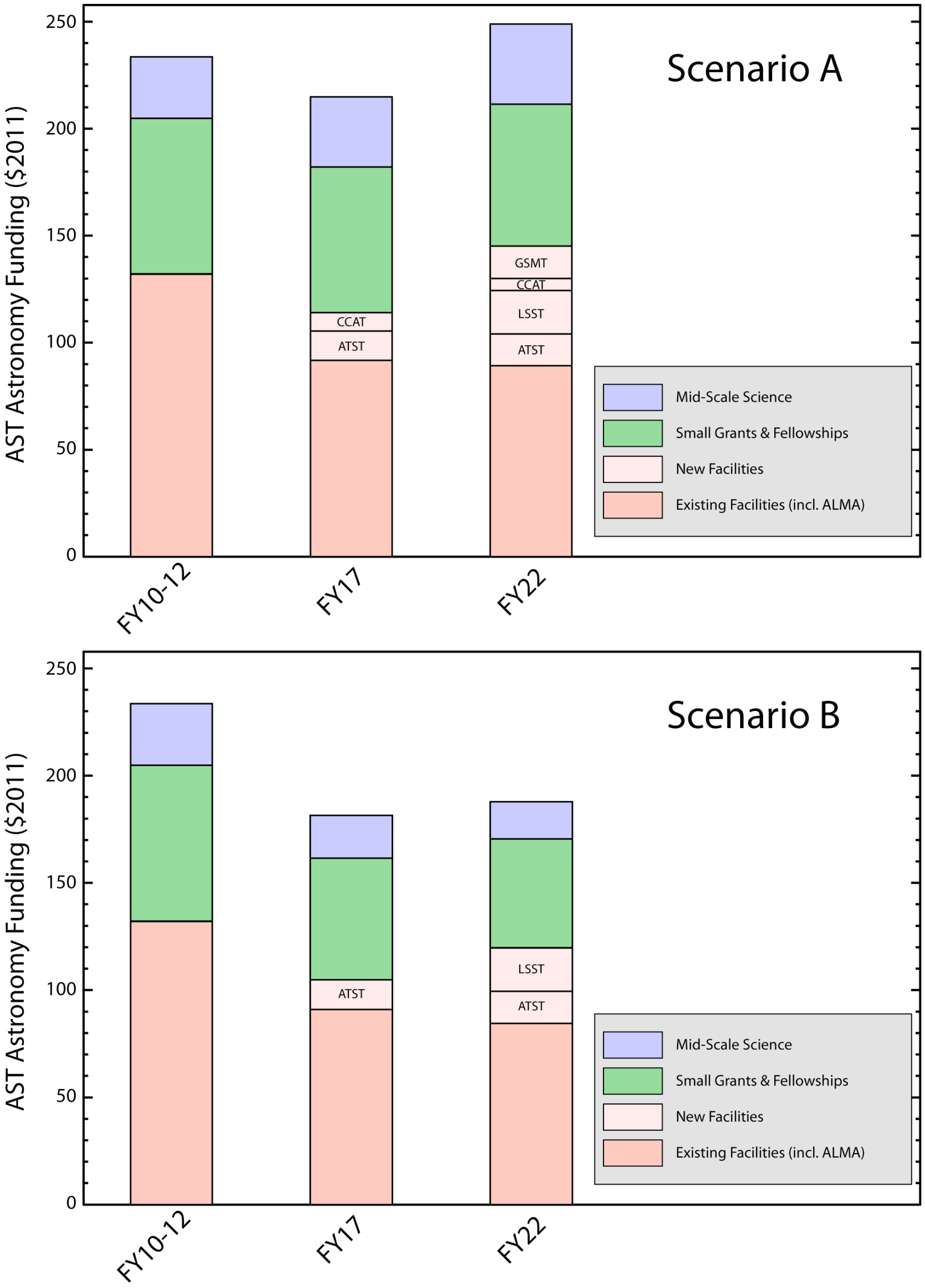

Figure 10.1 — Top-level summaries of the two portfolios. Scenario A is in the top panel; Scenario B is in the bottom panel. All values are scaled by 2.5% annual inflation to FY11 dollars. The blue bars are mid-scale grants, including strategic investments; the green bars are small grants and fellowships. The red bars are funding for current facilities, including ALMA. The beige bars are new facility initiatives, labeled.

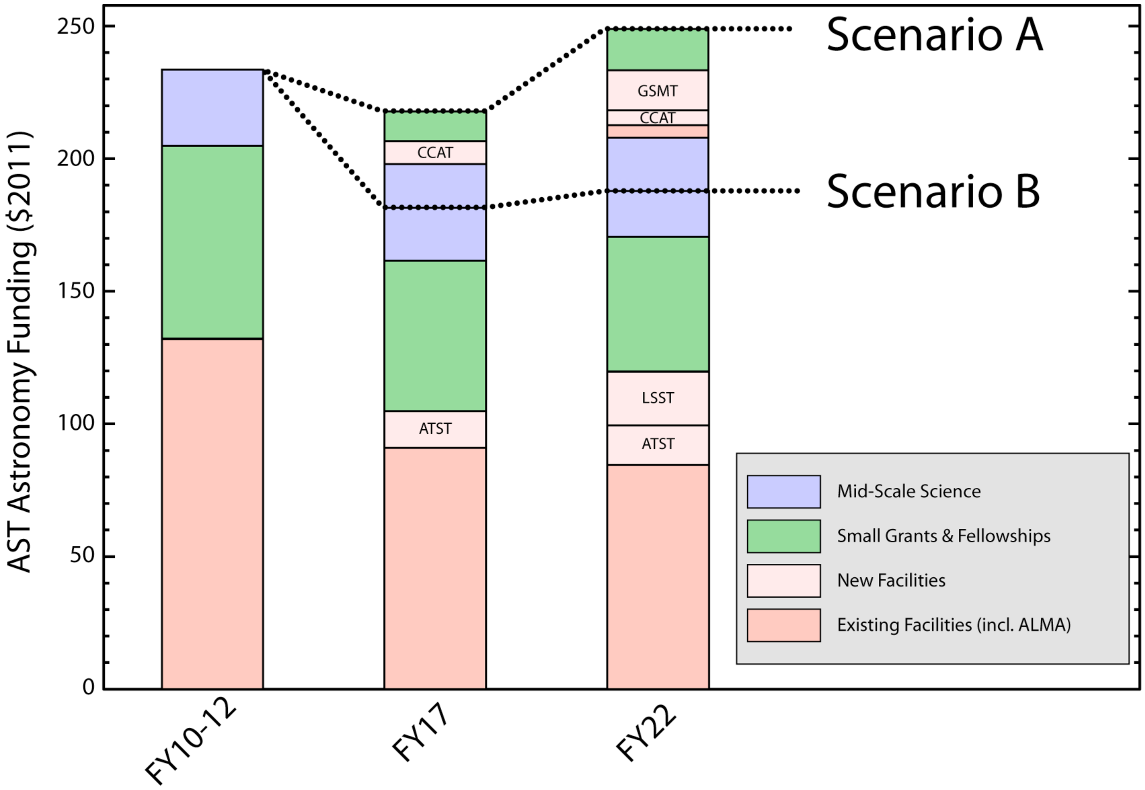

Figure 10.2 — Another representation of the recommended portfolio focusing on the differences between Scenarios A and B. Colors are as in Figures 10.1. All values are scaled by 2.5% annual inflation to FY11 dollars.

10.2 Evaluation of Technical Capabilities of the Recommended Portfolios

Having identified in Chapter 5 the critical technical capabilities for achieving *NWNH* science priorities, we recommend a portfolio of AST facilities and programs that will provide these capabilities in the most effective and forward-looking manner, consistent with the budget scenarios and with maintaining the health of the profession. Here we examine the means by which each critical technical capability would be provided within the recommended portfolio. The ordering of these technical capabilities does not have significance. For each technical capability, we reiterate the science areas for which it was deemed critical, and its relative ranking within that science theme. We also boldface the AST portfolio elements that we propose to provide the capability.

Solar Technical Capabilities

TC-A. Sub-arcsecond solar magnetometry and spectroscopy: (SSE: 3) The **ATST** will be the world leader in this capability and is supported in all scenarios. Observations and development at the **DST** are supported until effort switches to the ATST.

Lab, Theory, and Computational Technical Capabilities

TC-B. Supercomputing to support suites of 3-D simulations: (CFP: 4; GAL: 3; SSE: 2; PSSF: 12) At present, AST support for supercomputing takes the form of personnel support through the **AAG** program, while the computing resources are obtained through NSF-supported centers and other programs such as MRI. The recommended portfolio continues this practice in both scenarios and adds support for **Theory and Computation Networks**.

TC-C. Data-driven science infrastructure: (SSE: 8) This capability can be funded by several grants programs, including **AAG**, **MSIP**, and other NSF programs such as Big Data. A data archive, identified in both portfolios, would put such infrastructure into practice. **Theory & Computation Networks** might enhance this infrastructure in some cases, although it is not the principal focus of the program.

TC-D. Laboratory astrophysics, to measure key atomic and molecular line frequencies and collisional cross sections (PSSF: 9) Proposals to provide this capability would compete in the **AAG, ATI,** and **Mid-Scale Science** programs, depending on scale. MRI support is also possible. The provision of public spectral-line physical databases would also be appropriate for proposals to the **Open Access Capabilities** program. The mid-scale programs are substantially enhanced in Scenario A.

RMS Technical Capabilities

TC-E. High-angular-resolution (milliarcsecond to arcsecond) submillimeter/mm imaging spectroscopy (interferometric arrays): (GAL: 2;

PSSF: 2) World-leading capabilities provided by **ALMA** are supported in all proposed portfolios. New specialized or developmental capabilities for ALMA should compete in the **Mid-Scale Science** and **Open Access Capabilities** programs according to the emphasis on directed science or general use, respectively.

TC-F. CMB polarization experiments (arcmin-scale mm/cm polarimetry): (CFP: 3) This capability is very well suited to compete in the **Mid-Scale Science** program, which has a much stronger budget in Scenario A.

TC-G. High-angular-resolution (subarcsecond to arcsecond) mm/cm imaging and kinematics (interferometric arrays): (GAL: 6) World-leading capabilities provided by **ALMA** (mm) and the **VLA** (mm/cm) are supported in all proposed portfolios. New specialized or developmental capabilities for ALMA or the VLA should compete in the **Mid-Scale Science** and **Open Access Capabilities** programs according to the emphasis on directed science or general use, respectively.

TC-H. Moderate-angular-resolution (few-arcsecond) submillimeter/mm imaging spectroscopy over wide fields (degree) with polarimetry (single dish): (PSSF: 6) Provision of this capability with the full power envisioned by *NWNH* awaits the construction of **CCAT** and receiver array cameras. AST support of CCAT would be part of the **Strategic Investments Program** in Scenario A. The recommended divestment from the GBT has a moderate impact, as a receiver camera providing this capability at >3 mm could be placed there. More modest mapping capabilities exist or could be built at private facilities, *e.g.,* the Large Millimeter Telescope (LMT), Arizona Radio Observatory (ARO), Caltech Submillimeter Observatory (CSO), and Combined Array for Research in Millimeter-wave Astronomy (CARMA) – development of and/or open access to these capabilities could compete in the **Mid-Scale Science** and **Open Access Capabilities** programs, which are much enhanced in Scenario A.

TC-I. Radar characterization (cm) of primitive solar system bodies (single dish): (PSSF: 11) The **Arecibo** capability is unique and is supported in all scenarios. The bistatic mode, necessary for the closest-approaching objects and for degeneracy-breaking, is currently implemented using the GBT and VLBA as receiving stations. In our recommended portfolios, the "speckle mode" capability using the VLBA would be lost, but the capability of GBT in bistatic operations could be provided by phased-array operation of the **VLA**.

TC-J. High-angular-resolution (sub-arcsecond to arcsecond) mm/cm continuum observations with polarimetry (interferometric arrays): (GAL: 9) World-leading capabilities at **ALMA** and **VLA** are supported in all proposed portfolios. New specialized or developmental capabilities will compete in the **Mid-Scale Science** and **Open Access Capabilities** programs according to their emphasis on directed science or general use, respectively.

