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October 23, 2006

Michael Witherell
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Dear Michael:

I herewith submit a report by the NSF division of Astronomical Science Senior Review Committee entitled "From the Ground Up: Balancing the NSF Astronomy Program", commissioned by the NSF Mathematical and Physical Sciences Advisory Committee.

I look forward to discussing this report with you and your colleagues on November 3rd .

Sincerely,

Roger Blandford

Errata for From the Ground UP: Balancing the NSF ASTRONOMY PROGRAM

The error reports are grouped by section and page number.

1.4 Senior Review Challenges

Page 13: "ratios of roughly eight percent which are much smaller." to "ratios of only eight percent[12]."

Page 13: "its annual[12] running costs are" to "its annual running costs (Sec. 4.1) are"

Page 13: "[12] See Sec. 4 for an explanation" to "[12] http://www.noao.edu/system/tsip/keck_cost.html & http://www.noao.edu/system/tsip/mmt_mag_cost.html."

2.2.2 Stars and Planets

Page 22: "over 600 rotations per second" to "over 700 rotations per second"

3.6.1 Observations

Page 32: "endeavors – GMT" to "endeavors—GMT"

4.3.2.1 Cerro Tololo Inter-American Observatory – figure 10a

Page 39: "the 4m Wisconsin-Indiana-Yale-NOAO (WIYN) 4m optical telescope" to "the 3.5m Wisconsin-Indiana-Yale-NOAO (WIYN) optical telescope"

6.2.1 Arecibo

Page 63: "(20 percent of the total budget)" to "(24 percent of the total budget)"

6.2.6 Radio-Millimeter-Submillimeter Summary

Page 65: "$22M allocated annually for GBT operations, administration, science and that this" to "$22M spent annually by NRAO on administration, science and GBT operations and that this"

7.3.1.4 Large Survey Telescope

Page 74: "by SEUOIF." to "by SEUOIF (Fig. 17)."

Page 75: "Large Synoptic Telescope (LST)" to "Large Survey Telescope (LST)"

7.3.1.5 Square Kilometer Array

Page 75: “on the SKA.” to “on the SKA (Fig. 18).”

7.5 Summary and Future Reviews

Page 80: “entirely, identifying efficiencies within NRAO,” to “entirely, identifying efficiencies within NRAO,”

Page 81: “next survey” to “next decadal survey”

FROM THE GROUND UP:
BALANCING THE NSF ASTRONOMY PROGRAM

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

October 22 2006

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Executive Summary

Astronomy – the scientific study of the universe and its contents – has furnished some remarkable discoveries in recent years, from new planets around nearby stars to black holes at the far reaches of the universe, to the tiny gravitational ripples that grew to form the structure that we see around us today. The science is driven by observations made using new telescopes, especially those located at ground-based observatories. However, this confluence of revolutionary scientific opportunities and new technology has led to an historically unprecedented demand on the development and operation of astronomical facilities. The National Science Foundation's Astronomy Senior Review Committee was charged with examining the Division of Astronomical Sciences portfolio of facilities and other selected, discretionary activities with the goal of redistributing roughly $30M of annual spending, roughly 15 percent of the total budget and 25 percent of the budget currently spent on facilities. The committee considered the balance of investment between the support of current research activities and the development of necessary future facilities as specified in National Research Council studies over the past five years. This process of renewal within strict budgetary limits is essential for maintaining the remarkable rate of scientific discovery in astronomy, although it comes with great cost.

Specifically, the Committee was charged with establishing criteria for developing its recommendations. It chose to do this in the form of six Principles:

1. ***Optimizing the Science.*** *The prime criterion, when making difficult choices between operating existing facilities and investing in new ones, is maximizing the integrated science impact for the overall US financial investment.*
2. ***Optimizing the Workforce.*** *The implementation of the proposed program should consider diverse workforce needs within the Division of Astronomical Sciences-supported observatory system and should provide for the training of the next generation of scientists and engineers. The observatories should seize opportunities for operating with higher efficiency.*
3. ***The Public Dividend.*** *Public awareness of astronomical discoveries, the observatories that produce them, and the personnel who are responsible for them, are a critical part of the current AST program that must be maintained.*
4. ***Bridging Artificial Divisions.*** *In order to complete its ambitious proposed program, the entire astronomical community needs to work together and to combine its many resources and strengths.*
5. ***Engaging the University Community.*** *The US astronomical facilities and the US university enterprise should align their strategic goals to enhance the research and education activities of the entire system.*
6. ***Astronomy without Borders.*** *The increasingly international character of astronomical research should be recognized and strategic cooperation should be pursued where advantageous or necessary in the construction and operation of next generation large facilities.*

In making its recommendations, the Committee has chosen to distinguish a Base Program, consisting of those components of the current program that should be preserved over the next five years and a Transition Program that comprises elements where significant changes are proposed. These programs can be loosely subdivided into an optical-infrared (OIR) component, a radio-millimeter-submillimeter (RMS) component and a solar astronomy component.

There are four Recommendations for the Base Program:

1. ***Grants Program.*** *The Division of Astronomical Sciences should anticipate that pressure on the grants program will intensify over the next five years and should be prepared to increase its level of support to reflect the quality and quantity of proposals.*
2. ***Optical-Infrared Astronomy Base Program.*** *The Optical-Infrared Astronomy Base program should be led by the National Optical Astronomy Observatory. It should deliver community access to an optimized suite of high performance telescopes of all apertures through Gemini time allocation, management of the Telescope System Instrumentation Program and operation of existing or possibly new telescopes at Cerro Tololo Inter-American Observatory in the south and Kitt Peak National Observatory or elsewhere in the north. The balance of investment within the Base Program should be determined by the comparative quality and promise of the proposed science. In addition, there should be ongoing support of technology development at independent observatories through the Adaptive Optics Development and the Advanced Technologies and Instrumentation Programs.*
3. ***Radio-Millimeter-Submillimeter Astronomy Base Program.*** *The Radio-Millimeter-Submillimeter Base program should comprise the Atacama Large Millimeter Array, the Green Bank Telescope and the Expanded Very Large Array operations together with support for University Radio Observatories and technology research and development through the Advanced Technologies and Instrumentation program.*
4. ***Solar Astronomy Base Program.*** *The Synoptic Optical Long-term Investigations of the Sun facility is the only current solar astronomy facility that should remain in the Base Program in the Advanced Technology Solar Telescope era.*

In order to implement a forward-looking, large-facility program and act rapidly on new scientific opportunities, it will be necessary to develop new technology and release resources by reducing support to some existing facilities.

There are three recommendations for the Transition Program:

5. ***Optical-Infrared Astronomy Transition Program.*** *Gemini operations will continue through 2012. Decisions on new Gemini instrumentation and negotiations for operation beyond 2012 should be guided by a comparison with the cost, performance, and plans of other large optical telescopes. The National Optical Astronomy Observatory should plan to reduce its major instrumentation, data products, administrative and science research staff over the next five years and concentrate on executing its base program more efficiently. Growth in*

support of a Giant Segmented Mirror Telescope and a Large Survey Telescope should be paced by Federal project choices and the schedule for Major Research Equipment and Facilities Construction account funding as well as progress by the partners in these projects.

6. ***Radio-Millimeter-Submillimeter Astronomy Transition Program.*** *The National Astronomy and Ionosphere Center and the National Radio Astronomy Observatory, which are heavily subscribed by other communities, should seek partners who will contribute personnel or financial support to the operation of Arecibo and the Very Long Baseline Array respectively by 2011 or else these facilities should be closed. Reductions in the cost of Green Bank Telescope operations, administrative support and the scientific staff at the National Radio Astronomy Observatory should be sought. US participation in the international Square Kilometer Array program, including precursor facilities, should remain community-driven until the US is in a position to commit to a major partnership in the project.*
7. ***Solar Astronomy Transition Program.*** *The National Solar Observatory should organize an orderly withdrawal of personnel and resources, including the Synoptic Optical Long-term Investigations of the Sun telescope, from Kitt Peak/Tucson and Sacramento Peak and start to close down operations at these sites as soon as the Advanced Technology Solar Telescope funding begins. It should also consolidate its management and science into a single headquarters. Support of the Global Oscillations Network Group project should cease one year after the successful deployment of the Solar Dynamics Observatory.*

Although the Senior Review was not charged with addressing the nature or implementation of the proposed future AST program, it found that it was impossible to carry out its task in isolation. As a result of reflecting upon the relationship between the current and proposed programs the Committee presents five additional findings:

1. ***The Scientific Challenge.*** *Proper maintenance of current facilities while simultaneously developing and beginning operation of the proposed new facilities is infeasible under any reasonable expectations for federal budget support based on past funding levels. The cuts that are recommended here are as deep as they can be without causing irreparable damage and will only allow a start to be made on the new initiatives. The scientific promise of the proposed new facilities is so compelling and of such broad interest and importance that there is a strong case for increasing the overall AST budget to execute as much of the science as possible.*
2. ***The Operations Challenge.*** *Major astronomical observatories typically take at least a decade to plan, construct and commission. They are usually operated for several decades. The full costs of operating, maintaining, upgrading, exploiting, and decommissioning them are many times the costs of construction. Realistic life cycle costing for the observatories that are under construction or consideration is an essential part of planning.*
3. ***The Strategic Challenge.*** *Construction on the Advanced Technology Solar Telescope may begin as early as 2009 (so as to be operational in 2014) and there*

is a strong scientific case for proceeding with the Giant Segmented Mirror Telescope, the Large Survey Telescope and the Square Kilometer Array projects as soon as feasible thereafter. A realistic implementation plan for these projects involves other agencies and independent and international partners. Some choices need to be made soon; others can await the conclusions of the next decadal survey. Much work is needed, scientifically, technically and diplomatically, to inform this plan.

4. ***Towards a Coherent National Astronomy Enterprise**. In order to meet the challenge of (multi-)billion dollar, ground-based optical-infrared and radio observatories, there will have to be strong collaboration between the federal and independent components of the US astronomical enterprise and firm leadership by AST. A high-level commission addressing optical-infrared facilities provides one way to start to bring together the diverse components of the national program to realize the full potential of the US system.*
5. ***Future Reviews.** Balancing the demands of the current program against the aspirations of the future program is an ongoing obligation. The Senior Review process should be implemented as a standard practice within the Division of Astronomical Sciences and should be a consideration included in the next decadal survey.*

1. Introduction

1.1 The Senior Review

Over the past few decades, astronomers have transformed our view of the universe and made fundamental and dramatic changes to our understanding of it. The list of astronomical discoveries made over the past half-century rivals the triumphs of previous centuries when the basic laws of classical dynamics were established and applied to the solar system. Astronomers, supported wholly or partially by the National Science Foundation (NSF[1]), have measured precisely the large-scale dynamical properties of the universe by observing microwave background fluctuations, supernova explosions, clusters of galaxies, and gravitational lenses and thereby have shown convincingly that the universe mostly comprises two mysterious substances: dark matter and dark energy. Closer to home, they have probed the interior of the sun and demonstrated that it radiates neutrinos with finite masses. In between these distance extremes, astronomers have discovered extra-solar planets and new dwarf planets within our solar system and described in some detail how such planets and their parent stars are born. They have detected black holes, hot stellar remnants, and cool stars in abundance and come to some understanding of stellar life and death. General relativity has been tested with extreme precision and protons and gamma rays of enormous energy detected from cosmic sources. Astronomers are starting to perceive how galaxies begin their lives. These advances have opened up new fields of scientific inquiry that are now being actively exploited by the community of astronomers, which itself has grown and is becoming a more representative cross section of the American public.

NSF initiatives in new facilities and technology have been so enormously effective that the pace of discovery should continue for several decades. However, the cost of maintaining top quality research over all the subfields of astronomy now outstrips available resources and it is necessary to make difficult choices between many productive facilities and fields in order to optimize the research output from the whole program.

In October 2005, the first NSF Astronomy Senior Review Committee[2] (SR) was convened and charged[3] to examine the NSF Division of Astronomical Sciences (AST) investment portfolio, balancing the needs of the ambitious new program proposed in the National Research Council (NRC) 2001 Decadal Survey "Astronomy and Astrophysics in the New Millennium" (AANM) and the 2003 report "Connecting Quarks with the Cosmos" (CQC)[4] with the support of existing facilities and technology development under the constraint that the AST budget grow no faster than inflation for the rest of the decade. The SR was instructed to accept the priorities and recommendations of

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[1] A list of acronyms can be found in Appendix A.
[2] See Appendix B
[3] See Appendix C
[4] A federal implementation plan issued by Office of Science and Technology Policy (OSTP) entitled *"A 21st Century Frontier of Discovery: The Physics of the Universe"*(2004) is also highly relevant.

community reports and not to attempt to allocate future resources. A target of $30M by 2011 was suggested for the redistribution from lower priority components of the current program to resources for developing and operating new facilities. The SR was asked to frame its recommendations in the context of the larger US and international astronomy program. In order to address this task, the SR studied the current NSF portfolio in ground-based astronomy that is now summarized.

1.2 NSF Support of Ground-Based Astronomy

NSF is the major, federal steward for US ground-based astronomy.[5] The total 2006 AST budget, (excluding MREFC funding and $8M in NSF-wide initiatives) is $191M, an increase of roughly two thirds over two decades (Fig. 1).[6] Expenditures are dominated by the support of five national observatories:

- The Gemini Observatory (Gemini) is operated on behalf of the International Gemini Partnership by the Association of Universities for Research in Astronomy, Inc. (AURA) and supports two 8m optical telescopes, one in each hemisphere. The current AST operations and development budget is $17M, half of the total Gemini budget.
- The National Optical Astronomy Observatory (NOAO) is also managed by AURA and operates several telescopes on Cerro Tololo and Cerro Pachon in the southern hemisphere and on Kitt Peak in the north, and also serves as the portal to Gemini for U.S. observers. Its current budget is $24M.
- The National Astronomy and Ionosphere Center (NAIC) is operated by Cornell University and runs the Arecibo Observatory. Its current budget is $12M comprising $10M from NSF/AST and $2M from NSF/Division of Atmospheric Sciences (ATM).
- The National Radio Astronomy Observatory (NRAO) is managed by Associated Universities, Inc. (AUI) and operates the Very Large Array (VLA), the Very Long Baseline Array (VLBA), and the Green Bank Telescope (GBT) and has started to provide operating funds for the Atacama Large Millimeter Array (ALMA). Its current budget is $51M, including ALMA operations but excluding ALMA construction, which has a 2006 budget of $49M from MREFC.
- The National Solar Observatory (NSO) is also managed by AURA. It operates telescopes on Kitt Peak and Sacramento Peak and six worldwide Global Oscillations Network Group (GONG) stations. Its AST budget is $10M.

In addition, NSF supports research grants ($50M), comprising $33M for the Astronomy and Astrophysics Research Grants Program (AAG), $7M for the CAREER and postdoctoral grants programs and $10M associated with the Physics of the Universe (PoU), the Virtual Observatory (VO) and other targeted programs. The budget for technology development is $17M, distributed over several programs including $8M for

[5] Astronomy will be taken to include solar astronomy and those parts of planetary science that fall under AST throughout this report.
[6] All costs quoted in this report are rounded and inflated where necessary to the nearest $M(2006). All budgets are annual for 2006 and include only AST contributions unless otherwise stated.

the Advanced Technologies and Instrumentation Program (ATI). Finally, grants to independent observatories total $11M, including $8M for the University Radio Observatory program (URO) and $3M to OIR observatories through the Telescope System Instrumentation Program (TSIP) and the Program for Research and Education with Small Telescopes (PREST).

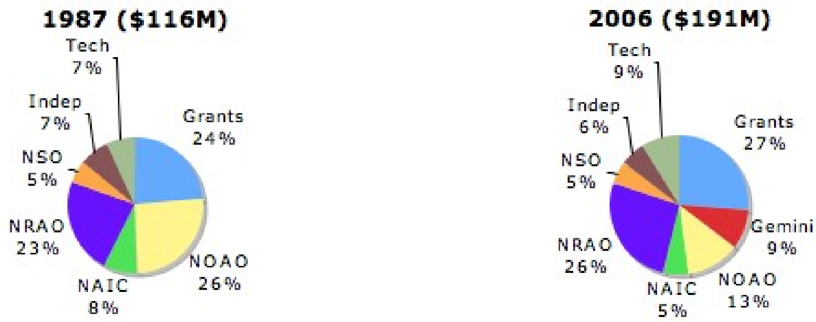

Figure 1. Distribution of AST funds in 1987 and 2006. "Grants" includes Career, Postdoc, PoU and VO programs. "Tech" includes AODP, ATI, CfAO programs as well as support for technology development for Gemini, GSMT and LST. "Indep" denotes support of independent radio observatories through the URO program and optical observatories through TSIP and PREST. The 1987 budget excludes VLBA construction and the 2006 budget excludes ALMA construction.

The distribution between grants, technology, OIR, RMS and solar components has remained constant to one or two percent over the past two decades, if one allows for the transfer of OIR technology development from the NOAO budget to separate programs.

Ground-based astronomy is also supported through collaborative AST ventures involving NSF-Physics, National Aeronautics and Space Administration (NASA) and Department of Energy (DOE) as well as the Smithsonian Institution, US Air Force (USAF), US Naval Observatory (USNO), NASA, National Research Lab (NRL) and Defense Advanced Research Projects Agency (DARPA) for specific programs. In addition, some ground-based astronomy, specifically involving gravitational radiation, neutrinos and Very High Energy gamma rays is supported by NSF-Physics and is not considered here.

1.3 Proposed Program

Strategic planning in astronomy has been guided strongly by a sequence of five decadal surveys. The most recent decadal survey, AANM, recommended realization of the following new initiatives in ground-based astronomy:

- Major Projects
  1. A Giant Segmented Mirror Telescope (GSMT)
  2. An Expansion to the VLA (EVLA)

3. A Large Synoptic Survey Telescope (LSST)[7]

- Moderate Projects
  1. The Telescope System Instrumentation Program (TSIP)
  2. An Advanced Technology Solar Telescope (ATST)
  3. Technology development for the Square Kilometer Array (SKA)
  4. A Combined Array for Research in Millimeter Astronomy (CARMA)
  5. A Very Energetic Radiation Imaging Telescope Array System (VERITAS)
  6. A Frequency Agile Solar Radio Telescope (FASR)
  7. A South Pole Submillimeter wave Telescope (SPST)[8]
- Small Projects
  1. The National Virtual Observatory. This is now known as the Virtual Observatory (VO), reflecting its international nature.
  2. The Laboratory Astrophysics Program
  3. A LOw Frequency ARray (LOFAR)
  4. A Theoretical Astrophysics Postdoctoral Fellowship Program.
  5. An expansion of the Synoptic Optical Long-term Investigations of the Sun (SOLIS).

These recommendations were ranked within size category but not between categories. The decadal study process, heretofore, has only set priorities for new facilities and programs, with limited consideration given to operating costs and generally no consideration given to existing facilities.