TC-K. Moderate-angular-resolution (few arcsecond) mm/submillimeter continuum imaging over wide (degree) scales with large-format detector arrays: (PSSF: 7) Provision of this capability with the full power envisioned by *NWNH* awaits the construction of **CCAT** and direct detector array cameras. AST support of CCAT would be part of the **Strategic Investments Program** in Scenario A. The recommended divestment from the GBT has a moderate impact, as the MUSTANG bolometer array provides continuum mapping capability at >3 mm, with upgrades possible. More modest mapping capabilities exist or could be built at current mid-scale (e.g., Atacama Cosmology Telescope, South Pole Telescope) and private facilities (*e.g.* the LMT, ARO, CSO) – development of and/or open access to these capabilities could compete in the **Mid-Scale Science** and **Open Access Capabilities** programs, which are much enhanced in Scenario A.

TC-L. Centimeter-wave broadband continuum observations using large collecting area and pulsar timing backends: (SSE: 5) The recommended divestment from the GBT will seriously impact this capability as it is currently available and routinely used with the GUPPI backend. However, the identical PUPPI backend on **Arecibo** will provide this capability. Outside the declination range accessible to Arecibo, this capability could be implemented through phased-array observations from the **VLA**. Development of the necessary equipment and methods, along with observational projects, could be proposed to the **ATI** and **Mid-Scale Science** programs.

TC-M. Moderate- to high-angular-resolution (sub-arcsecond to arcsecond) cm continuum follow-up observations: (SSE: 9) The **VLA** offers open access to the world's best implementation of this capability, and will continue operation in all scenarios. The recommended divestment from the **VLBA** will somewhat impact this capability as it provides an order of magnitude more accurate positional information for follow-up observations of transient sources that are bright enough to be observed.

OIR Technical Capabilities

TC-N. Wide-field optical imaging, including the time domain: (CFP: 1; GAL: 1; SSE: 1; PSSF: 5) The Dark Energy Camera (DECam), nearing commissioning on the **Blanco**, will provide world-leading wide-field optical imaging of the Southern Hemisphere and will have U.S. open-access time. Only the Japanese Hyper-SuprimeCam, also soon to be commissioned on Subaru in the Northern Hemisphere, has a larger product of aperture and field of view. With a timely MREFC start, the **LSST** will be the world-leading facility of this type, with survey operations to start in 2021. Both DECam and LSST leverage substantial DOE support. We recommend continuing both Blanco and LSST in any scenario.

However, both portfolios recommend divestment from the Mayall and WIYN, which feature existing (Mayall/Mosaic) and upcoming (WIYN/ODI) imaging cameras that provide open-access in the Northern Hemisphere. Neither of these instruments is competitive with HyperSuprimeCam, and there are several other competitive wide-field imagers with private U.S. access in the Northern Hemisphere, including PanSTARRS, the Palomar Transient Factory, the Canada-France-Hawaii Telescope MegaCam, and the LBT Large Binocular Camera, as well as ODI through the non-AST partners. However, the loss of Northern wide-field imaging is a significant loss to the open-access community; one that might be addressed with the **Open Access Capabilities** program.

TC-O. High-multiplex, *R*~few thousand spectral resolution optical spectroscopy: (CFP: 2; GAL: 5) The capability to measure thousands of objects at once does not currently exist anywhere in the world. Among existing U.S. telescopes, either public or private, the Mayall and Blanco telescopes are uniquely suited to implement the necessary wide-field capability. There are proposals to build high-multiplex instruments for each telescope, with substantial leverage from DOE (BigBOSS and DESpec, respectively). Instruments and/or surveys for either site would be highly competitive in the **Mid-Scale Science** and **Open Access Capabilities** programs in our proposed portfolios. While we recommend ending operation of the Mayall as a user facility, this would not preclude its operation as a dedicated survey facility with funds from the competed MSIP and/or outside agencies. Funding for U.S. use of the proposed Subaru Prime Focus Spectrograph could also be requested through the MSIP program. The likelihood of successful implementation of this critical technical capability is higher in Scenario A than in Scenario B given the twice-larger MSIP funding in the former scenario.

TC-P. Moderate-multiplex, *R*~few thousand spectral resolution optical spectroscopy of faint targets: (CFP: 5; GAL: 4) Open access to this capability over the full sky will be provided by the GMOS instruments on **Gemini-N** and **Gemini-S**. Every private telescope of 6.5-meter aperture or larger also provides this capability. Improved future instrumentation on Gemini, plus open access to existing and improved instruments on private telescopes, would compete in the **Open Access Capabilities** program. Improved private instrumentation with directed science programs would compete in the **Mid-Scale Science** program. These opportunities for improved instrumentation and open access would be substantially enhanced by the larger MSIP budget in Scenario A.

TC-Q. Target-of-Opportunity optical imaging and spectroscopy on large telescopes: (CFP: 6; GAL: 4) As for capability **TC-P,** open access to this capability over the full sky will be provided by the GMOS instruments on **Gemini-N** and **Gemini-S**, and most large private telescopes have suitable, high-efficiency instruments with this capability. Improved future instrumentation and/or increased public access would compete in the **Open Access Capabilities**, which is substantially enhanced in Scenario A.

TC-R. Workhorse instruments on mid-sized telescopes (modest-field optical & NIR imaging and spectroscopy), including synoptic monitoring: (SSE: 6; PSSF: 8) Open access to this capability in the South will continue at the **Blanco** and **SOAR** telescopes in both scenarios. In the North, the recommended divestiture from Mayall and WIYN will severely impact this capability. Making up for this, however, should be an improved ability for **Gemini-N** to execute short workhorse-style programs that would have taken much longer on Mayall or WIYN. A vigorous **Open Access Capabilities** program would also be essential to keeping this capability strong and forward-looking in both hemispheres. The Open Access Capabilities program will be stronger with the larger MSIP budget in Scenario A.

TC-S. High-spectral-resolution optical spectroscopy, leading to GSMT implementations: (SSE: 7) Open access to this capability will be provided by the GRACES project at **Gemini-N** and by the GHOS project at **Gemini-S**. The **Open Access Capabilities** program could fund additional instrumentation or acquire access to existing/new capabilities on the private large telescopes. The Open Access Capabilities program will be stronger with the larger MSIP budget in Scenario A. Funding for **GSMT** capabilities would enter the **Strategic Investments Program** in Scenario A.

TC-T. Extreme-precision optical (10 cm/s) and NIR (1 m/s) Doppler spectroscopy: (PSSF: 1) This capability does not currently exist anywhere in the world. Developmental efforts would compete in the **ATI** and **Mid-Scale Science** programs (depending upon proposal scale). Deployment of an instrument would compete in the **Mid-Scale Science** and/or **Open Access Capabilities** programs, which are much better funded in Scenario A. The **Gemini** telescopes are available as potential platforms for the new spectrograph in either scenario, as would be numerous private telescopes.

TC-U. NIR/mid-IR R~few hundred spectral resolution, high-angular-resolution spectroscopy (AO): (PSSF: 3) The GeMS AO system on **Gemini-S** will provide open access to this capability at the 8-meter diffraction limit. The ALTAIR system at **Gemini-N** would continue to be available. Continued development and operation of this capability on large private telescopes, and/or open access to such capabilities, (e.g. the Large Binocular Telescope Interferometer) would occur through the **Mid-Scale Science** and **Open Access Capabilities** programs, which are much enhanced in Scenario A. Funding for **GSMT** capabilities would enter the **Strategic Investments Program** in Scenario A.

TC-V. Diffraction-limited imaging and integral field spectroscopy on large OIR telescopes with adaptive optics: (GAL: 7) The GeMS AO system on **Gemini-S** will provide open access to this capability at the 8-meter diffraction limit. Continued development and operation of visible/NIR AO capabilities on 8m-class private telescopes, and/or open access to such capabilities, would occur through the **Mid-Scale Science** and **Open Access Capabilities** programs, which are much enhanced in Scenario A. Funding for **GSMT** capabilities would enter through the **Strategic Investments Program** in Scenario A.

TC-W. Moderate-multiplex R~few thousand spectral resolution NIR spectroscopy of faint targets: (GAL: 8) The Flamingos-2 instrument on **Gemini-S** will soon provide Southern open access to this capability. Several U.S. private large telescopes have this capability at present. Improved instrumentation for **Gemini-N, Gemini-S,** and private telescopes, plus open access to the private resources, would compete in the **Mid-Scale Science** and **Open Access Opportunities** programs, which are much enhanced in Scenario A.

TC-X. Low to moderate spectral resolution NIR spectroscopy of faint targets: (PSSF: 10) Full-sky open access to this capability will continue to be provided through **Gemini-N** and **Gemini-S** telescopes in all proposed portfolios, including adaptive optics for higher signal-to-noise-ratio observations on single targets. Improved instrumentation for **Gemini-N** and **Gemini-S** and for private telescopes, plus open access to the private resources, would compete in the **Mid-Scale Science** and **Open Access Opportunities** programs, which are much enhanced in Scenario A. Funding for **GSMT** capabilities would enter through the **Strategic Investments Program** in Scenario A.

TC-Y. NIR high contrast imaging and coronography for direct detection of planets: (PSSF: 4) The current ALTAIR/NIRI on **Gemini-N** and the upcoming, more capable GPI on **Gemini-S** will provide open access to this capability in all scenarios. Private telescopes are developing improved capabilities in the North. Future instrumentation for **Gemini-S** and for private telescopes would compete in the **Mid-Scale Science** and **Open Access Opportunities** programs, which are much enhanced in Scenario A. Funding for **GSMT** capabilities would enter the **Strategic Investments Program** in Scenario A.

10.3 Evaluation of Health of the Profession Capabilities of the Recommended Portfolios

Access to Facilities and Resources

HP-A. The ability to compete regularly for access to telescopes, instruments, and observing opportunities to carry out innovative astronomical research.

HP-B. Cost-effective allocation and sharing of resources through the federal and non-federal elements of the OIR and RMS systems.

HP-C. Access to surveys and archival astronomical data, after a reasonable proprietary period.

HP-D. Access to the software necessary for basic reductions of astronomical data and the generation of catalogs in the case of surveys.

The divestment from the Mayall, WIYN, and 2.1-meter OIR telescopes at Kitt Peak, GBT, VLBA, and the McMath-Pierce solar telescope in our portfolios represents a significant loss of open-access observing time, particularly in the Northern Hemisphere. A larger **MSIP Open-Access Capabilities** program should restore some of that time across a more diverse set of facilities and capabilities. The **URO** program will end, but fixed-term RMS projects will be able to compete in the overall **MSIP** program. Access to archival data and open access surveys (e.g., DES) produced by NSF-funded facilities and **AAG**-and **MSIP**-funded science programs will be provided more uniformly. For example, all levels of LSST data products will become available to U.S. institutions. The new **Strategic Investments** funding line for **Data Stewardship** will offer opportunities for better data curation on many scales. Larger projects proposing for **MSIP Open Access Capabilities** funds will be selected in part by giving heavy weight to the ability to reduce data to a usable scientific form through software if necessary.

HP-E. The ability to compete regularly for access to world-leading computational facilities to carry out innovative numerical simulations and calculations.

HP-F. The ability to perform innovative theoretical calculations including pure theory and phenomenology.

These capabilities are supported in the proposed portfolios through the regular individual-investigator grants (**AAG**), the postdoc grants (**AAPF**), and a new **Theory & Computational Networks** program that has dedicated funding for such projects (slightly more support in Scenario A than Scenario B). In addition, for fixed-term numerical simulation initiatives above the threshold for the TCN program, opportunities exist in the **MSIP** line.

HP-G. The ability to carry out innovative experiments in laboratory astrophysics.

This capability is supported in the proposed portfolios through the regular individual-investigator grants (**AAG**). Proposals of larger scale and longer term would be considered in the **Mid-Scale Science** line, and contributions to public databases of lines and cross-sections would be appropriate for consideration as **Open Access Capabilities**. Subject to the outcome of peer-review competition in these programs, laboratory astrophysics purchasing power would follow the overall grants funding profiles discussed in both Scenarios. In Scenario B, this would make it difficult to follow the *NWNH* recommendation: "…NASA and NSF support for laboratory astrophysics under the Astronomy and Physics Research and Analysis program and the Astronomy and Astrophysics Research Grants program, respectively, should continue at current or higher levels over the coming decade because laboratory astrophysics is vital for optimizing the science return from current and planned facilities…" (p. 162)

HP-H. The funding support for both scientific groups and individual investigators to engage in creative and innovative astronomical research.

Although this capability is supported in all of the proposed portfolios (through **AAG, AAPF, AST Observatories Postdoctoral Fellowship, ATI, TCN** opportunities and other small grants), there is some loss in the purchasing power of **AAG** and **ATI** in both of our budget scenarios. In Scenario B, the total purchasing power of all grants is about 68-76% of the current level. This is improved in Scenario A, and in particular the **MSIP** will get a significant boost to restore funding for investigators across a more diverse set of facilities and capabilities.

Instrumentation

HP-I. The ability to design, develop and build instrumentation that is necessary to pursue forefront astronomical research.

HP-J. Grants opportunities at small, medium and large scales to encourage the continuity, longevity, and advancement of existing instrumentation groups (including continuity of soft-money technical staff) and support the development of new instrumentation groups.

HP-K. The ability to pursue research on innovative "blue sky instrumentation" to make important advances on technical fronts.

HP-L. The ability to afford and construct the most complex instruments that the next generation of large telescopes across the electromagnetic spectrum will require.

Capabilities for astronomical instrumentation are supported in all of the proposed portfolios. In addition to the regular individual-investigator grants (**AAG**), opportunities exist through the **ATI** line (for technology development), and through the two strands of **MSIP**: **Mid-scale Science and Open Access Capabilities**, both of which have an emphasis on instrumentation for fixed-term projects. For longer-term projects or instruments, there may be very limited funding available through the **Strategic Investments Program (SIP)**. Though the national facilities are facing budget cutbacks, there should be room in their budgets to handle instrument upgrades and small new experiments, and deal with occasional instrumentation failures. The NSF-wide **MRI** line will also continue to support such efforts up to $4M. Very large and complex instrumentation, requiring tens of millions of dollars, will need funding from the **MSIP** program.

The recommended termination in all budget scenarios of the wavelength-based instrumentation and access programs (i.e., URO, TSIP, ReSTAR, etc) may impact the ability of all of these groups to remain active and for their facility operations to be fully funded. However, competitive funding for fixed-term, science-driven instrumentation and facility projects for these groups is available through the **MSIP** line (which is boosted in Scenario A).

Training for personnel for instrumentation is supported through regular individual-investigator grants (**AAG**), postdoctoral grants (**AAPF** and the **AST Observatories Postdoctoral Fellowship Program**), the **REU** program, and the **MSIP** line (which is boosted in Scenario A). However, **ATI** is a key component in building small and/or innovative instrumentation projects that would welcome undergraduate participation.

Career support and progression

HP-M. Opportunities to participate in creative and innovative research at all stages of a career, including undergraduate and graduate education, postdoctoral fellows, soft-money science positions, research positions, and tenure-track faculty.

HP-N. The ability to receive training and mentoring to prepare for differing astronomical specialties, including education, instrumentation, theory, laboratory work, data-mining, and computation. The ability to receive

advanced training in non-research skills such as communication and management needed for scientific activities.

HP-O. Opportunities to progress through different stages of a scientific career, and have the opportunity to have a long-term career in astronomy.

HP-P. Opportunities to contribute to stewardship activities that benefit the entire community, including, but not limited to: software development, instrument development, educational materials, lab measurement, and calibration activities.

The dominant funding source in the AST portfolio for personnel outside of the national facilities is the **AAG** program plus other grants aimed at small groups of investigators (such as **ATI** and **Theory and Computational Networks**). Under our two scenarios, the AAG together with ATI grants would lose purchasing power of about 10% in the more optimistic Scenario A, and about 30% (24% in FY17 and 34% in FY22) in the pessimistic Scenario B. Personnel of all career stages would also be funded under the **MSIP** line. For **MSIP**, there is an increase of purchasing power under Scenario A of about 30% and a decrease of about 30% under Scenario B.

The **REU** program is preserved in its current form under all budget scenarios. The **AAPF** program is preserved under all budget scenarios, albeit with a small cut in the pessimistic Scenario B. The AST Observatories Postdoctoral Fellowship will add more flexibility to postdoctoral fellows wishing to participate at national facilities with roughly the same number of positions funded. Many programs such as **GRF**, **CAREER**, and **ADVANCE** are NSF-wide and will continue if determined by NSF.

Overall, the purchasing power for personnel will be approximately flat in Scenario A and suffer a 30% cut in purchasing power in Scenario B. This will be a qualitative shift in the overall path of the profession, as it is a reversal of the trend of the last decade in which the funding for individual AST grants increased significantly.

Interruptions in funding grants and facilities divesting or closing are likely to have disproportionate negative impact on astronomers in the postdoctoral fellow phase or those in soft-money positions in astronomy. For pre-tenure faculty, the low success rates for AAG proposals may hamper the ability to continue to more senior positions since many research universities use the ability to attract grants as one of the selection criteria for promotion.

Within the national facilities, there will be significant reductions of scientific personnel. In either scenario, facilities that employ large numbers of astronomers will divest or be closed, and the personnel will either seek other astronomical employment or will leave the field. This may be partially compensated by new facilities coming on line in Scenario A, but it is unclear what the net effect would be.

Training and mentoring in astronomy occur most commonly at universities at the graduate and undergraduate level supported by **AAG** and other small grants which will suffer a 30% cut in purchasing power in Scenario B. Many undergraduate and graduate students learn the skills of observing from using small telescopes, making the closing of the public OIR facilities and the URO program of great concern. Some of these opportunities could be restored under the **MSIP Open Access Capabilities** program.

Diversity of the Workforce

HP-Q. Opportunities for all those interested and capable of doing astronomical work to do so.

HP-R. New groundbreaking programs to significantly increase the involvement and numbers of underrepresented minorities in the field.

Generally, there are no changes to HP-Q within either scenario from the current state of the portfolio, since selection of scientific programs relies on the two background-neutral criteria of Intellectual Merit and Broader Impact. However, care must be taken in implementation to avoid obstacles in reaching a more diverse population or in excluding a class of citizens.

The cut in the **AAG** program in Scenario B is likely to affect the rate at which diversity is achieved as the investment on younger, more diverse, workforce is deterred. Divestment from observatories will negatively affect outreach programs associated with them. The recommended changes in the **PAARE** program should increase the opportunities for programs to encourage diversity. The additional $1M/year intended for minority recruitment and retention in astrophysics should enable additional creative programs to be funded in this important area.

Education and Public Outreach

HP-S. The ability to deliver effective and innovative astronomy education and outreach programs to K-12 students, college students, and the general public through activities at small and large scales.

The previously mentioned **AAG** cuts in Scenario B will also have a negative impact on this capability, as the amount of Broader Impact projects scales with small-grants funding. However, the preservation of funds for the **AAPF** program in both scenarios will positively influence this capability. The NSF-wide **CAREER** program will likewise allow for positive EPO programs.

Several of the facilities being closed have nearby visitor centers, making the divestment of facilities a negative impact on this capability. The Green Bank Science Center and the Kitt Peak National Observatory Visitor Center & Museum may suffer negative impacts from the adjacent telescopes being divested, though the exact amount of impact is unclear. Similarly, NRAO, NOAO and NSO have professional EPO personnel who might be downsized in observatory restructuring.

10.4 Impact of the Recommended Portfolios

We conclude this Chapter by summarizing the impact of the recommended portfolios. How well would they do in providing the technical and workforce critical capabilities for *NWNH* and *V&V* science goals? What might we predict about the future of U.S. leadership in astronomy and the health of the profession in these scenarios?

We find it possible in Scenario A to create an AST portfolio that provides nearly all critical ground-based capabilities for *NWNH* and *V&V* science, albeit with less U.S. (especially public) share in some of them and substantially less support for the astronomical workforce than *NWNH* recommended. Several areas are readily identified as exceptional strengths of U.S. astronomy under Scenario A. With DECam on Blanco, then the advent of LSST giving world's-best capability **TC-N**, and a well-funded MSIP that could support massive-multiplex optical spectroscopy (**TC-O**), U.S. leadership in OIR wide-field/survey astronomy would be likely. In addition, there are U.S. institutional partners in superb new wide-field capabilities on the Subaru telescope. ATST would secure world-leading progress in ground-based solar astronomy goals through capability **TC-A**. The VLA and ALMA would dominate world capabilities in spectroscopic and continuum observations of resolved objects and point sources from the cm through the submillimeter (**TC-E, TC-G**, **TC-J**, and **TC-M**). Toward the end of the decade, CCAT would enable U.S. leadership in science with mm/submillimeter wide-area surveys as well (**TC-H** and **TC-K**), with substantial U.S. public access, although divestment from GBT may reduce nearer-term capabilities in the mm and cm. Advanced adaptive optics capabilities on Gemini-S and on private 8m-class telescopes in the North should enable U.S. leadership in direct detection of exoplanets (**TC-Y**), and the strong MSIP should enable extreme-precision spectroscopy for Doppler detection of exoplanets (**TC-T**). Arecibo's planetary radar would remain uniquely powerful in the world (**TC-I**) and the most sensitive pulsar receiver (**TC-L**). A strong MSIP should enable first-rate ground-based CMB polarization experiments (**TC-F**) as well.

Outright U.S. leadership in non-survey OIR imaging and spectroscopy capabilities (**TC-P**, **TC-Q**, **TC-R**, **TC-S**, **TC-U**, **TC-V**, **TC-W**, **TC-X**) is less assured in Scenario A, especially given the heavy international investments in the ESO Very Large Telescope (VLT, four 8-meter telescopes) and planned Extremely Large Telescope (39-meter), but AST and private funding will provide significant access to the capabilities for the U.S. community. With AST OIR facilities funding more heavily focused on Gemini and a strong MSIP program that funds instrumentation upgrades for public as well as private facilities, we would expect a substantial enhancement in the 8m-class capabilities available through AST-funded open access, as well as leveraging of these funds to keep instrumentation on the more numerous large private telescopes at the state of the art. Scenario A gives the open-access community some entry into the era of 20+-meter telescopes through AST funding of operations and/or instrumentation of a GSMT, although the capital investment needed to obtain a 25% share (as recommended by *NWNH*) would require MREFC funding. Divestments will reduce the *quantity* of time available via open access to moderate/small OIR telescopes, but the portfolio aims to increase the value of each night, by raising the average aperture, site quality, and instrumentation quality of AST-funded OIR observations, and leaving the OIR portfolio with stronger capabilities for *NWNH* science at the close of the decade.

Divestitures would reduce the reach of single-dish RMS observations, and VLBI available to U.S. astronomers. Our portfolios are designed, however, to maintain as much access as possible to the *critical capabilities* by funding those facilities most powerful and relevant to *NWNH* science goals.

Either scenario would mark the end of the last decades' expansion in AST support of the astronomical workforce through small grants. Given that we do not anticipate that NASA will substantially increase astronomy grants support, it is the entirety of U.S. astronomy grants, not just those from AST, that will manifest this issue. Under Scenario A, small-grants support in AST is at 90-95% of FY10-12 purchasing power through the decade.

Our portfolios steward the health of the profession in this no-growth era by maintaining funding opportunities through the career progression and balancing the portfolio to enable projects at individual, mid-, and large scales, and providing support to enable continued U.S. leadership in theoretical and computational astronomy, including technical critical capabilities **TC-B** and **TC-C** as well as health-of-the-profession critical capabilities.

Our Scenario B portfolio still provides most critical capabilities and enables U.S. leadership in many current and new fields, but there would be inevitable significant loss of capabilities, and consequently U.S. leadership, compared to Scenario A. Scenario B contains no GSMT or CCAT funding through AST, so in the absence of MREFC funds there would be no AST support for the revolution of 20-30m optical telescopes, nor for great advances in mm/submillimeter wide-area astronomy, leaving several critical capabilities at very reduced capacity or available only through private/international facilities. AST funding of small grants would drop to 70% of its FY10-12 level by FY22, damaging the health of the profession and making it harder to maintain U.S. leadership in theory and computation.

Perhaps most worrisome in Scenario B would be the factor-of-two reduction of mid-scale programs from $49M in FY22 (135% of the FY10-12 average purchasing power) to $23M (63% of FY10-12 purchasing power). This would certainly lead us to fall short in attaining some of the many critical capabilities that rely on mid-scale funding, *e.g.* massive-multiplex optical spectroscopy, extreme-precision Doppler exoplanet searches, CMB polarization measurements, and upgrading of instrumentation on federal and private telescopes at all wavelengths. Moreover, we note that while peer-reviewed competition in the MSIP allows a flexible response to the most promising opportunities, it also means that the MSIP cannot be pre-planned to support specific capabilities, facilities, or science goals.