AANM also recommended the SR process[9] and strongly advocated adequate funding of the unrestricted grants program.[10]

Following AANM and in the context of dramatic scientific developments at the beginning of the 21st century, CQC addressed science at the interface between physics and astronomy. Inter-agency collaboration on major projects was also strongly endorsed. The two unranked CQC recommendations relevant to AST are:

- To measure the polarization of microwave background fluctuations in order to study a putative inflationary epoch in the early universe.
- To construct LSST[7] in order to study dark energy.

A 2005 NRC "letter report" (Chair, Meg Urry), affirmed the priorities of AANM and CQC.

Also relevant is the most recent decadal survey for planetary science,

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[7] Subsequently generalized to a Large Survey Telescope (LST)

[8] Subsequently call the South Pole Telescope (SPT)

[9] " Cross disciplinary competitive reviews should be held about every 5 years for all NSF astronomy facilities. In these reviews, it should be standard policy to set priorities and consider possible closure or privatization."

[10] "…new initiatives should not be undertaken at the expense of the unrestricted grants program."

- *New Frontiers in the Solar Systems An Integrated Exploration Strategy* (NFSS, 2003. Chair, Mike Belton),

which supported the LST, and that for solar physics,

- *The Sun to the Earth - and Beyond: A Decadal Research Strategy in Solar and Space Physics* (SEB, 2002. Chair, Lou Lanzerotti)

which endorsed ATST and FASR and discussed the synergy between ground- and space-based observatories.

In addition to these four NRC reports, there have been two recent studies requested by AST and commissioned by AURA and AUI discussing Optical-InfraRed (OIR) and Radio-Millimeter-Submillimeter (RMS) astronomy respectively.

- *Strategies for Evolution of US Optical/Infrared Facilities* (SEUOIF, 2005. Chair, Catherine Pilachowski).

This report recommended that NSF support GSMT technology and that a choice for federal investment be made in 2008 between a Thirty Meter Telescope option (TMT) and a 22m alternative, the Giant Magellan Telescope (GMT). In addition, two possible implementations of the LST, the single aperture LSST and the 4-aperture Pan-STARRS (PS4) alternative, were identified and it was also expected that a choice would be made by NSF over the next several years. The report also reaffirmed the long-term value of the VO.

- *Report of the Radio, Millimeter and Submillimeter Planning Group* (RMSPG, 2005. Chair, Martha Haynes).

This report advocated support of Cosmic Microwave Background (CMB) research, ALMA, CARMA, the second phase of EVLA, GBT, Arecibo, VLBA, SKA, the independent radio observatories, and low frequency arrays to study the epoch of re-ionization.

Out of the above proposed projects, EVLA (Phase 1), SOLIS, TSIP, CARMA, and VO are underway. VERITAS is also under construction but awaits permission to move onto Kitt Peak. While LOFAR is being constructed in the Netherlands, without US participation, US groups are independently pursuing parallel goals with several smaller projects. A South Pole Telescope for microwave background observations is supported by NSF Office of Polar Programs. GSMT and LST development have also been supported.

1.4 Senior Review Challenges

Carrying out a SR, in order to recommend an optimal balance between the current and the proposed program, is complicated because many facilities are operated collaboratively. Some collaborations were established under binding international agreements, like Gemini and ALMA. Other facilities are US-owned but have a large fraction of foreign Principal Investigators owing to their unique capabilities and the US "Open Skies" policy – the allocation of telescope observing time based not on citizenship or residence but purely on scientific merit. Other facilities, including independent radio observatories, are associated with US universities. In addition, there are observatories constructed with funds from the Keck Foundation and Carnegie Institution and operated by university and other private consortia, where support for the development of new instrumentation is provided by AST under the TSIP program, in exchange for community-competed telescope time. The ATI and Major Research Instrumentation (MRI) programs also support technology and instrument development at independent observatories and, here, the return of observing time is not a requirement. Finally, there are also collaborations between different agencies. In each of these cases, several stakeholders may have to agree to modify existing agreements or to align objectives and schedules for future initiatives.

An additional factor that will recur often in this report is the high cost of running current and proposed facilities. Indeed ongoing costs are the single, largest challenge to the future of observational astronomy. Their importance was spelled out in AANM, but they have been included unevenly in subsequent strategic planning. A common rule of thumb is that the ongoing, annual running cost of a facility is ten percent of the capital cost in fixed year dollars. In AANM, it is proposed that this ten percent comprises seven percent for operations and three percent for new instrumentation and minor facility upgrades. In addition, it is argued that three (five) percent of capital costs must be set aside to support the science from large (moderate) facilities for each of the first five years of operation, with a smaller allowance in subsequent years. The cost of running facilities in other countries appears to be at least ten percent of capital cost, after correcting for accounting differences.

Actual performance figures are instructive. The current total running cost of Gemini is 17 percent of the capital cost ($200M in total)[11] and it is proposed to increase this fraction to 22 percent by the end of the decade, in order to construct new instruments. This is over twice the rule of thumb. By contrast, the perceived cost of running independent observatories is usually less than that of running similar national facilities for several reasons including the relative stability of the user community, the lower level of support services deemed acceptable and the hidden subsidy of faculty and science staff salaries. For example, the two Keck telescopes, which had capital costs of $240M, and the two Magellan telescopes, with capital costs of $85M, both have running cost to capital cost ratios of roughly eight percent which are much smaller.

Turning to radio telescopes, the 26 year old VLA is the most economical facility by these criteria as its annual[12] running costs are $11M or three percent[13] of its inflated cost of $360M. This partly reflects its age, the delay in upgrading and the fact that it involves many similar telescopes, which can introduce economies of scale and may make operations relatively cheaper. By contrast the operations costs of the GBT are $10M or 12 percent of the construction costs of $85M.

Whichever rule is adopted, the integrated operations burden is large because most observatories have long lives. The VLA remains the premier radio interferometer in the world and will be about 40 years old when the SKA might be completed. ALMA is already planned as a 40 year observatory. Applying the ten percent rule over forty years

[11] AST paid for half the capital cost and is responsible for half the running cost.
[12] See Sec. 4 for an explanation.
[13] This should be increased to four percent if the cost of the EVLA upgrade is included.

to a facility quintuples the life-cycle cost. In a steady state, with several telescopes in simultaneous operation, the running costs dominate the capital costs. Furthermore, while capital costs may be derived from private benefactors, the running costs are historically of less interest to private patrons, so they are likely to fall upon the federal agencies.

Roughly two thirds of the AST budget ($130M) is already spent supporting existing facilities. Looking ahead, funds for additional running costs will have to be found. The current estimate of the US share of ALMA annual operations is $30M, including some provision for upgrading. This is only six percent of the US share of the capital costs ($500M) and well below the ten percent rule for running costs. ATST is projected to cost NSF $145M and the operating costs to AST are estimated as $10M. Although, this is consistent with the seven percent operations rule, there is no provision here for upgrading the instrumentation which suggests that ATST support could also be under-estimated. The larger version of GSMT, TMT, is advertised to cost $750M. If NSF were to have to pay all of the operating and new instrumentation costs, this would amount to $75M per year, adopting the ten percent rule or about $150M per year, scaling from Gemini. A similar rule applied to a one third share of SKA adds a further $35M per year. LSST, the larger of the two LST choices is estimated to cost $300M in total and AST would have to find $14M per year for its share of operations, assuming the partners fund their share.

Although each of these estimates deserves scrutiny and could change following detailed costing, the sum of the annual operating and upgrading costs of the projected and desired new facilities probably lies in the $150-250M range. To this should be added the cost of carrying out the science, roughly a further $50-70M. The AST budget would have to increase by more than a factor of 2 to 2.5 to absorb these commitments. Addressing the challenge of operating future facilities does not lie within the SR charge. However, it has framed the discussion leading to the recommendations below regarding current facilities.

These considerations motivate AST and challenge the astronomical community to close existing facilities. However, savings are generally not realized as soon as a facility is scheduled for closure. Some telescopes will be very hard to dismantle and many observatories were constructed under agreements that the land will be returned to its natural state, involving expensive environmental and cultural studies followed by implementation. Additional costs involve staff severance and relocation, which are hard to estimate, but may be considerable. In many cases, the greatest savings to AST and the best service to the astronomical community will be found in keeping facilities operating at higher efficiency and with external contributions.

1.5 This Report

In the following section we present a brief summary of the scientific landscape of the AST program that is intended to provide a context for the various observatory programs and the choices that are being recommended. The charge to the SR requested that it define and describe the principles that underlie its recommendations. These are discussed in Sec. 3. The current program is summarized in Sec. 4. Those elements of the existing program that are recommended to continue at roughly present levels over the next five years are called the “Base Program” and are discussed in Sec. 5, while those for which AST funding is recommended to change significantly are part of the “Transition Program” which is covered in Sec. 6. It is not within the purview of the SR to make recommendations on the future program. Nevertheless, the committee had to understand the options under consideration in order to make its recommendations and these deliberations led to some Findings, which are presented in Sec. 7.

1.6 Acknowledgments

This report relied heavily on several sources of input. The Directors of the five observatory managements received requests from NSF for detailed information concerning the scientific rationales for each element of the observatory operation along with defensible costs associated with both continued operation and closure. They each responded with major publications that have been widely consulted not just by the SR, but also by the user community.[14] They also each met twice with the committee.[15] These meetings were all frank and constructive. A subsequent request for supplementary data issued by the committee in November was promptly addressed. The US astronomical community also rose to the challenge of providing input to the SR over the course of seven "town meetings"[16] and by posting written opinions to the Senior Review website. Several hundred thoughtful communications have been heard and read. The SR also acknowledges the contribution of Virginia Trimble who shared useful data on bibliographic metrics that helped the committee to understand better the value and shortcomings of this approach to comparing facilities. A draft version of this report was carefully reviewed by five anonymous readers who all made constructive suggestions to improve its presentation. Finally, this review has required an immense amount of work by the AST staff, notably Wayne Van Citters and Eileen Friel, who have been extremely patient as the committee struggled to understand a very complicated network of research dependencies and obligations.