11 National Observatories

The landscape that AST-funded national observatories operate within has changed significantly since they were first established. The creation of new federal facilities at new sites, the growth of public-private partnerships, and increasing NSF participation in international consortia that come with their own management structures has created a complex system for the national observatories and their NSF overseers. The notion of a national observatory being restricted to a particular set of observatory sites with sole control over the facilities is no longer valid for many of the facilities that have U.S. community access.

Within this changing climate, the national observatories continue to have a critical role within the U.S. astronomy landscape. For many astronomers, the national observatories are the primary route through which access to telescopes is obtained. Through their time allocation processes, user committees, and other avenues of user interaction such as newsletters, planning meetings, user satisfaction polls, and as providers of archival data, the national observatories are seen by many in the community as the representatives for their interests and observational needs in their various areas of research.

11.1 NOAO, Gemini, and the OIR system

The role of the national observatories is being challenged by the complexities of the changing landscape. The challenges have been manifested most clearly in the OIR system, where the mix of public, private, international, and public/private facilities has created a productive but also complex system.

User satisfaction with Gemini has been a particular issue of concern, which is surprising given that Gemini has two modern superb 8-m telescopes located on excellent sites. The 2009 ALTAIR survey stressed dissatisfaction within the U.S. community with respect to Gemini Observatory, in particular with respect to its instrumentation program. *NWNH* echoed this finding. Both reports attributed at least part of the problem to the governance structure of Gemini, in particular the separation of Gemini from the national U.S. optical observatory, NOAO, which has been perceived by many in the U.S. community as leading to poor representation of their interests in Gemini. It is difficult to disentangle all the issues that have affected the productivity of Gemini over the past decade. They include governance and management issues at various levels, as well as overreaching ambition in the instrumentation program. The ALTAIR survey demonstrated a mismatch between the desires of a U.S. community that wanted to see more workhorse instrumentation, and the direction that Gemini had been going in. Gemini has taken important steps in the recent years to improve planning of future instrumentation, simplify observing preparation, and accommodate more classical observing. Nevertheless, the lack of integration of the U.S. perspective between NOAO and Gemini persists.

The vision for the best use of NSF investments in OIR is not necessarily the same for those with private telescope access and those who solely rely on the publicly funded facilities. But the entire OIR community does have high demand for the national facilities, and both the private and public systems can benefit from optimizing coordination of the resources. The organization that coordinates U.S. open-access OIR interests in many areas, NOAO, is currently excluded from Gemini governance structures because of conflicts of interest raised by the fact that NOAO and Gemini have the same managing organization (AURA) and hence NOAO employees cannot be in governance roles. In addition, while AURA manages NOAO and Gemini for the NSF, the roles of AURA are different. In the case of Gemini, AURA is to implement scientific direction set by the Gemini Board. AURA is formally prevented from providing input in scientific direction. In the case of NOAO, AURA manages and sets its scientific direction with input from the community. The U.S. representatives on the Gemini Board have generally not had effective channels for community input, and there have been frequent changes in Board membership. In all, this has limited opportunity for coordination with the national facilities run by NOAO and the OIR system in general and led to delays in responding to community concerns, as the ALTAIR survey demonstrated.

NWNH (pp. 178-179) recommended that "To exploit the opportunity for an improved partnership between federal, private, and international components of the optical and infrared system, NSF should explore the feasibility of restructuring the management and operations of Gemini and acquiring an increased share of the observing time. It should consider consolidating the National Optical Astronomy Observatory and Gemini under a single operational structure, both to maximize cost-effectiveness and to be more responsive to the needs of the U.S. astronomical community." While such a significant step may not be required or feasible, stronger coordination of Gemini with the U.S. national observatory and the public/private system is pressing especially in times of declining budgets.

Our recommendations in Chapter 10 imply a significant reduction in current NOAO facilities. This poses a significant challenge to NOAO's mission to lead development of and provide open access to OIR astronomy. *NWNH* anticipated this challenge and suggested that "NOAO could also assume a larger role in managing the federal interest in Gemini, LSST, and GSMT. Now is the time for NSF to re-evaluate the OIR system and NOAO's role in it under cost-constrained conditions" (p.178). With the continuing opportunities provided by the Mid-Scale Innovations Program, it is plausible that the role that NOAO has played in coordinating the public access to private facilities (the former TSIP program) will also continue. Hence, we see further evolution in the role of NOAO, one that continues the shift from managing facilities only to one that includes participation in and coordination of the wider OIR system. In particular, in the LSST era the OIR system needs to be optimally attuned to respond to the large amount of LSST follow-up that will be required, while still providing a broad set of other critical capabilities that the community needs as well. The OIR system may eventually also involve federal participation in a GSMT and this would naturally fit within the evolved NOAO mission.

Findings: We find that there continues to be an important role for the National Optical Astronomy Observatory in the changing OIR landscape. In the longer term, NOAO is slated to play a critical role in the proposed LSST project. In the immediate future and continuing beyond that, appropriate roles of a national observatory include coordination of U.S. interests and participation in international partnerships such as Gemini, planning and coordination of capabilities across the evolving public/private observatories, allocation of observing time to astronomers, and representation of the U.S. astronomy community's interests in national and public/private partner facilities.

The purpose of closer ties between NOAO and U.S. participation in Gemini would not be to absorb Gemini into NOAO or vice versa, but to assure coordination of U.S. community interests and priorities in both organizations. Likewise, the role that NOAO plays in coordinating access to the private facilities is not to be interpreted as NOAO setting priorities for private facilities. Rather, NOAO would represent the community's participation and interest in these partnerships, helping to ensure that the critical capabilities needed exist within the general OIR landscape and enabling access to those capabilities for the U.S. community.

Our committee's recommendation to give high priority to the Gemini Observatory is premised on the expectation that the governance and management issues will continue to improve and thus increase responsiveness to the U.S. community needs. Clearly this is more changeable than the size of telescopes or quality of sites. The NSF and the U.S. representation need to expect high performance and responsiveness from the Gemini Observatory and to exert significant governance pressure to achieve this.

Recommendation 11.1: **The NSF should negotiate a post-2015 Gemini international agreement with the international partners that assures that the U.S. can coordinate its participation in Gemini and NOAO much more closely than has been done in the past.**

11.2 NRAO, ALMA, and the RMS system

On the RMS side, the system is currently less complex than in OIR, where private investments have been significant and have produced some of the largest facilities. There are nevertheless significant facilities outside the national radio observatory, NRAO. An example is the Arecibo telescope which is slated to remain a component of the evolving RMS system. NRAO can take on a coordinating role for the critical capabilities that require NRAO facilities and Arecibo. Examples include the coordinated role that Arecibo and VLA have in enabling key scientific goals like nanoGrav and planetary radar.

The governance arrangement is also different on the radio side, where U.S. participation in the international ALMA Observatory and NRAO operations are managed through different components of a single cooperative agreement. While there has been a significant investment by the U.S. in RMS facilities outside the scope of NRAO (e.g. through the URO program), the largest investments of AST in the RMS system are coordinated through a single national observatory. ALMA is the most ambitious ground-based telescope yet constructed, on a scale that is significantly larger than Gemini. Unlike Gemini, the ALMA partnership is more or less equally distributed among three participating organizations. The ALMA management structure is far from simple, with three different managing organizations, and as a new facility ALMA has yet to demonstrate how effective it will be at meeting the expectations of the community.

Findings: ALMA operations are still ramping up and it is too early to assess how well the management structure will serve the different partner communities in general, and the U.S. in particular. However, the current management structure of ALMA seems to have the ability for coordination of U.S. interests through the direct involvement of NRAO in ALMA. While competition of major facility operations cooperative agreements can potentially lead to cost savings and create new models for observatory operations, there is also the risk that it may lead to fractionation and loss of representation and planning. We see a significant risk if such future cooperative agreements might involve splitting off ALMA from NRAO.

Recommendation 11.2: **In re-competing future operations cooperative agreements for ALMA, the NSF should ensure that strong coordination and planning of the U.S. community interests in the national RMS facilities and its participation in ALMA and other possible international partnerships is protected.**

11.3 Observatory Scope

The PRC was not tasked to consider in detail the budgets of the various AST-funded observatories. Such a study was done by the NSF after the 2006 Senior Review, with the conclusion that the operations and maintenance budgets seemed appropriate given the scope of the observatories. However, these studies did not ask the larger question of what the appropriate scope of each observatory should be. A minimum scope would be for an observatory to ensure that telescopes and instruments are working properly and that good quality data are delivered to the user in a usable form; this may be through service observing, classical observing, or remote observing. The scope must also include awarding telescope time through organizing the competitive proposal review process. Additional items, which significantly enhance the capabilities of the facilities but require higher operations budgets, include: operating telescopes in optimum ways such as e.g. queue mode observing; running a "system" that coordinates open access time to private facilities; producing software pipelines for the data; planning for the next generation of instruments; designing and building instruments; providing training opportunities and mentoring for students and postdocs; running education and public outreach programs; enhancing interactions with the community and observatory planning through organizing meetings and workshops; and optimizing the quality of the facility by having scientific staff with research programs using the facilities. Reduced scope could lead to cost savings but at loss of some of these capabilities. Assessing this is challenging due to the large size and intertwined roles of these organizations, and the impacts that scope changes may have on the ability to deliver the required capabilities to the community.

The PRC discussed an alternative model for the national observatories structure that separated them into two distinct components: facility operations and scientific integration. In this model, the facilities would be run at minimal cost with a strict focus on delivering the capabilities to the user. The scientific integration organization (one for OIR, one for RMS, and possibly one for Solar) would be the user interface to a set of facilities and would provide strategic direction for new developments. The "facilities aspect" of this model is how many of the private OIR facilities are run; the "scientific integration role" in these cases is provided by faculty and staff at the participating institutions. A difference between the alternative model and the current national observatory model is that the new model may avoid duplicating the broad observatory scope, defined in the above paragraph, at each physical observatory location in the OIR and RMS systems. The latter is currently the case for several (but by no means all) of the extended activities listed in the previous paragraph. Such a model would also offer the significant advantage that it would allow the scientific integrating organization to coordinate many facilities, while avoiding having a monolithic organization that is so large as to make the re-competition of the management contract difficult. However, the resulting impact on the many roles of the national observatories was too extensive to assess adequately for this report. Implementation of this model in international partnerships would also need further study. The "scientific integration" component of the relevant U.S. national observatory would coordinate U.S. participation, but definition of the scope of the facility itself would clearly not be up to the U.S. alone. AST may want to consider investigating alternative models such as this one in more detail through a separate study.

12 Open Skies

The NSF has a long-standing policy known as “open skies” that access to telescope time it funds should be determined purely on the basis of the quality of the proposed science, not on the institutional or national affiliation of the proposer. This means that scientists outside of the U.S. have full standing to propose for open-access telescope time. In international partnerships like Gemini and ALMA, written or at least understood policy is that scientists from partner countries will not submit proposals to use other partners' time.

The open skies policy generally is of great benefit. It allows the strongest science to be done with the facilities, and it fosters international collaboration and communication of ideas, without being heavy-handed about who must lead the work. In several cases, it is reciprocated by other nations, thereby allowing U.S. astronomers access to a broader set of facilities and technical capabilities. Also, open skies is part of a larger exchange of scientific access beyond solely astronomy.

Of course, this policy also has the drawback of reducing the amount of time available to U.S. astronomers and forcing U.S. astronomers into competitions with non-U.S. competitors. The issue may be most pressing for facilities that offer unique capabilities. We note that at some facilities the fraction of non-U.S. users is of order 50%. A cap on foreign access to NSF-funded facilities might be appropriate if there are facilities for which we have reached the tipping point and the U.S. user community is being under-served. However, this can be difficult to define and assess, and the best outcome would be an increase in reciprocity rather than a cap. An alternative would be to consider user fees, a common cost-recovery mechanism in large computational or specialized lab facilities.

We note several cases in which the open skies policy requires monitoring. One is ALMA. The current agreement is that successful proposals from non-partners will receive up to 5% of the telescope time, taken directly from the total amount of available time. The provision of this open time by all partners is an important and welcome step in broadening the open skies policy. However, the 5% fraction may well be too small to meet user demand and if the share of non-partner time awarded by the (single) ALMA TAC were to exceed 5%, the additional time for successful proposals would come from the North American share, as it is the only partner with a fully open skies policy. We cannot forecast if this situation will arise to put disproportionate pressure on the time available to U.S. astronomers, but the NSF should monitor with an eye to renegotiating the open skies agreement if needed.

A second case is ATST. The current set of users of NSO facilities is close to equally split between U.S. and foreign scientists. ATST will be the world’s leading facility for high-resolution solar astronomy. The European Solar Telescope has been postponed, and it seems likely that European astronomers will make significant use of ATST. NSF might seek collaboration on operations funding (although previous discussions were unsuccessful), or it might negotiate for increased access to

European solar facilities as the Dunn and McMath-Pierce telescopes ramp down in advance of ATST. Other opportunities for non-U.S. users to contribute to ATST may be through supplying instrumentation that would be available to the broader community in return for some guaranteed access and for continued competed open access. On balance, we support open skies for ATST at this point. The ground-based solar community in the U.S. is re-establishing a stronger base at universities across the U.S., and the open skies policy will create stronger collaboration opportunities and increased productivity for this leading facility.

Finally, the facility for which a reconsideration of open skies might be most profitable is LSST. The current plan is that there will be three classes of LSST data products, two of which will be made available to all (and can therefore be thought of as open skies). So-called level 3 data products, which require significant additional processing, are not intended to be open skies. Currently they will be public immediately only to scientists and educators at U.S. and Chilean institutions, as well as to other contributors to the project, and may be available to other non-contributors only after expiration of a proprietary period.[2] Access to level 3 products might be exchanged for operations funding or to obtain access to other data sets or to follow-up time.

Recommendation 12.1: **Within the context of open skies, NSF should look to leverage its assets to maximize the ability of U.S. astronomers to access non-U.S. capabilities or to obtain contributions toward operations and maintenance costs for U.S. facilities with high fractions of foreign users.**

We encourage AST to pursue agreements that will broaden access for U.S. astronomers to critical capabilities. Furthermore, we believe that AST should be free to consider capping the fraction of open skies time on facilities when foreign demand surpasses some critical threshold, or establish user fees. Such a situation would require careful case-by-case consideration, both in terms of the impact on the productivity of the facility and on the broader issue of open skies and reciprocity in access.

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[2] This access replaces the 10% of telescope time that has traditionally been granted to Chilean astronomers on telescopes in their country.

13 Conclusions

Astronomy in the U.S. remains a vibrant field with a wide range of scientific topics and technical opportunities. The recent decadal survey reports, *New Worlds, New Horizons* and *Vision and Voyages,* have laid out bold plans for astronomical research in the coming decade, recommending a combination of new and existing facilities and increased investment in research grants and mid-scale projects.

Molding the AST portfolio to match the ambitions of *NWNH* in a cost-constrained environment is a significant challenge. ALMA, ATST, LSST, CCAT, and GSMT are all powerful new facilities that promise major advances in the field. However, they are expensive to construct and operate, and implementing them while protecting the very important (and heavily over-subscribed) small-grants and mid-scale programs implies that AST must find significant reductions elsewhere in the portfolio. This is an uncomfortable but necessary step. With astronomy advancing very rapidly, we must invest in the latest facilities, technologies, and instruments or face a decline in U.S. leadership. Similarly, we must attract and train the next generation of astronomers and retain top talent in the field by offering an exciting range of opportunities. We have to judge the continuation of existing programs and facilities against the opportunities made possible by new investment. However, we must also recognize that existing facilities offer secure, near-term science opportunities.

The portfolios we have described in Chapter 10 offer a balance between the existing facilities and investment in small grants, mid-scale projects, and new facilities. We have judged the balance in the portfolio by using the critical capabilities for the NWNH science goals and health of the profession (Chapters 5 & 6); the detailed assessment of our portfolios for these capabilities is presented in Chapter 10. We find it possible in Scenario A to create an AST portfolio which provides nearly all critical ground-based capabilities for *NWNH* and *V&V* science, albeit with less U.S. (especially public) share in some of them and substantially less support for the astronomical workforce than *NWNH* recommended.

In Scenario B, our recommended portfolio still provides most critical capabilities and enables U.S. leadership in many current and new fields, but there are major losses from A: no Federal participation in the revolution of 20-30m optical telescopes, strongly limited capabilities in mm/submillimeter wide-area astronomy, and a factor-of-two reduction in MSIP funds for new innovative experiments and upgraded instrumentation. We regard the level of mid-scale and small grants funding in Scenario B as highly stressed. We recommend that AST plan its facility portfolio assuming Scenario B so as not to put the grants programs at further risk.

The portfolios give high priority to the critical capabilities provided by the newer state-of-the-art facilities ALMA, VLA, Gemini, LSST, and ATST, as well as a best-in-class wide-field capability with the Blanco 4m telescope. It continues operations support for Arecibo, SOAR, and NISP. It aims to promote world-class instrumentation for these and other facilities via competition in a vigorous and well-funded MSIP. This same program will return open-access time to the astronomical community via competitive selections and will provide clear opportunities for mid-scale experiments and surveys. Finally, the portfolio provides strong support for the individual-investigator grants programs (notably AAG and ATI), which is essential for preserving flexibility and a diverse astronomical research base.

To make these advances possible, AST must divest from or find cost-saving partnerships for some of its facilities less critical to *NWNH* and *V&V* science priorities. We have provided a ranked list in Chapter 10. We recommend that AST divest from the Mayall, WIYN, 2.1-meter OIR telescopes at Kitt Peak, the Green Bank Telescope, the Very Long Baseline Array, and the McMath-Pierce solar telescope. The result will be a significant loss of open-access telescope time from workhorse mid-sized optical telescopes and the loss of significant radio and solar capabilities. Some of these losses can be compensated with the open-access component of the MSIP, and U.S. institutions do have private access to many other workhorse telescopes, particularly in the optical and near infrared. We recommend more competitive opportunities for instrumentation and mid-scale projects to couple with the flagship facilities.

The astronomy profession is caught between budget realities and the transformative opportunities of new technologies. To continue to lead the field, we must be prepared to continually renew the portfolio with competitive selection of new projects and the generation of new research capabilities. This goal maps well to the NSF's strength in competitive proposal review. While the divestment from familiar and productive facilities is not easy by any stretch, we look forward to an AST portfolio with state-of-the-art facilities and diverse funding opportunities to support the U.S. astronomy community in the continuing exploration of the Universe.

13.1 List of Recommendations

Chapter 7

7.1. We recommend adding a "Theory and Computation Networks" program to the small-grants portfolio at a funding level of at least $1M/year.

7.2. We recommend that the NSF and AST continue to support the Research Experiences for Undergraduates (REU) program, both through site awards and REU supplements to AAG awards.

7.3. The Astronomy and Astrophysics Postdoctoral Fellowships (AAPF) program should be continued.

7.4. We recommend that the national observatory prize fellowships be combined into a single program that would fund postdoctoral fellows with strong research ties to one or more of the AST-funded observatories: NRAO/ALMA, NOAO, Gemini, NSO, and Arecibo.

7.5. AST should broaden and sustain or increase funding for the Partnerships in Astronomy & Astrophysics Research and Education (PAARE) program: (1) to allow proposals to be led by any institution that can present a compelling plan for increasing minority participation, with strong preference for minority serving institutions (MSIs), and (2) to develop a mechanism for funding small grants for exploratory projects that initiate programs between MSIs, community colleges, and other research institutions.

7.6. AST should increase funding by $1M/year for grants programs or projects that directly seek to improve recruitment and retention of underrepresented minorities in astrophysics.

Chapter 8

8.1. Funding of projects beyond the scale of the AAG and ATI programs, but below the major facilities scale, should be provided through a Mid-scale Innovations Program (MSIP) and a Strategic Investments Program (SIP).

8.2. All MSIP projects should be competitively selected by peer review. Projects are envisioned to cost $3-50M total over no more than five years. MSIP funds should not be used for continuing commitments to any project for longer than five years without re-competition.

8.3. MSIP would subsume projects historically included in the TSIP, ReSTAR, and URO programs, as well as fixed-term experiments such as ACT, SDSS, and PAPER that have previously had no defined funding line. Proposals that include a component of observatory operations, while providing a compelling scientific result or a resource (observing time and/or data) to the community, are also appropriate for MSIP. We recommend that major new instrumentation at NOAO, Gemini, NSO, Arecibo, and NRAO be included in this same competition, as well as laboratory astrophysics and fixed-term numerical simulation initiatives above the ATI or the new Theory and Computation Networks program scale.

8.4. The national facilities should continue to have sufficient resources built into their budgets to maintain their critical core competencies, handle instrument upgrades, initiate small new experiments, and deal with occasional instrumentation failures.

8.5. MSIP should have two strands, Mid-scale Science and Open Access Capabilities, the former having as its primary selection criterion the quality of science returned by the proposers, and the latter having as its primary criterion the quality and quantity of science capabilities made available to the full U.S. astronomy community. Proposers would choose which of these criteria is best matched to their project.

8.6. Open access to data reduction pipelines and data access tools should be judged as an essential part of open access capabilities proposals.

8.7. To remain vibrant, the MSIP should support at least two new project starts per year in each strand.

8.8. Following *NWNH*, we recommend the funding of one or more Data Stewardship projects to address the need for the long-term curation of astronomical data sets of enduring value and benefit to the community. This should be funded at a minimum level of $1M per year.

Chapter 9

9.1. We recommend that the Large Synoptic Survey Telescope (LSST) begin construction with an MREFC start in FY14 or as soon as possible thereafter, so as to maintain an expected start of operations in late 2021 or early 2022.

9.2. We recommend that the federal government (NSF and DOE), as the majority LSST partner, avoid any contractual structure that prevents it from unilaterally reviewing and setting the federal operations support level.

9.3. Following *NWNH*, we place major funding for the Giant Segmented Mirror Telescope (GSMT) projects at lower priority than executing LSST and maintaining a vigorous MSIP.

9.4. We recommend that the U.S. retain at least a 50% share of the Gemini telescopes. However, we also recommend a cost cap on the U.S. share of $17M (FY17), excluding major instruments, which will be competed through the mid-scale program. We further recommend that the U.S. negotiate a Gemini partnership so that the instrumentation investments can be more entrepreneurial between partner countries, e.g., with investments to be compensated from transfer of nights from partners that have not invested in instruments.

9.5. The U.S. should aim to continue to lower the Gemini operations cost per night by focusing on simpler operations at Gemini-N and maturing instrumentation at Gemini-S. We recommend that Gemini end next-generation AO development for the Gemini-N and that the observatory prepare capabilities for both telescopes toward the end of the decade that will emphasize the synergy with LSST.

9.6. We recommend that AST continue its agreement for Southern Astrophysical Research Telescope (SOAR) operations support through 2018.

9.7. We recommend that the NSF support Atacama Large Millimeter/sub–millimeter Array (ALMA) operations and development over the next decade but cap the U.S. share of operations at ~$40M/year over this time period in Scenario B.

9.8. We recommend that NSF continue to fund the Karl G. Jansky Very Large Array (VLA) at its current scope.

9.9. We recommend that AST discontinue the University Radio Observatory (URO) program. To provide an opportunity to preserve the valuable contributions from university-based radio instrumentation groups, we recommend that these groups compete in the MSIP for fixed-term, science-driven projects.

9.10. We recommend that AST provide partial funding to the construction and/or operations of CCAT through the Strategic Investments Program later in the decade, if and when funding for the Mid-Scale Program exceeds $30M per year.

9.11. AST and NSO should plan for the continued use of the Dunn Solar Telescope (DST) as a world-class scientific observatory, supporting the solar physics community, to within two years of ATST first light, as well as utilize it as a test bed for development of critical ATST instrumentation.

9.12. AST and NSO should develop a plan for the NSO Integrated Synoptic Program (NISP) that includes GONG and SOLIS but that limits AST funding to no more than $2M (FY17) annually. Expanded partnerships for operations should be sought, and the plan should be completed in time for implementation in the FY16 budget. If a partner cannot be found, NISP should be divested entirely.

9.13. The AST PRC reiterates the importance of the finding of *NWNH* that "NSF should work with the solar, heliospheric, stellar, planetary, and geospace communities to determine the best route to an effective and balanced ground-based solar astronomy program that maintains multidisciplinary ties."

9.14. We recommend that support for the Atmospheric Čerenkov Telescope Array (ACTA) be considered by NSF/AST later in the decade through the MSIP or Strategic Initiatives Program, but at lower priority than LSST, CCAT, and GSMT.