This report is the sole responsibility of the SR. However, it would have been a much weaker document without the assistance of all the above to whom the committee offers its sincere thanks.

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[14] *Focus on the Future: Transforming the U.S. Ground-based OR/IR System*, Report to the NSF Senior Review, July 29, 2005
(http://www.noao.edu/dir/seniorreview/).
National Solar Observatory, Response to the National Science Foundation, Division of Astronomical Sciences, Review of Senior Facilities, August 2005
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[15] A record of committee meetings is given in Appendix D.

[16] See Appendix E

2. The Scientific Landscape

This is a time of exciting and ongoing discovery in astronomy. The story that unfolds below could not have been written with the same degree of confidence and authority ten years ago. The scientific impact from remarkable recent developments in technology and advances in astronomical capability has now placed astrophysics and cosmology on a secure physics-based foundation. Many of these advances, as indicated below, have been made possible using facilities and researchers supported by NSF.[17]

2.1 The Revolution in Technology

Progress in astronomy has been fueled by the application of modern technology to the ancient craft of observing the sky. Today, telescopes image cosmic sources across the entire electromagnetic spectrum; from 10-meter wavelength radio waves to 100 zeptometer (10^{-19}m) gamma rays. Indeed, exploration of the universe is no longer confined to the electromagnetic spectrum. Cosmic neutrinos and relativistic protons with macroscopic energies almost a billion times those accelerated at Fermilab have already been detected and searches are underway for dark matter particles and gravitational radiation. NSF has been at the cutting edge, supporting research at each of these frontiers. Within NSF, AST has been primarily engaged in supporting telescopes that observe the electromagnetic spectrum at radio, millimeter, submillimeter, near-infrared and optical wavelengths.

The size of telescopes has also increased substantially; the total collecting area of optical telescopes around the world, with apertures as large as 10 meters, has more than tripled in the past 15 years. Plans are underway to construct optical telescopes with diameters of 30m, or even larger. At radio wavelengths, collecting area of single telescopes is still dominated by Arecibo (roughly 70,000 m^2) and, for interferometers, by the VLA (roughly $10^4 m^2$).[18] ALMA, presently being constructed, will have a collecting area of roughly 6000$m.^2$ Larger aperture means improved sensitivity to fainter objects and increased clarity of images. However, it is not just the size of a telescope that matters; the gain in efficiency that results from performing many functions simultaneously and the ability to measure spectra and monitor rapid variation are also important figures of merit.

Many new techniques are under development. Advances in adaptive optics (AO), such as those being made using the Gemini telescopes, hold promise to transform the next generation of large aperture, ground-based, optical telescopes by correcting for the time-dependent distortion caused by the Earth's atmosphere. These techniques achieve impressive angular resolution, routinely better than 50 milliarcseconds in the near infrared, matching the resolution obtained by the VLA and "radio adaptive optics" as pioneered by NRAO. Long baseline interferometry at millimeter wavelengths, using the VLBA, can achieve a thousand times better angular resolution. In addition, advances in

[17] The five observatory submissions to the SR contain excellent and more extensive scientific narratives.

[18] The Indian "Giant Metre-Wave Radio Telescope" has three times the collecting area of the VLA but cannot observe above a frequency of 2 GHz.

spectroscopic methods and instrumentation have increased the scientific reach of today's telescopes immensely by improving spectral precision, efficiency, and multiplex capability.

Detectors are also improving. Gone are the photographic plates of old; today's telescopes are outfitted with digital electronic array detectors that increase a hundredfold the sensitivity and efficiency of optical and infrared light detection (Fig 2a). Superconducting Tunnel Junction Photodetectors introduce the capability to measure a spectrum on a single pixel. At radio and millimeter wavelengths, the development of advanced bolometric and Microwave Monolithic Integrated Circuits promise analogous capabilities and gains in performance.

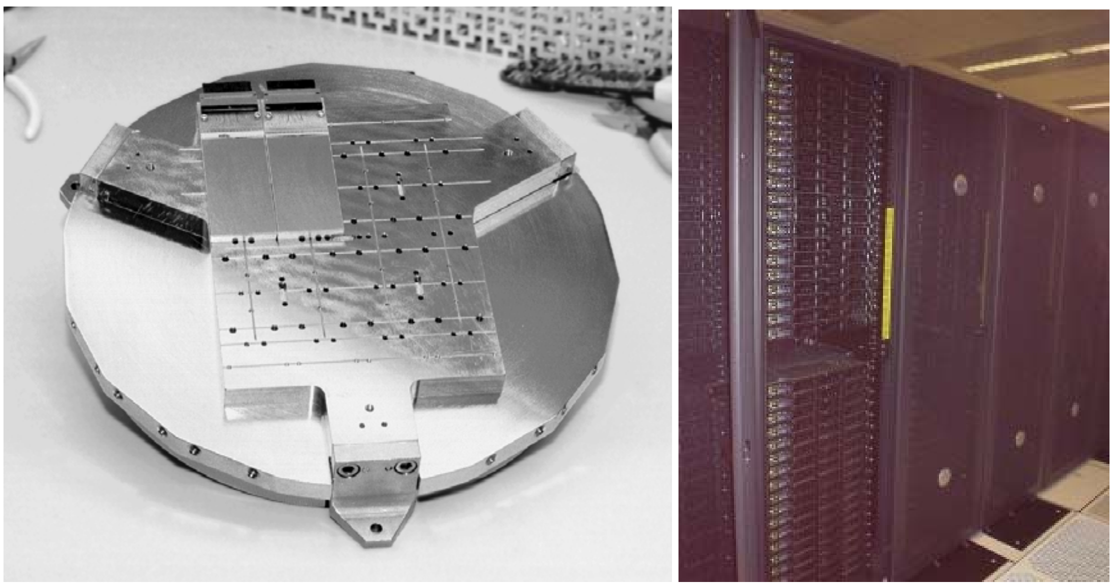

Figure 2. (a) On the left, large format CCD cameras in the future will supercede modest sized cameras of the past such as this 64 Megapixel NOAO optical camera by two to three orders of magnitude allowing rapid and efficient surveying of the sky and deep integrations to reveal distant parts of the universe. The number of pixels in "cameras" at millimeter and infrared wavelengths are similarly undergoing rapid development and will open new opportunities. [Image credit: NOAO/AURA/NSF] (b) Large computer clusters such as the one shown on the right and deployed at the NSF National Center for Supercomputing at the University of Illinois are used for astrophysical processes and cosmology as well as for analysis of large data sets. NSF is supporting the development of the VO to provide effective and efficient access to the digital archives of astronomical images and spectra. [Image credit: NCSA/University of Illinois]

Information processing, coupled with modern digital electronics, allows automation in many aspects of data acquisition, telescope operation and the ability to collect very large data sets with ease and skill. The internet and modern computation capabilities place the data and analysis tools for these large data sets at the fingertips of researchers, students and amateur astronomers around the world (Fig. 2b). These advances have enabled wide field telescopes to conduct semi-automated surveys of large fractions of the visible sky, revealing the structures of the universe on the grandest scales and detecting transient events. There have been parallel developments in space astronomy. Today, observations from the ground and from space are regarded as highly complementary and are often combined to reveal far deeper insights than can be obtained from one single wavelength or technique.

All of the above advances have revolutionized the way scientists approach astronomy in the modern era. Yet, astronomy remains a technologically young field in the sense that further great gains in sensitivity, angular resolution, spectral resolution, time resolution, and accuracy are achievable and affordable. As a consequence, discovery space will continue to be opened up well beyond the horizon of this report.

2.2 The New Cosmos

2.2.1 Cosmology

This multiplication in the number of windows on the universe has allowed astronomers and physicists to uncover deep and fundamental truths about the nature of the universe and to observe previously unimagined cosmic phenomena. Armed with a wealth of data gathered using these tools, astronomers have synthesized a standard, cosmological model. We now understand that the universe began expanding 13.7 billion years ago and that the rate of expansion is increasing due to an unidentified “dark energy,” which accounts for 74 percent of the matter-energy of the universe. In addition, there is a second unknown component called “dark matter” which accounts for 22 percent of the universe and whose gravitational effects are evident in studies of galaxy dynamics (pioneered using NOAO telescopes). Dark matter and energy do not fit within the standard model of elementary particle physics and are suspected to comprise new fundamental particles and fields whose detection has eluded all modern particle accelerator experiments. The next generation of particle accelerators may reveal the secrets of the elementary building blocks of nature and the presently unknown physics that lies beyond the standard model. The elucidation of these properties and principles will, in turn, enhance our understanding of the earliest moments of the universe. Ordinary matter, the matter that forms luminous stars, planets, interstellar gas and living beings, makes up the remaining four percent of the universe. One of the great surprises in astronomy has been the revelation that stars account for only about one per cent of the mass of the universe they were once thought to dominate.