9.15. The committee regards ALMA, VLA, ATST, Gemini-South, Blanco, and DST as essential facilities for the AST portfolio.

9.16. Based on their capabilities and current cost, the committee ranks the remaining facilities in the priority order (highest to lowest): Gemini-North, Arecibo, Mayall, VLBA, NISP, GBT, SOAR, WIYN, and McMath-Pierce.

Chapter 10

10.1. AST should maintain substantial funding to AAG, ATI, and a mid-scale program as a top priority.

10.2. AST should plan its facility portfolio assuming the more pessimistic range of forecasts (e.g., Scenario B), with the result that more optimistic budgets (e.g., Scenario A) can have heavier re-investment in the field through the small-grants and mid-scale programs.

10.3. Our recommended portfolio includes ALMA, ATST, VLA, Gemini, Blanco, DST, Arecibo, NISP, and SOAR.

10.4. AST should reevaluate its participation in Arecibo and SOAR later in the decade in light of the science opportunities and budget forecasts at that time.

10.5. In our Scenario A, we recommend that AST contribute of order $20M/year to GSMT late in the decade.

10.6. We recommend that AST divest from the Mayall, WIYN, and 2.1-meter telescopes at Kitt Peak, the Robert C. Byrd Green Bank Telescope, the Very Long Baseline Array, and the McMath-Pierce solar telescope.

10.7. We recommend that AST divest in a manner that is responsible to its fellow tenants at observatories and to its long-duration user programs.

10.8. We recommend heavy investment into the mid-scale innovations program (MSIP), particularly in the more optimistic Scenario A portfolio.

10.9. In the near term, we recommend only minimal funding of additional strategic investments beyond CCAT, GSMT, and data archive(s).

Chapter 11

11.1. The NSF should negotiate a post-2015 Gemini international agreement with the international partners that assures that the U.S. can coordinate its participation in Gemini and NOAO much more closely than has been done in the past.

11.2. In re-competing future operations cooperative agreements for ALMA, the NSF should ensure that strong coordination and planning of the U.S. community interests in the national RMS facilities and its participation in ALMA and other possible international partnerships is protected.

Chapter 12

12.1. Within the context of open skies, NSF should look to leverage its assets to maximize the ability of U.S. astronomers to access non-U.S. capabilities or to obtain contributions toward operations and maintenance costs for U.S. facilities with high fractions of foreign users.

14 Appendix A: Committee Process

The NSF's Portfolio Review Committee (PRC) was appointed by the Division of Astronomical Sciences Director, Jim Ulvestad, in August and September, 2011, with a charge of making recommendations to the Advisory Committee of the NSF Directorate of Mathematical and Physical Sciences (MPSAC) by the end of June, 2012. In accordance with federal advisory requirements, the PRC was constituted as a subcommittee of the MPSAC. The charge to the Committee and the Committee membership are included in Appendix B.

The work of the committee was largely carried out during more than 30 weekly telecons, run by NSF staff, and three face-to-face meetings attended by committee members and NSF staff. Various sub-committees that were formed as described below also regularly met by telecon with NSF staff present. Physical meetings took place 21-23 October 2011 at NSF Headquarters in Arlington, VA 12-14 January 2012 near the Dallas-Fort Worth, TX Airport, and 12-14 April 2012 at NSF Headquarters. Confidentiality was a very important consideration, and most information exchange and report development took place on a password-protected Wiki hosted by the NSF. Any documents that circulated among committee members were also password-protected. Committee members were briefed by NSF staff at the first face-to-face meeting on ways to maintain confidentiality during the process and all committee members also signed conflict of interest forms at that meeting.

At the first face-to-face meeting, NSF staff gave a briefing on the charge to the committee, and summarized the relevant aspects of the AST budget process and the Decadal Survey recommendations. They also gave informational summaries of all the major elements of the AST portfolio, including facilities, grants programs, and items in the budget that were mandates or NSF-wide. The committee was presented with two budget scenarios to use in formulating its recommendations. Conceptually, the task of the committee divided into two parts: understanding the observational, theoretical and experimental capabilities required to deliver on the highest ranked science priorities of the *New Worlds, New Horizons* and *Vision and Voyages* reports of the Decadal Surveys, and mapping those capabilities into current and future facilities as well as other NSF-funded programs. This ultimately led to a recommended portfolio for AST under each of the two budget scenarios. The committee was asked not to consider divestment cost or implementation in its recommendations.

Soon after this meeting, the astronomical community was solicited for input to the PRC process by the Division Director Jim Ulvestad, with a window of 26 October 2011 to 31 January 2012 for submissions to be considered by the committee. The call for community input is included in Appendix B, and further details are given in Chapter 4. By the deadline, 131 responses were received; all of these were posted on the wiki, where all committee members were expected to read them. Community input was grouped according to topic and summaries of the input by topic were prepared by one or more committee members and discussed during the weekly telecons.

Throughout the PRC's activities, numerous presentations, reports and relevant documents were provided to the Committee, including the facility program plans and long-range plans.

Subsequent to the first face-to-face meeting, the committee of 17 members split into 4 working groups according to scientific expertise in order to map the highly-ranked Decadal survey science questions into the critical capabilities required to address those questions. Both the *NWNH* and *V&V* reports were considered; the *NWNH* panel reports were used as supplementary material. Per the charge to the committee, this exercise considered existing and planned facilities, and it considered the landscape of federally and non-federally funded facilities, and also U.S. and non-U.S. or international facilities. The sub-group areas, Cosmology, Galaxies, Stars and Stellar System, and Planet and Star Formation, were similar to the discipline groups in the NSF Astronomy and Astrophysics Research Grants program. The committee derived a draft statement of principles that formed the basis for the portfolio review. In December 2011, the four science-based working groups were augmented by additional groups (using overlapping sub-groups of the overall committee) to examine the critical capabilities required in terms to make progress in theory, computation and laboratory astrophysics, and the capabilities required to maintain the health of the profession in terms of education and career development, open access, and U.S. leadership in the field.

At the second face-to-face meeting in January 2012 in Dallas, TX, the four science sub-groups presented their recommended capabilities, with each capability marked as high, medium, or low priority, or unranked, and there was extensive discussion. The rankings were combined into a single list but with no ranking across disciplines. There were also presentations on the required capabilities for aspects beyond the four science topic areas, and additional discussion of these. The committee heard about each of the major astronomical facilities supported (wholly or in part) by the NSF, with the program officer responsible for overseeing that facility making the presentation.

After the second face-to-face meeting, the committee began work on the second part of their charge, mapping critical technical capabilities to facilities and making portfolio recommendations on that basis. In addition, the committee split into 3 independent and parallel sub-groups to consider possible recommendations (or decision units) that might be recommended to the NSF, and to develop draft portfolios under each of the two budget scenarios. There was some discussion of observatory scope as it related to budget and continued discussion of ways to maintain the health of the profession in the face of the pessimistic budget scenario.

Meanwhile, a second solicitation for input to the committee was made in February 2012, specifically to the Observatory Directors and Principal Investigators of OIR (optical and infrared) and RMS (radio, millimeter, and submillimeter) facilities. It included specific questions developed by the committee about the future directions for these facilities. As with the community input described earlier, each committee member was asked to read all the responses and one committee member developed a summary of the OIR or RMR responses. These community inputs were discussed in the weekly telecons. Overall, the community input described above encompassed a very broad and thoughtful set of materials that were integral to the committee's subsequent discussions and deliberations.

Through February and March 2012, the committee continued to work on the mapping of critical and supporting capabilities to facilities. The role of individual-investigator grants and mid-scale programs was also assessed.. At the end of March, the three sub-groups presented their portfolios to the committee as a whole, under the two budget scenarios advanced by the NSF, paying particular attention to the portfolio balance in FY17 and FY22. This exercise was a test-bed for achieving consensus on a final portfolio.

At the third and final face-to-face meeting in April 2012 in Arlington, VA, the AST facilities were discussed, focusing on the capabilities they provided in service of the high priority science goals of the Decadal Survey. The facilities were ranked based on polling of all committee members, and there was extensive discussion of the rankings. A draft portfolio was presented and it was adopted by consensus after discussion. NSF staff talked about how the report would be rolled out, and the committee moved after the meeting into the writing phase, with the goal of making the process and logic of the decision-making clear. Much of the discussion during the telecons in May and June involved the proposed recommendations, and drafts of different chapters of the report were prepared and combined during this period.

NSF staff provided feedback on the entire draft report in May and again in June; this feedback was limited to editorial and factual comments and suggestions to keep the committee focused on its charge, and it did not involve recommendations about facilities or about the portfolio itself. While there was some division of responsibility during the writing phase, all committee members were asked to read and contribute to all chapters of the report. The report was delivered to the Division Director on July 31, 2012, for review by the MPS Advisory Committee in advance of the report's presentation to that committee in August.

15 Appendix B: Supporting Documents

15.1 AST Portfolio Review Charge to the Committee

Context

This review, a recommendation of the Astro2010 astronomy and astrophysics Decadal Survey, is motivated by the aspirations and priorities of the astronomical community, as evidenced in Astro2010, and by the current challenging outlook for the Federal budget.

The review is designed to examine the balance across the entire portfolio of activities supported by NSF's Division of Astronomical Sciences (AST). (The 2005--06 AST Senior Review, in contrast, was confined to facilities.) The primary goal of this review, and of any resulting adjustments of the AST portfolio, is to maximize progress on the compelling science described in Chapter 2 of the Astro2010 report by balancing the recommendations for new facilities, instrumentation and programmatic enhancements with the capabilities enabled by existing facilities, grants programs, and other supported activities.

The following boundary conditions should be adopted for the review:

All of the AST-funded facilities, grants programs, and other activities should be considered together with the Astro2010 recommendations. The review should be forward-looking and focus on the potential of all facilities, programs, and activities for delivering the desired capabilities and not on past performance.

The review should assume several budget scenarios, to be provided by AST to encompass the period through 2025, and consider the costs of (i) delivering the existing capabilities and programs, as well as of (ii) new facilities as determined by the Astro2010 estimating processes.

The review will not reopen debate on the recommendations and science program of Astro2010.

The Committee's deliberations should take into consideration the national and international astronomy landscape and the consequences of its recommendations for domestic and international partnerships as well as for the state of the profession.

The Charge

The Committee is asked to construct its recommendations in a two-stage process:

1. Recommend the *critical capabilities* needed over the period from 2015 to 2025 that would enable progress on the science program articulated in Chapter 2 of Astro2010. These recommendations should encompass not only

observational capabilities, but also theoretical, computational, and laboratory capabilities, as well as capabilities in research support, workforce, and education.

2. Recommend the *balance of investments* in new and in existing, but evolved, facilities, grants programs, and other activities that would deliver the needed capabilities within the constraints of each of the provided budgetary scenarios. These recommendations may include closure or divestment of facilities as well as termination of programs and other activities.

The elements of the recommended portfolio should be prioritized in sufficient detail to enable AST to make subsequent adjustments in response to variations in Federal and non-Federal funding.

The Committee should consider the effects of its recommendations on the future landscape of U.S. ground-based astronomy and theoretical and laboratory astrophysics. The recommended portfolio and any changes should be viable and lead to a vigorous and sustainable future. In particular, the Committee is asked to examine how the recommended portfolio supports and develops a workforce with the requisite abilities and diversity to exploit the recommended research and education investments.

The Committee will be a sub-committee of the Directorate for Mathematical and Physical Sciences Advisory Committee (MPSAC). The Committee is asked to provide its recommendations by 31 March 2012 for presentation to the MPSAC, so NSF can consider them in formulating the FY14 Budget Request.