Cosmologists are concerned with more than just measuring mass, length, and time. They are also historians who have pieced together a remarkable story of the expanding universe from the earliest moments of the big bang to the present day. It is conjectured that, soon after the big bang, the universe underwent a period of rapid expansion, called inflation, that allowed our present universe to reach its enormous size. As the universe continued to expand and cool, elementary particles were somehow left over to form the ordinary matter of today. By the time the universe was a few minutes old, it was mostly in the form of hydrogen, helium, radiation, and inert particles called neutrinos. This is the epoch of nucleosynthesis and it is understood well. The universe was quite opaque at this time and remained so until it was almost four hundred thousand years old when it quickly became transparent. This is the epoch of recombination and its radiation, now reaching us, we call the microwave background radiation. Again, we have a good understanding of this epoch. Exquisitely precise measurements of tiny fluctuations in this background radiation, made from telescopes on the ground and in space, describe the fluctuations in the distribution of dark matter in the early universe.

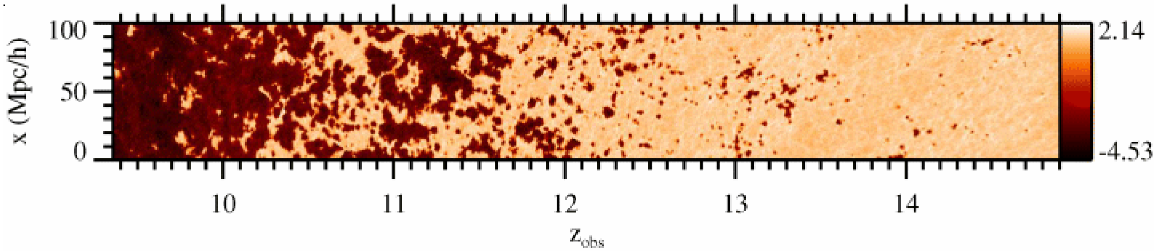

Figure 3. This diagram shows a computer simulation of the level of emission of the 21cm wavelength spin flip transition of hydrogen in a slice (vertical axis) of the early universe during the interval when first stars and galaxies form from 300 to 600 million years after the big bang, corresponding to redshifts (z_{obs}) from 15 to 9. The emission level in milliKelvins is given by logarithmic scale on the right. Probing this epoch of the first stars for this quantum emission and a number of other approaches is a frontier research topic. [Image credit: Mellema 2006.]

When the universe was perhaps a few hundred million years old, at the end of an era called the dark ages, dark matter concentrations had grown enough under the influence of gravity to trap ordinary matter to form the very first stars. These first generation stars produced ultraviolet radiation that converted the atoms of hydrogen back into a plasma of protons and electrons. The details of this epoch of (re-)ionization remain poorly understood (Fig. 3). The first galaxies formed around this time and quickly developed massive black holes in their nuclei. These black holes accreted gaseous fuel which radiated more ultraviolet radiation as quasars - the most powerful type of active galactic nucleus (henceforth AGN). Following reionization, more and more of the plasma was converted into the stars and galaxies we observe today.

Figure 4. The realm of galaxies from a deep survey of galaxies across a wide angular field with the NOAO Mayall 4m telescope. Imaging and redshift surveys allow astronomers to chart the evolution of galaxies through cosmic time. [Image credit: B.Jannuzi, A.Dey, NDWFS team/NOAO/AURA/NSF]

The structure of the universe is also revealed in the distribution of galaxies. Large optical and radio surveys of the sky (led by NOAO and NRAO, respectively), have shown that galaxies are not randomly distributed; instead, most are found in groups and clusters which are part of larger-scale structures known as sheets and filaments, separated by giant voids (Fig. 4). Remarkably, it is possible to relate this structure in the modern universe directly to the microwave background fluctuations from the ancient universe.

Ultimately, it is hoped to relate polarization measurements of the fluctuations back to their quantum mechanical seeds formed during the epoch of inflation. This standard model of the universe provides the context for all other astronomical research.

2.2.2 Stars and Planets

The sun is considered a rather ordinary star in the Galaxy. It is important to humanity, of course, because it creates a habitable zone in which life can flourish, at least on Earth. The sun is a magnetically active star with a 22-year cycle modulated by its interior dynamo. The sun's magnetically active surface heats its corona to millions of degrees and powers an outflowing wind of energetic particles (Fig. 5a). Space “weather,” a direct consequence of the magnetic behavior of the sun, influences the heliosphere and the planets, including life on Earth. Solar flares and coronal mass ejections, in particular, interfere with human spaceflight, communications, power transmission grids, and navigation systems. A major objective of NSO’s program is to understand and some day predict, the sun’s effects. Consequently, solar physicists monitor the sun's interior properties and surface magnetic regions (such as sunspots) throughout the magnetic cycle.

Beyond these pragmatic concerns, the sun provides an astrophysical laboratory to study how plasma and magnetic fields behave under extreme conditions, as well as a proving ground for the physics that underlies much of stellar astronomy. For example, detailed measurements of naturally occuring seismic oscillations in the sun led to the validation of the standard model of stellar interior structure (Fig. 5b). Yet, terrestrial observations failed to record the predicted flux of the elusive, subatomic particles called neutrinos expected from nuclear burning in the sun's core. The resolution of the disagreement was that these neutrinos come in three types with finite mass and can change their type. These are profound results for physics with implications for cosmology and an important example of interconnectivity in science.

Stars are the powerhouses and chemical factories of the Galaxy. Like people, stars are born, they mature and they die. One of the crowning achievements of 20th century science was the development of a theory that accurately accounts for stellar structure and evolution as well as the formation of the chemical elements. According to this theory, the subsequent life history of a star is essentially determined by its birth mass. Consequently, unraveling the mystery of star formation is critical to understanding the origin and evolution of all stellar systems, including galaxies. Stars provide the energy necessary for the development of life and for driving biological evolution, which has occurred on at least one planetary system accompanying a star. Understanding star formation is therefore a fundamental step toward understanding the origin of both planets and life.

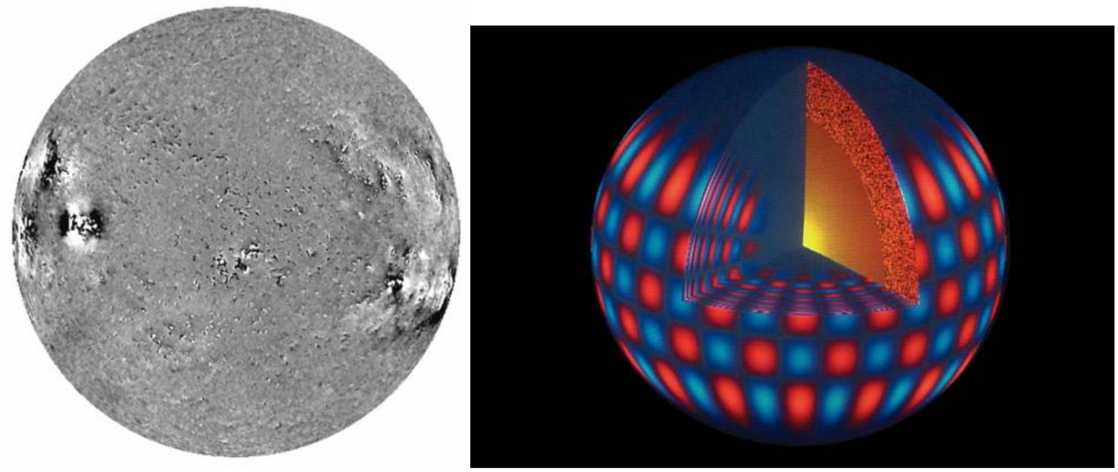

Figure 5. (a) On the left, the dark and light regions of the solar image delineate opposing polarities of the magnetic field on the surface of the sun in this NSO SOLIS magnetogram. Nearby opposing magnetic fields annihilate each other and lead to dramatic solar flares that produce energetic particles that can severely perturb satellites and terrestrial communications. (b) On the right is an image of a solar oscillation mode analyzed using the GONG telescope. (Blue denotes rising motion and red falling motion.) Modal analysis of these data provides solar physicists with direct measures of the interior temperature, density, energy generation, and heat transfer properties of the sun. [Image credit: NSO/AURA/NSF]

Most star formation appears to take place in Giant Molecular Clouds, the largest and coldest objects in the Galaxy. As they are opaque to visible light, they are best studied at infrared and millimeter wavelengths. Techniques developed for investigating these clouds provide a means of studying both star formation in distant galaxies and the origin of galaxies. Star formation studies are also relevant to the earliest cosmological epochs when the very first stars were formed in nascent galaxies.

Although planetary science is popularly associated with space missions, there is a long and distinguished tradition of fundamental discovery that have been with ground-based telescopes supported by AST. One of Arecibo's main accomplishments has been to use active radar mapping to measure surface topographies and rotation rates of Mercury, Venus and the Moon. The Gemini telescope has recently been able to study the meteorology of Saturn's largest moon, Titan. However, the discovery that has attracted the most recent attention is of large numbers of dwarf planets that can be larger than Pluto.

Another recent and exciting discovery of recent years has been of nearly 200 extra-solar planets orbiting nearby stars similar to our sun. These planets have a range of properties quite different from the planets in our solar system. The challenge now is to image bloated, newborn planets and to observe their dynamical interactions with the disks of gas, dust and rocks out of which they grow. These studies will help us understand how our solar system came into being.

All of this research is relevant to the growing field of astrobiology, which has the primary goal of understanding the nature and incidence of life in the universe. Like the big questions of cosmology, the ancient philosophical questions of “What is life?” “Where did humans come from?” and “Are we alone?” are proving amenable to scientific study and starting to furnish some secure answers.

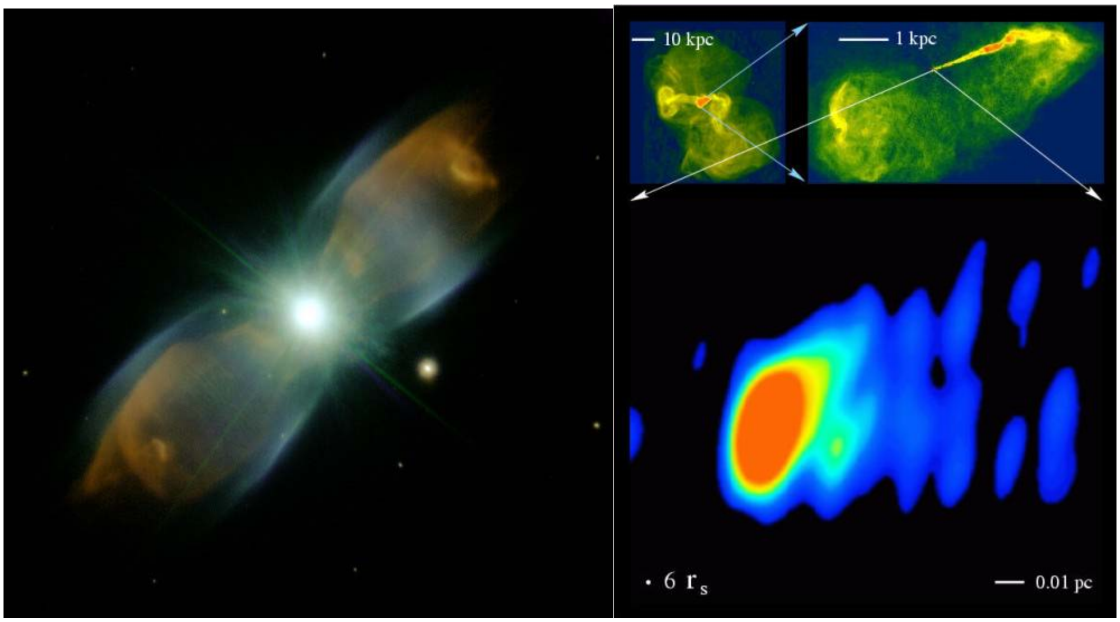

Figure 6. (a) On the left is a multicolor image of the planetary nebula M2-9 made using the adaptive optics system on Gemini North. This image reveals remarkable details in the dynamic gas outflows from a dying star. It is thought that our sun might meet a similar fate in 4-5 billion years. Understanding the death of stars of different masses is an important goal for both stellar evolution studies and as tools for probing the distant universe. [Image credit: Gemini Observatory/Travis Rector, U. Alaska, Anchorage] (b) On the right are radio images of a nearby galaxy, M87, containing a three billion solar mass black hole in its nucleus. This black hole and its surrounding disk of gas create a pair of outflowing jets. The lower millimeter wave image of the innermost portion of the jets was made using the VLBA; the VLA was used for the upper two radio images, on larger scale. The jets in M87 are observed at infrared, optical, X-ray, and TeV gamma ray energies and their nature can only be understood by combining observations throughout the electromagnetic spectrum. [Image courtesy of NRAO/AUI and W. Junor, J. Biretta and M. Livio.]

Turning from the origins of stars and planets to their endpoints, we know that stars evolve, swelling to form “giants” which engulf most of their planets. Eventually the most massive stars die in supernova explosions, which form neutron stars and black holes. Neutron stars are only ten km in radius and can spin rapidly - over 600 rotations per second. These pulsars (which are extensively studied using the Arecibo and Green Bank telescopes), have provided wonderful tools for testing fundamental physics and for probing interstellar space. (Occasionally, they come with planets.) A minority of supernova explosions, perhaps those that form black holes, create gamma ray bursts - brilliant flashes of gamma rays of duration from seconds to minutes that can be seen across the universe. Like black holes, neutron stars can be extremely luminous when they accrete gas from stellar companions.

Less massive stars evolve more slowly and less dramatically into white dwarfs, shedding much of their mass as spectacular nebulae (Fig. 6a). Sometimes these white dwarfs blow up completely, in a different type of supernova explosion when they accrete gas from companion stars. (These white dwarf supernovae have turned out to be useful tools for measuring cosmological distance, a technique pioneered at CTIO, and provided the first strong evidence for dark energy.) All supernova explosions form expanding shells of gas that heat the interstellar gas and disseminate heavy elements throughout the Galaxy. These elements provide raw material for the next generation of stars, planets, and ultimately life. Supernova remnants are also the site of acceleration of most cosmic ray particles; cosmic rays that have an impact on life by inducing genetic mutations.

2.2.3 Galaxies and their Nuclei

The great advances in our understanding of the structural and evolutionary properties of stars form a basis for research in the formation and evolution of galaxies. Galaxy shapes and mass distributions are related to their formation conditions through hierarchical mergers and infall of gas. Despite great advances, a comprehensive understanding of galactic evolution over the lifetime of the universe remains a major challenge. Huge surveys of galaxies in the nearby universe are furnishing statistical information on the properties of local galaxies. The next step is to extend these surveys to galaxies at great distances that we see at a time when the universe was much younger. In this way we can reconstruct the empirical history of galaxy formation and evolution. We can begin to understand how much structure in the universe, particularly on small scales, is associated with clumps of dark matter from which most of the luminous gas has been expelled by supernova explosions, rendering the clump invisible. This research has long been carried out using NOAO telescopes and is becoming a priority for Gemini.

A new element in the story of galaxy evolution has been introduced in recent years with the discovery that most normal galaxies, including our own, harbor in their nuclei massive black holes, with masses ranging from millions to billions of solar masses. Most black holes are dormant now and are best studied by their gravitational effects on the surrounding stars. However, in the past, many were AGN when they were supplied with gaseous fuel. This has two observable consequences. The first is that as the gas spirals inward onto the central black hole, it releases some of its gravitational energy in the form of radiation. This process is nearly a hundred times more efficient than the nuclear reactions that occur within stars. The most powerful black holes, called quasars, outshine the stars of their host galaxies by factors of many thousands.

The second consequence is that many active black holes generate powerful outflows or winds and pairs of jets traveling with speeds close to that of light, as exhibited by the VLA and VLBA (Fig. 6b). These jets can inflate giant double radio sources outside the host galaxy. It is now clear that these outflows are intimately involved in galaxy evolution and formation. They provide a natural feedback mechanism, which moderates the rate of star formation and provides a major heat source for the circumgalactic gas.

The environmental impact that evolving stars have on the interstellar medium is mirrored by the impact that evolving galaxies have on the intergalactic medium. As VLA observations have shown, these effects are particularly apparent inside the giant clusters, where thousands of galaxies are bound by an enormous concentration of dark matter and hot, X-ray-emitting gas.

2.2.4 AST Role

As this brief sketch makes clear, AST has had a major role in the rapid growth in our understanding of the cosmos. An important feature of this research is its interconnectivity. Cosmic objects do not form and evolve in isolation. Consequently, they are rarely observed and considered in isolation or at one wavelength. To give one out of countless examples, astronomers today find and study the properties of rich clusters of galaxies using deep optical and radio galaxy surveys, x-ray observations, measurements of local reductions in the microwave background, studies of gravitational lensing and optical spectroscopy. The results of these investigations impact our understanding of the properties of dark matter and dark energy.

Through its support of telescopes observing throughout the electromagnetic spectrum and a highly competitive grants program, AST has actively fostered multi-wavelength astronomy. It has also supported a very productive theory program that has uncovered general principles and unsuspected connections between disparate sets of observations.

2.3 Societal Impact

America's failure in technical and scientific education at early levels is now universally recognized and is regarded as a national emergency that threatens the future prosperity and security of the whole country. This is the theme that underpins the recent American Competitiveness Initiative.[19] Astronomy is in a unique position among the hard sciences to help recruit the next generation for the nation's science and technology workforce as it is highly visual, rapidly moving, and generates countless news articles, popular books, and TV documentaries. Roughly a quarter of a million undergraduates per year take an astronomy course in the US. Fortunately, astronomy fosters a professional culture that respects and encourages outreach and formal and informal education at all levels, with participants ranging from practicing researchers to K-14[20] teachers to amateur astronomers.[21] Indeed, these activities form an important part of the basis for any federal support of astronomical research.

In addition to the scientific connections with the disciplines of physics, chemistry, and biology outlined above, astronomy has also had a direct impact on the Nation's technical infrastructure. This has occurred through the development of devices (e.g. sensitive detectors for all astronomical wavebands) and techniques (e.g. adaptive optics) that have found broad applicability. Astronomers continue to challenge industry to address problems of some generality in a high visibility environment. Many PhD astronomers

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[19] See http://www.whitehouse.gov/stateoftheunion/2006/aci/

[20] K-14 includes two years of college before specialization.

[21] Additional information on the workforce may be found at http://www.aip.org/statistics/trends/reports/emp.pdf.

seek employment in high technology and computing industries. Their training in problem solving at the cutting edge of physical understanding is a highly sought-after attribute by industrial, commercial, and financial employers. In these ways, astronomy has stimulated advances in imaging, data analysis, data mining, communications technology, and detector development within the industrial community.

3. Observations and Principles

The committee was charged to develop its recommendations "based on well-understood criteria established by the committee and articulated to the community." After extensive committee discussion and consultation with the astronomical community and the management of the national observatories, the SR arrived at the following fundamental observations and principles.