15.2 Committee Membership

Name	Affiliation
Daniel Eisenstein (Chair)	Harvard University
Joe Miller (Vice-Chair)	University of California at Santa Cruz
Marcel Agüeros	Columbia University
Gary Bernstein	University of Pennsylvania
Geoffrey Blake	California Institute of Technology
John Feldmeier	Youngstown State University
Debra Fischer	Yale University
Chris Impey	University of Arizona
Cornelia Lang	University of Iowa
Amy Lovell	Agnes Scott College
Melissa McGrath	NASA Marshall Space Flight Center
Michael Norman	University of California San Diego
Angela Olinto	University of Chicago
Karel Schrijver	Lockheed Martin Advanced Technology Center
Michael Skrutskie	University of Virginia
Juri Toomre	University of Colorado
Rene Walterbos	New Mexico State University

15.3 Letter Requesting Facility Long-Range Plans

National Science Foundation
Division of Astronomical Sciences
4201 Wilson Boulevard
Arlington, Virginia 22230

7 November 2011

Letter by e-mail

Dr. Robert Kerr, SRI International
Dr. Ethan Schreier, Associated Universities, Inc
Dr. William Smith, Association of Universities for Research in Astronomy

Dear Drs. Kerr, Schreier, and Smith:

Further to my letter of 26 October 2011, I am writing to invite you to submit input to the AST Portfolio Review. These submissions should address two timeframes – the near term, 5 years; and the longer term, 10-15 years, and be structured as follows.

(A) An up-to-date long range plan for each observatory (AO, NRAO, Gemini, NOAO, NSO), sometimes referred to as the five-year plan. At a minimum, this update should describe the observatory's capabilities, activities and plans for this near-term period and should map these capabilities and activities to the decadal survey science frontiers identified in New Worlds, New Horizons (NWNH) (Astro2010) and Visions and Voyages (VV) (the Planetary Sciences Decadal Survey, 2011). Please organize your mapping according to the science areas and questions listed in Chapter 2 of NWNH and Chapter 3 of VV. For these plans, assume five-year budget guidance you have been given by AST.

(B) On the longer term, to 2020 and 2025, your vision for each observatory 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. For these submissions to be of most value in the Portfolio Review Committee's deliberations, please send responses via your AST Program Officer no later than 6 January 2012. If you have any questions, please contact your Program Officer.

The Portfolio Review Committee will be generating more specific questions that are not otherwise addressed in the items described above. Those questions should be distributed within the next few weeks.

Sincerely yours,

Vernon Pankonin
Deputy Director
Division of Astronomical Sciences

Cc: Fred Lo, Director, NRAO
Fred Chaffee, Interim Director, Gemini
David Silva, Director, NOAO
Stephen Keil, Director, NSO

15.4 Letter Requesting Community Input

COMMUNITY INPUT TO THE AST PORTFOLIO REVIEW

The NSF Division of Astronomical Sciences (AST) invites input to its Portfolio Review process from members of the scientific community. The input window will be open from October 26, 2011, through January 31, 2012. Submitted comments or documents are limited to 5 pages in length, but may contain a URL link to a longer document (see below).

HOW YOUR INPUT WILL BE USED

Community input will be made available, in original form, only to the Portfolio Review Committee and to NSF staff. AST Division staff will sort and categorize submitted comments for better organization and access, and may produce synthesized summary documents, combining the views of many individual submitters, as needed by the Committee.

MAKE YOUR INPUT COUNT

Useful community input will directly address the Charge to the Committee and its context, which are discussed more fully on the Portfolio Review web site at http://www.nsf.gov/mps/ast/ast_portfolio_review.jsp.

The Astro2010 Decadal Survey recommendations laid out in "New Worlds, New Horizons in Astronomy and Astrophysics" (*NWNH*) were made under the assumption of an AST budget that, with inflation, would approximately double to nearly $500M by 2020. However, current projections predict a 2020 AST budget of between $250M and $350M. Thus, future budgets will be insufficient to fully maintain the portfolio of existing and upcoming facilities, projects, and programs as well as to implement the Astro2010 recommendations for new facilities and program enhancements.

The Committee is being asked to determine (1) the capabilities needed to optimize progress on the Science Program articulated by Astro2010 (Chapter 2 of *NWNH*), and (2) the combination of new, upcoming, and existing-but-evolved facilities, projects, and programs that will best deliver these capabilities given the budgetary constraints. It may help to think of this process as interleaving the Astro2010 recommendations with the existing portfolio.

Examples of helpful input would include: priority orderings of key capabilities needed for particular science goals; alternative ways to achieve desired capabilities; suggested evolution or combination of public, private, and university resources to achieve high-priority capabilities; or discussions of the effects of changes to the portfolio on the status of the profession.

Examples of unhelpful input would include: advocating for a new project not endorsed by Astro2010; recommending re-ordering of Astro2010 priorities from the main Astro2010 report; arguing for increased support for some set of activities without a viable suggestion for offsetting costs; suggesting that AST ask, hope, or lobby for more funding; or any comments sent anonymously.

HOW TO SEND YOUR INPUT

If your comments can be expressed succinctly using text alone, then compose your input in the body of a plain-text Email message (the preferred method). You may send a single Word or searchable PDF document as an attachment; but if you do, provide a short executive summary in the body of the Email. With any method of submitting input, please be brief and to the point. No input longer than 5 pages will be accepted. You may include a URL link to a longer document, but keep in mind that the committee is not required to read it; a crisp executive summary may be more effective. Try to make it as easy as possible for the Committee to read and understand your input. Summarize the focus of your input on the subject line of the email (e.g., "midscale projects," "AAG program," etc.), and be more descriptive than just "comments for portfolio review."

Please do not send Astro2010 white papers or revisions of them, reprints of journal articles, copies of publicly available documents (cite a URL), proposals for funding, or other material not related to the Charge to the Committee. The original Astro2010 white papers are public documents and will be available to the Committee, so they need not be resubmitted. The Committee will have access to the Astro2010 main report and panel reports and to the Planetary Sciences Decadal Survey report.

WHERE TO SEND INPUT

Send your comments to astportfolio@nsf.gov. Please do not contact committee members individually.

CHECKLIST

- Comments in plain text Email or a single Word or PDF attachment?
- If sending an attachment, executive summary in the Email body?
- Comments directly connected to the Charge to the Committee?
- As concise as possible?
- Helpful few-word description in the subject line?
- No more than 5 pages in length?

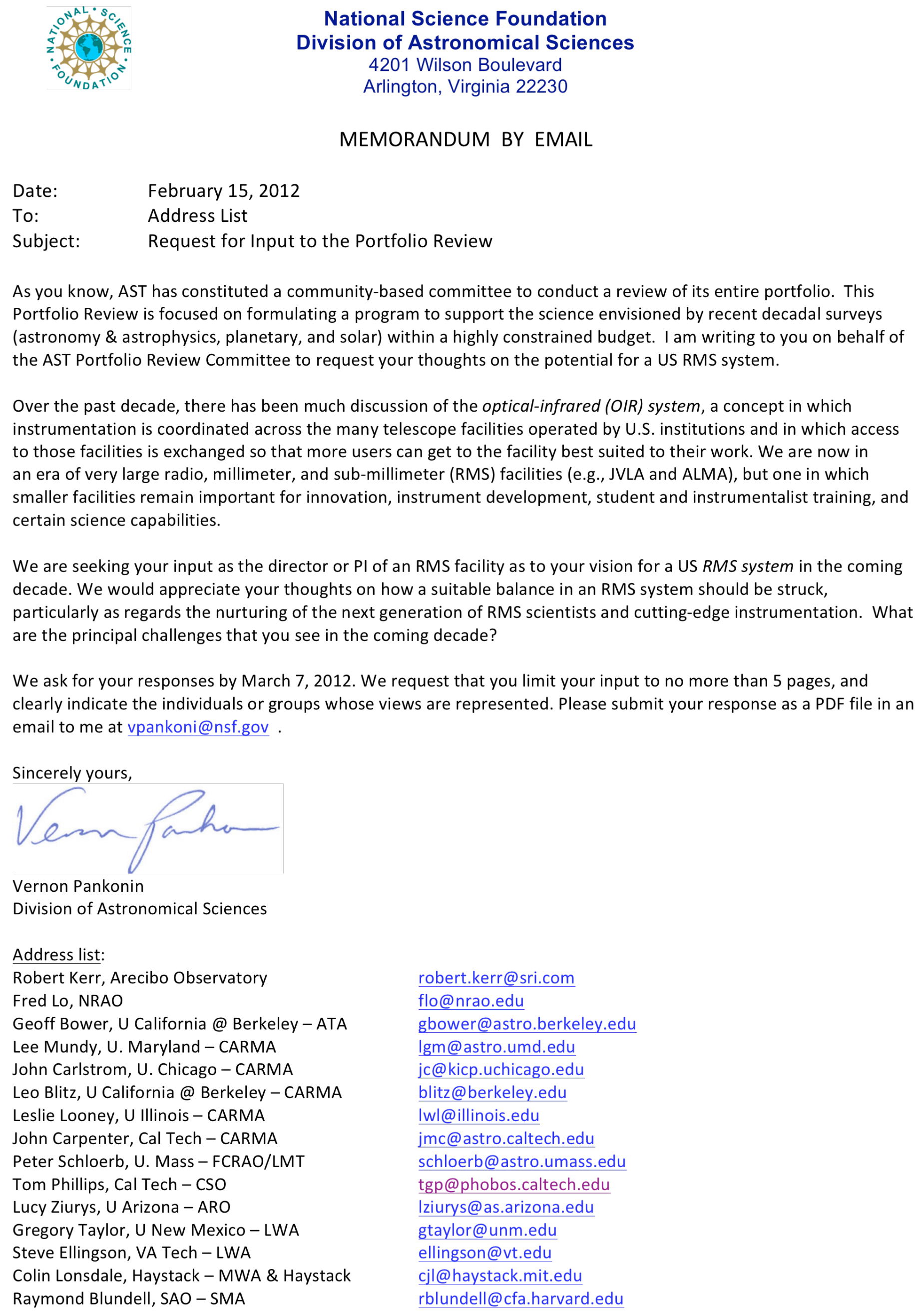
We thank you in advance for your comments and the effort you are making to participate in this important process.

James S. Ulvestad

Director, Division of Astronomical Sciences

Mailed 27 October 2011

15.5 Letter to RMS Directors



National Science Foundation
Division of Astronomical Sciences
4201 Wilson Boulevard
Arlington, Virginia 22230

MEMORANDUM BY EMAIL

Date: February 15, 2012
To: Address List
Subject: Request for Input to the Portfolio Review

As you know, AST has constituted a community-based committee to conduct a review of its entire portfolio. This Portfolio Review is focused on formulating a program to support the science envisioned by recent decadal surveys (astronomy & astrophysics, planetary, and solar) within a highly constrained budget. I am writing to you on behalf of the AST Portfolio Review Committee to request your thoughts on the potential for a US RMS system.

Over the past decade, there has been much discussion of the *optical-infrared (OIR) system*, a concept in which instrumentation is coordinated across the many telescope facilities operated by U.S. institutions and in which access to those facilities is exchanged so that more users can get to the facility best suited to their work. We are now in an era of very large radio, millimeter, and sub-millimeter (RMS) facilities (e.g., JVLA and ALMA), but one in which smaller facilities remain important for innovation, instrument development, student and instrumentalist training, and certain science capabilities.

We are seeking your input as the director or PI of an RMS facility as to your vision for a US *RMS system* in the coming decade. We would appreciate your thoughts on how a suitable balance in an RMS system should be struck, particularly as regards the nurturing of the next generation of RMS scientists and cutting-edge instrumentation. What are the principal challenges that you see in the coming decade?

We ask for your responses by March 7, 2012. We request that you limit your input to no more than 5 pages, and clearly indicate the individuals or groups whose views are represented. Please submit your response as a PDF file in an email to me at vpankoni@nsf.gov .