3.1 Optimizing the Science

3.1.1 Observations

The SR was confronted with several choices between supporting existing facilities that continue to produce excellent science and that enjoy a committed user base, or developing new facilities with greater capabilities that may become operational in the future. While such transformations seem both necessary and inevitable for progress, they require sacrifices both from individuals and institutions. Astronomical facilities should plan for a natural life cycle ending, in every case, with closure. In an era when the level of aspirations relative to resources is higher than it has ever been, this means that some facilities must be closed long before they no longer produce important research and that some very promising initiatives must be deferred. This choice is faced regularly in peer proposal review. The most important criterion that should govern all such choices is optimization of the overall potential for science and discovery - the net contribution to the breadth and depth of human knowledge.

In an ideal world, any new facility would be constructed rapidly and the user community from any predecessor facility would quickly migrate to it and perform superior science. However, in the real world, new facilities are often very expensive and technically complex, with considerable construction and operating costs, which may involve delays and de-scoping. In the interim, there might be a user community lacking telescope access for many years. This would lead to an interruption in the flow of students and researchers that could damage science in the long run. Alternatively, the new facility might serve a quite different community.[22]

Assessing the scientific impact of existing facilities is important but necessarily subjective. The five observatories provided to the committee a wealth of statistical material on user demographics, efficiency of operations, publications and citations, which informed the SR's deliberations. However, publication and citation practices vary widely between fields of comparable quality and these statistics, although instructive, should be used with circumspection.

In addition to performance metrics, the other major considerations are facility and operations costs. Given a choice between two facilities producing comparable science, priority presumably would be given to the one that was cheaper to run. Again, much

[22] The SR saw no requirement to match new facilities to the subfields or observatories of those slated for closure. It also took the view that the existence of a user community was an insufficient criterion for maintaining or replacing a telescope.

information was provided by the five observatories. The true cost of running a telescope is difficult to assess in the presence of many hidden subsidies and the reality that most employees have multiple responsibilities. In assessing costs, it is also necessary to consider the possibility of enormous divestiture costs for some major facilities that might have to be borne by the rest of the AST science program. The overall impact on science of a closure could be far more than the loss of the facility and its staff.

These observations led to the first principle:

3.1.2 Principle 1

The prime criterion, when making difficult choices between operating existing facilities and investing in new ones, is maximizing the integrated science impact for the overall US financial investment.

3.2 Optimizing the Workforce

3.2.1 Observations

The flood of unprecedented astronomical discovery is not just a consequence of new technology or happenstance. It is a direct reflection of the efforts of over a thousand FTEs[23] - scientists, technical staff, administrators and other personnel - who are supported by AST funding in the five observatories and the nearly two thousand scientists and engineers who receive partial support through the grants program.[24] Indeed, the dominant item in each observatory budget is staff salaries. Generally, observatory staff members have served their organizations with professionalism, diligence and loyalty, often for decades. They represent a human investment and asset that would be difficult and expensive to replace. However, some transformations must occur and upheavals are unavoidable. As the AST program evolves, some people will relocate, some will learn new jobs, and some will be replaced by new employees bringing new skills to bear on astronomical problems. Fortunately, AST is not facing a genuine budget cut, but a reallocation of resources, and that offers some flexibility. The transition to developing and operating new facilities requires management organizations that can handle relocation of personnel or responsibilities so as to ensure that these facilities are operated efficiently.

A longstanding issue is the need for a scientific staff within the national observatories. On the one hand, there are great benefits to having regular users involved in the day to day, and night to night running of major telescopes and the planning of the next generation facilities. They have a far better appreciation than non-users of the subtle

[23] In this estimate, personnel who are partially supported by the NSF are partially counted.

[24] A different measure of the size of the astronomical community is the membership of the American Astronomical Society which increased from around 4500 in 1985 to 6500 in 1995 and has remained roughly constant over the past decade, although there has been significant growth in the astrophysics division of the American Physical Society.

choices that have to be made to optimize the scientific use of a facility. In addition, it has long been argued that theorists, who are conspicuously under-represented in national facilities, would bring fresh perspectives to the program. On the other hand, the support of a scientific staff is a significant part of the budget for NOAO and NRAO, while similar observatories, both public and independent, are operated almost exclusively by a technical staff. The SR recommendations on the scientific staff have to be handled on a case by case basis.

The AST program has supported the education and training of many generations of scientists and engineers at the undergraduate, graduate, and postdoctoral level by providing the facilities and resources for hands-on experience. It has also been at the vanguard of increasing the proportion of women entering physical science. These individuals have gone on to varied successes in academia, observatory support, industry and commerce. The development and operation of next generation astronomical facilities requires concomitant investment in the development of next generation personnel and the retention of key individuals with highly specialized skills and abilities. This leads to our second Principle:

3.2.2 Principle 2

The implementation of the proposed program should consider diverse workforce needs within the Division of Astronomical Sciences-supported observatory system and should provide for the training of the next generation of scientists and engineers. The observatories should seize opportunities for operating with higher efficiency.

3.3 The Public Dividend

3.3.1 Observations

Astronomy does not belong to astronomers alone. The discoveries from giant telescopes in remote locations belong as much to the public, which has financed them, as they do to the scientific community. They belong, especially, to the young, whose exposure to science and its benefits is enhanced considerably by the dissemination of astronomical results. Astronomers have long recognized the importance of their field in education and public outreach (E/PO). They have also been creative in finding new ways to reach larger communities and have cooperated well with media professionals. Foremost in these efforts have been the E/PO efforts at the five observatories. For example, the Visitor Centers at Arecibo, Green Bank, and the VLA are major attractions and present modern astronomy in an exciting manner to diverse communities. In addition to a popular visitor center at Kitt Peak, NOAO has innovative schemes that allow night-time access to working optical telescopes for members of the public. Gemini has pioneered new approaches to engaging K-14 teachers in their program. The national observatories also have highly effective summer student and dynamic teacher training programs. As outlined in AANM, astronomy has a proud record of attracting under-represented minorities into science. Any facility closures will likely impact the E/PO component of astronomy and this should be considered along with the science impact. Our third Principle is:

3.3.2 Principle 3

Public awareness of astronomical discoveries, the observatories that produce them, and the personnel who are responsible for them, are a critical part of the current AST program that must be maintained.

3.4 Bridging Artificial Divisions

3.4.1 Observations

The historical development of astronomy in the United States was underwritten by federal, state, and significant private funding sources. Consequently, it has suffered many tensions, sometimes resulting in artificial divisions. These tensions often are useful to exploit as they foster concentration on development of the most urgently needed and sophisticated techniques in specific areas. However, they can also lead to inefficiency and missed scientific opportunities. Examples of these divisions include:

- **Physics and astronomy.** Historically, these fields have drifted apart and then together again several times. In recent years, as discussed at length in CQC, there has been a strong confluence, especially in cosmology and high-energy astrophysics. This has greatly benefited astronomy through the influx of skilled experimentalists, fresh ideas, new technology, and modern data-handling approaches. However, it has also created some tension between the traditionally reductionist approach of experimental physics and the development of astronomy as a data-rich "environmental" science. This tension has mostly been creative and there are many advantages in continuing to foster links in future collaborations.
- **Astronomy and solar physics.** The sun is a normal star and the physical processes that govern its behavior are also of vital importance outside the solar system. Judicious comparisons are mutually beneficial, yet many astronomers and solar physicists are relatively ignorant of each other's fields. New facilities in solar physics, however, might provide increased opportunities for collaboration.
- **Optical/infrared and millimeter/radio observatories.** NOAO and NRAO have developed along separate paths and have often seen themselves as rivals for the same resources. This has happened despite the fact that, in many areas of astronomy, multi-wavelength techniques are critical for interpretation; radio astronomers have always been major users of optical telescopes and, to a somewhat lesser extent, vice versa. The NOAO-NRAO separation is in contrast to Europe where the European Southern Observatory (ESO) manages both Very Large Telescope (VLT) and ALMA (although it does not manage other RMS facilities). There are new opportunities for AST to foster cooperative ventures involving OIR and RMS facilities.
- **Non-federally- and federally-funded observatories.** Historically, this has been a source of considerable tension. "Big" astronomy began in the US with the construction of major telescopes by state and private institutions; these were not available to other US astronomers. In recent years, this imbalance has been ameliorated with the advent first of the national observatory in the late 1950's, and recently of Gemini and the use of the TSIP program. In addition, AST has supported independent radio observatories through the URO program. The proposed GSMT is

envisaged to be a public-private partnership and, as such, its success will require a healthy synthesis of two different approaches to management and funding.

- **Facilities and individuals.** AST is anomalous within the Directorate for Mathematical and Physical Sciences (MPS) and indeed NSF as a whole, in terms of the ratio of facility to individual investigator support. The roles and responsibilities of the national facilities are not always clear to the community. Specifically, the extent to which they should function as independent research enterprises, as opposed to service organizations, is an ongoing source of debate.
- **Ground-based and space-based astronomy.** Here, the disconnect between the two activities is less apparent in the science - the complementarity of ground-based and space-based telescopes is well recognized and exploited - but present at the managerial level. NASA has invested considerable effort and community time in developing consensual, science-based strategic plans and roadmaps. However, the implementation of these plans has not been smooth and several major changes in the overall direction of the agency have serious implications for AST, especially the recent decrease in Research and Analysis funding. NASA has been very clear that it does not regard the support of ground-based telescopes as part of its mandate although on those occasions when it has contributed in this manner, the results have usually been scientifically highly productive. There are good reasons now to revisit the working relationship between the two agencies. The relationship with DOE has a shorter history but is currently more stable.[25]
- **Big versus small science.** Astronomy is a scientific discipline in which many of the most important discoveries did not require the largest telescopes. A good recent example is the discovery of the first extra-solar planets around sun-like stars. However, large research programs on major and often special purpose facilities is increasingly the norm and there is often a culture-clash between the "big" project-driven science requiring large teams with significant infrastructure, and the "small," versatile PI-driven science performed by one or a few astronomers with a relatively small amount of observing time. This is especially relevant to younger astronomers who must not be denied the hands-on experience that will be essential to developing the next generation of telescopes. The single largest message that the SR took from the town meetings and the written input was that many astronomers are very concerned about the future of access to small (below 4 m) and to mid-sized (4-6m) OIR telescopes, specifically, and to intermediate-scale facilities, generally. They also fear that AST funding will become unbalanced with the demands of large and expensive observatories precluding faster turnaround science that is just as important scientifically.