Sincerely yours,

Vernon Pankonin

Vernon Pankonin
Division of Astronomical Sciences

Address list:

Robert Kerr, Arecibo Observatory	robert.kerr@sri.com
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Geoff Bower, U California @ Berkeley – ATA	gbower@astro.berkeley.edu
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John Carlstrom, U. Chicago – CARMA	jc@kicp.uchicago.edu
Leo Blitz, U California @ Berkeley – CARMA	blitz@berkeley.edu
Leslie Looney, U Illinois – CARMA	lwl@illinois.edu
John Carpenter, Cal Tech – CARMA	jmc@astro.caltech.edu
Peter Schloerb, U. Mass – FCRAO/LMT	schloerb@astro.umass.edu
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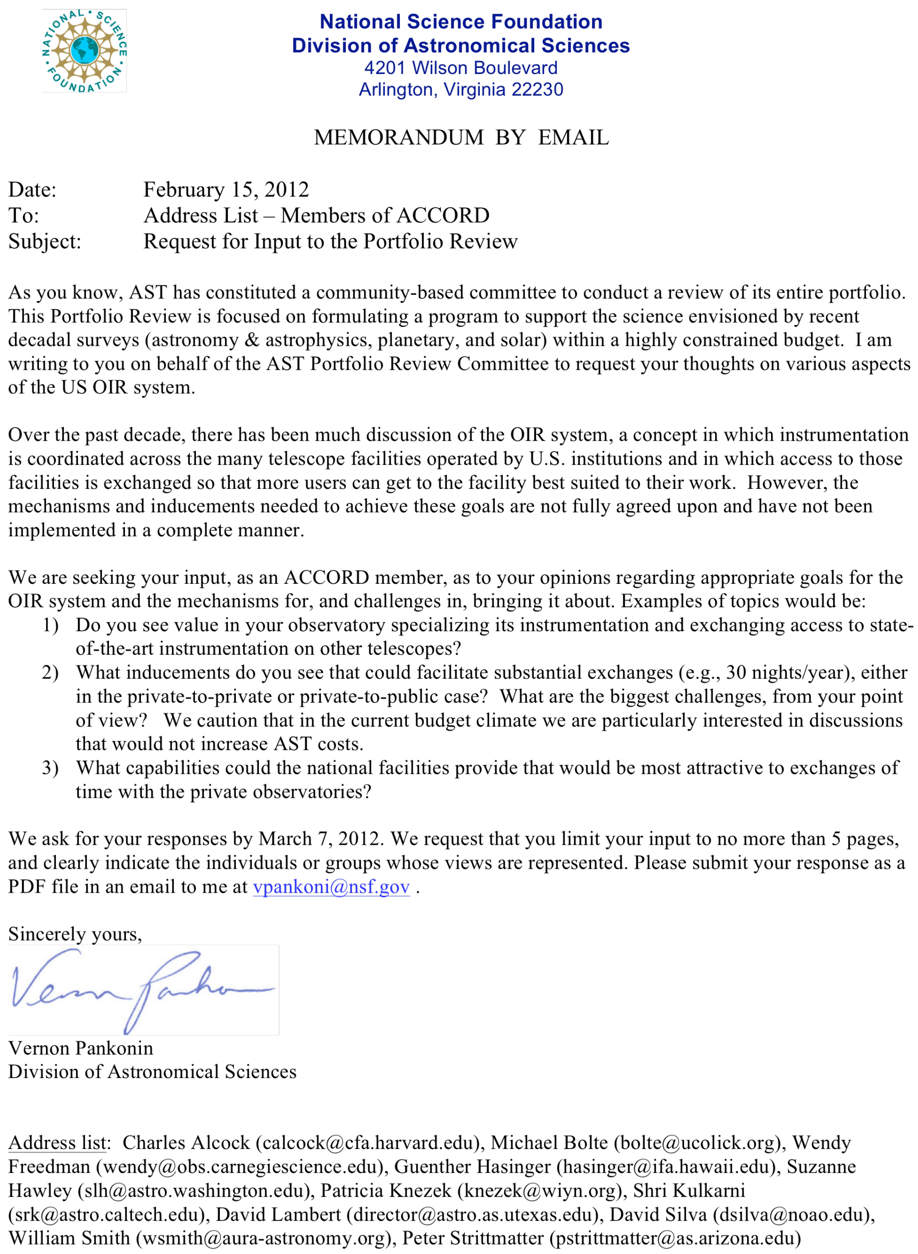
Lucy Ziurys, U Arizona – ARO	lziurys@as.arizona.edu
Gregory Taylor, U New Mexico – LWA	gtaylor@unm.edu
Steve Ellingson, VA Tech – LWA	ellingson@vt.edu
Colin Lonsdale, Haystack – MWA & Haystack	cjl@haystack.mit.edu
Raymond Blundell, SAO – SMA	rblundell@cfa.harvard.edu

15.6 Letter to ACCORD/OIR Directors



National Science Foundation
Division of Astronomical Sciences
4201 Wilson Boulevard
Arlington, Virginia 22230

MEMORANDUM BY EMAIL

Date: February 15, 2012
To: Address List – Members of ACCORD
Subject: Request for Input to the Portfolio Review

As you know, AST has constituted a community-based committee to conduct a review of its entire portfolio. This Portfolio Review is focused on formulating a program to support the science envisioned by recent decadal surveys (astronomy & astrophysics, planetary, and solar) within a highly constrained budget. I am writing to you on behalf of the AST Portfolio Review Committee to request your thoughts on various aspects of the US OIR system.

Over the past decade, there has been much discussion of the OIR system, a concept in which instrumentation is coordinated across the many telescope facilities operated by U.S. institutions and in which access to those facilities is exchanged so that more users can get to the facility best suited to their work. However, the mechanisms and inducements needed to achieve these goals are not fully agreed upon and have not been implemented in a complete manner.

We are seeking your input, as an ACCORD member, as to your opinions regarding appropriate goals for the OIR system and the mechanisms for, and challenges in, bringing it about. Examples of topics would be:

1) Do you see value in your observatory specializing its instrumentation and exchanging access to state-of-the-art instrumentation on other telescopes?
2) What inducements do you see that could facilitate substantial exchanges (e.g., 30 nights/year), either in the private-to-private or private-to-public case? What are the biggest challenges, from your point of view? We caution that in the current budget climate we are particularly interested in discussions that would not increase AST costs.
3) What capabilities could the national facilities provide that would be most attractive to exchanges of time with the private observatories?

We ask for your responses by March 7, 2012. We request that you limit your input to no more than 5 pages, and clearly indicate the individuals or groups whose views are represented. Please submit your response as a PDF file in an email to me at vpankoni@nsf.gov .

Sincerely yours,

Vernon Pankonin
Division of Astronomical Sciences

Address list: Charles Alcock (calcock@cfa.harvard.edu), Michael Bolte (bolte@ucolick.org), Wendy Freedman (wendy@obs.carnegiescience.edu), Guenther Hasinger (hasinger@ifa.hawaii.edu), Suzanne Hawley (slh@astro.washington.edu), Patricia Knezek (knezek@wiyn.org), Shri Kulkarni (srk@astro.caltech.edu), David Lambert (director@astro.as.utexas.edu), David Silva (dsilva@noao.edu), William Smith (wsmith@aura-astronomy.org), Peter Strittmatter (pstrittmatter@as.arizona.edu)

16 Appendix C: List of Acronyms

AAS	American Astronomical Society
AAG	Astronomy and Astrophysics Research Grants
AAPF	Astronomy and Astrophysics Postdoctoral Fellowships
ACT	Atacama Cosmology Telescope
ACTA	Advanced_Čerenkov Telescope Array
ADVANCE	Increasing the Participation and Advancement of Women in Academic Science and Engineering Careers
AGN	Active galactic nucleus
AGS	Division of Atmospheric and Geospace Sciences
ALFA	Arecibo L-band Feed Array
ALMA	Atacama Large Millimeter/submillimeter Array
ALTAIR	Access to Large Telescopes for Astronomical Instruction and Research *Also* Altitude Conjugate Adaptive Optics for the Infrared
AO	Adaptive optics
ARRA	American Recovery and Reinvestment Act
ARO	Arizona Radio Observatory
AST	Division of Astronomical Sciences
ATI	Advanced Technologies and Instrumentation
ATST	Advanced Technology Solar Telescope
AU	Astronomical unit
BAO	Baryon Acoustic Oscillations
BigBOSS	Big Baryon Oscilllation Spectroscopic Survey
CAREER	Faculty Early Career Development Program
CARMA	Combined Array for Research in Millimeter-wave Astronomy
CCAT	Cerro Chajnantor Atacama Telescope
CCD	Charge-coupled device
CDI	Cyber-Enabled Discovery and Innovation
CFHT	Canada-France-Hawaii Telescope
CFP	Cosmology and Fundamental Physics
CMB	Cosmic microwave background

COSMOS	Cerro Tololo Ohio State Multi-Object Spectrograph
CSO	Caltech Submillimeter Observatory
CTA	Čerenkov Telescope Array
CTIO	Cerro Tololo Interamerican Observatory
D&D	Design and Development
DECam	Dark Energy Camera
DES	Dark Energy Survey
DESpec	Dark Energy Spectrograph
DOE	Department of Energy
DST	Dunn Solar Telescope
EARS	Enhancing Access to the Radio Spectrum
EPO	Education and public outreach
ESO	European Southern Observatory
EVLA	Expanded Very Large Arrray
EVN	European VLBI Network
FASR	Frequency Agile Solar Radio Telescope
FOV	Field of View
GRACES	Gemini Remote Access to CFHT ESPaDOnS Spectrograph
HETDEX	Hobby-Eberly Telescope Dark Energy Experiment
HSA	High-Sensitivity Array
GAN	Galactic Neighborhood
GBT	Robert C. Byrd Green Bank Telescope
GCT	Galaxies Across Cosmic Time
GeMS	Gemini Multi-Conjugate Adaptive Optics System
GHOS	Gemini High-resolution Optical Spectrograph
GMOS	Gemini Multi-Object Spectrograph
GNIRS	Gemini Near-Infrared Spectrograph
GONG	Global Oscillation Network Group
GPI	Gemini Planet Imager
GRF	Graduate Research Fellowships
GSMT	Giant Segmented Mirror Telescope
GUPPI	Green Bank Ultimate Pulsar Processing Instrument
GW	Gravitational Wave
HAO	High Altitude Observatory

HMI	Helioseismic and Magnetic Imager
IACT	Imaging Atmospheric Čerenkov Telescope
IGM	Intergalactic Medium
IMF	Initial Mass Function
ISM	Interstellar Medium
JWST	James Webb Space Telescope
KOSMOS	Kitt Peak Ohio State Multi-Object Spectrograph
KPNO	Kitt Peak National Observatory
LBT	Large Binocular Telescope
LMT	Large Millimeter Telescope
LSST	Large Synoptic Survey Telescope
LIGO	Laser Interferometer Gravitational Wave Observatory
LCDM	Lambda / Cold Dark Matter
Ly-α	Lyman-α
MAST	Mikulski Archive for Space Telescopes
MPSAC	Advisory Committee of the NSF Directorate of Mathematical and Physical Sciences
MREFC	Major Research Equipment and Facilities Construction
MRI	Major Research Instrumentation
MSI	Minority-Serving Institution
MSIP	Mid-Scale Innovations Program
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NEO	Near-Earth Object
NEWFIRM	NOAO Extremely Wide Field Infrared Mosaic
NIR	Near infrared
NISP	NSO Integrated Synpotic Program
NOAO	National Optical Astronomy Observatory
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
NSO	National Solar Observatory
NST	New Solar Telescope
NWNH	*New Worlds, New Horizons*
O&M	Operations and Maintenance
OCI	Office of Cyberinfrastructure

ODI	One-Degree Imager
OIR	Optical and infrared
OPP	Office of Polar Programs
PAARE	Partnership in Astronomy & Astrophysics Research and Education
PanSTARRS	Panoramic Survey Telescope & Rapid Response System
PAPER	Precision Array to Probe the Epic of Reionization
PHY	Division of Physics
PI	Principal investigator
PRC	Portfolio Review Committee
PSSF	Planetary Systems and Star Formation
PUPPI	Puerto Rican Ultimate Pulsar Processing Instrument
ReSTAR	Renewing Small Telesopes for Astronomical Research
REU	Research Experiences for Undergraduates
RMS	Radio, Millimeter, and Submillimeter
RV	Radial velocity
SDO	Solar Dynamics Observatory
SDSS(-III)	Sloan Digital Sky Survey (III)
SIP	Strategic Investments Program
SKA	Square Kilometer Array
SN(e)	Supernova(e)
SOAR	Southern Astrophysical Research Telescope
SOLIS	Synoptic Optical Long-term Investigations of the Sun
SSE	Stars and Stellar Evolution
STEM	Science, Technology, Engineering, and Mathematics
TCN	Theory and Computational Networks
TSIP	Telescope System Instrumentation Program
URO	University Radio Observatories
V&V	*Vision & Voyages*
VAO	Virtual Astronomical Observatory
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VLA	Karl G. Jansky Very Large Array
VLBA	Very Long Baseline Array
VLBI	Very-long-baseline interferometry
VLT	Very Large Telescopes

WFIRST	Wide-field Infrared Space Telescope
WIMP	Weakly interacting massive particle
WIYN	Wisconsin-Indiana-Yale-NOAO Telescope
WMAP	Wilkinson Microwave Anisotropy Probe
XSEDE	Extreme Science and Engineering Digital Environment