Reconciling these different perspectives lies well beyond the SR's charge and no attempt has been made to present recommendations that aspire to do this. As stated above, there are many positive aspects of competition, which should be retained to address our first Principle. However, the polarizing impact of these divisions has informed many of the

[25] It is the charge of the Astronomy and Astrophysics Advisory Committee, established by Congress in 2003, to monitor these relationships.

committee's recommendations, and its findings relate to a desire to create an environment where common bridges to the future can be built.

3.4.2 Principle 4

In order to complete its ambitious, proposed program, the entire astronomical community needs to work together and to combine its many resources and strengths.

3.5 Engaging the University Community

3.5.1 Observations

US universities and colleges are NSF's most important operational partner in carrying out its mission. Within universities, faculty lead most NSF-funded research programs, train the next generation of researchers, and help to inaugurate Americans of all ages into scientific literacy. In astronomy, the contribution of university-based resources to national goals includes a widely distributed set of thousands of scientists in hundreds of institutions. Also, a small but substantial number of institutions directly subsidize research facilities which, especially in OIR astronomy, are world leading. The diverse backgrounds of researchers within universities strengthen the overall creativity and innovation, but also present an operational challenge to the efficient delivery of facility access in order to create the greatest benefit for both science and education goals. The quarter-million students taking introductory astronomy every year are mostly at institutions whose priorities do not include world-class independent astronomy facilities, yet benefit from the access their faculty have to public telescopes.

In its desire to maximize science return, NSF frequently leverages its funds by promoting efforts where universities provide research support and make substantial financial contributions. However, proprietary concerns sometimes exclude capable researchers in the US community from facilities that are supported federally and can also lead to inefficiencies through duplication of effort. These interactions are complex and an optimal result will not occur through individual advocacy or review of project proposals in isolation. The relationship between universities and national observatories needs to be managed with consistency and open access in mind.

3.5.2 Principle 5

The US astronomical facilities and the US university enterprise should align their strategic goals to enhance the research and education activities of the entire system.

3.6 Astronomy without Borders

3.6.1 Observations

AST is already heavily engaged in international collaboration and future large facilities will involve foreign partners, too. The US has half shares in Gemini and ALMA. NOAO's Cerro Tololo Inter-American Observatory (henceforth CTIO) was founded in collaboration with Chilean astronomers. Although the operating costs of Arecibo, GBT, VLA and VLBA are currently borne by AST, the research programs are often multi-national.[26]

As discussed in AANM, international collaboration frequently allows projects to be undertaken whose capital and operating costs would exceed the means of a single country. There is the added benefit of allowing a larger technical base to be involved in solving engineering challenges. A less-appreciated advantage is that international collaborations can develop an organizational momentum that renders them less likely to be canceled or radically de-scoped than purely national projects; such stability causes fewer distractions for the project management. Frequently cited drawbacks are that the total project cost is usually larger in an international project than would be the case if it were to be borne by a single country, and that the management structure becomes more cumbersome. Another claimed disadvantage is that, by withdrawing the one element of competition, project teams become more conservative and less creative. (The SR does not know of serious studies of these claims but believes that there is some truth to all of them.)   Finally, international agreements are difficult to enter into and difficult to exit, should the need arise.

The two largest projects on the horizon have developed in quite different ways. The SKA radio telescope was conceived as an international project and various competitive developments were encouraged with a view to choosing the best for a genuine, international endeavor. This is a similar approach to that being followed in other areas of physics. To date, AST investment in SKA is relatively modest, although innovative efforts in prototype instruments are underway (Sec. 7.3.1.5). By contrast, competitive OIR "extremely large telescope" (henceforth ELT) projects of 20-100m scope have developed independently in the US and Europe. The US effort, largely privately funded to date, comprises at least two separate endeavors-- GMT and TMT -- each of which is already partly international. Currently, there are no plans to involve the US in the European ELT. (China is also considering an ELT project.)

Independent of the manner in which the SKA and ELT evolve, the US can no longer automatically expect to be the lone, pre-eminent owner of state-of-the-art major telescopes in any subfield of astronomy. The international astronomy enterprise will be managed by multi-national organizations within which US institutions, including AST, will find themselves collaborating, cooperating, and competing. As is already the case with ALMA and Gemini, considerable negotiation is required to establish long term agreements in which each party strives to maximize its scientific return from its financial and human investment. Provided that all countries can learn to respect each other's differing scientific priorities and political systems, there exist mechanisms for achieving this consensus and these have been employed in countless healthy collaborations. The building of new collaborations that are economical and equitable should be regarded as a creative challenge rather than an overhead. One important principle is that both construction costs and operating costs should be shared. Finally, international agreements need a great deal of thought and careful negotiation before they can be set up successfully

[26] It is significant that roughly half of the electronic communications received by the SR were from astronomers not resident in the US. The majority of these wrote in support of continued operation of Arecibo and the VLBA.

and require clear exit clauses. The manifest success of organizations such as CERN and ESO, makes clear, however, the positive advantages of international collaboration.

As a consequence of this more business-oriented management of the largest facilities, the Open Skies policy will be under pressure. Budgetary constraints will lead to increasing formality of cooperation. If one country or collaboration chooses to make a telescope available to outside users who have not contributed to its construction or operation, it is likely to seek some recompense or reciprocity in its access to other telescopes. The SR supports the Open Skies policy but recognizes that some changes may be needed to preserve it.

3.6.2 Principle 6

The increasingly international character of astronomical research should be recognized and strategic cooperation should be pursued where advantageous or necessary in the construction and operation of next generation large facilities.

4. Current Program

4.1 Budget and Staffing

In order to address its charge, the SR had to familiarize itself with the AST budget. Inevitably, this is quite complicated and no summary can do full justice to the diversity and interconnectivity of the science as well as the intricate organization of working observatories. The SR has been presented with a large quantity of statistical data and made a good faith attempt to understand how resources are allocated in practice in the current AST program. It has chosen to represent the components of the AST budget in two ways:

1. Defining "function costs" of an observatory by dividing its AST budget into administration,[27] science,[28] instrumentation,[29] development,[30] construction,[31] and operations[32] (Fig. 7). Function costs for NSF programs that support grants, independent observatories and technology development are also shown for completeness. The sum of all function costs equals the total budget of the observatory.

2. Defining "burdened costs" for facilities or developmental programs within an observatory to be the sum of the operational costs and a proportionate share of the administration, science and instrumentation costs (Fig. 8). Burdened costs are a measure of the savings that should result on average in the event of cessation of all operations at a facility or completion of a development program and after all closure costs have been paid. In practice the actual savings will lie between the function and burdened costs. The sum of all burdened costs also equals the total budget of the observatory. This is only relevant for the four national observatories.

The staffing levels are even more complex because most employees should be included in more than one category. After some study, the SR concluded that an adequate rule of thumb for comparing the four national observatories is \$100k per FTE.[33] The equivalent

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[27] "administration" includes costs of running the Director's Office, computer infrastructure including VO-related activity and education and public outreach not covered by external funding.

[28] "science" refers to the partial support of personnel employed by an observatory to carry out research including postdocs and students.

[29] "instrumentation" refers to the cost of developing and upgrading instrumentation for existing telescopes.

[30] "development" refers to work on behalf of projects in the planning stage that are either entirely new facilities or major upgrades to existing telescopes.

[31] "construction" refers to building of approved projects that are included in the AST budget rather than the MREFC line.

[32] "operations" includes site infrastructure, telescope and instrument operations and maintenance and direct support of users.

[33] NAIC, NOAO, NRAO, NSO are roughly \$90k, \$100k, \$130k, \$110k per FTE in total.

figure for the Gemini international observatory is $170k (allowing for instrumentation subcontracts).

The SR recognizes that these representations are imperfect and approximate and involve subjective choices. However, it believes that they are sufficient for the purposes of comparing facilities and recommending savings. Much more detail can be found in the observatory submissions.

4.2 Grants Program

The grants program is the principal channel through which the national investment in ground-based astronomical facilities is recouped by scientific discovery. The AAG is administered through annual, peer-reviewed competition, and is balanced between various scientific areas such as extragalactic, galactic, stellar, and planetary astronomy. It is the main source of support for theoretical investigations.

Grants to individual investigators are typically $100k per annum and typically support partial summer salary for a university faculty member plus a fraction of a student or a fraction of a postdoc, and research expenses, which might include travel to observatories and scientific meetings as well as the cost of publication of research and undergraduate research programs. Some larger multi-investigator awards are also supported out of the grants program. At $33M, the AAG is at the highest level it has ever been. In addition there are CAREER and postdoctoral programs ($7M) and grants that are made in connection with the PoU, VO and other targeted programs ($10M). E/PO is an important feature of the grants programs.

4.3 Optical-Infrared Facilities

The OIR system is a major resource of contemporary astronomy. Over 40 percent of the American Astronomical Society (AAS) membership is identified with OIR astronomy,[34] (excluding solar astronomy). There is a complex network of telescopes and researchers that has evolved over the past few decades and AST has a significant involvement with many components of it. As a consequence, there is a diversity of opinions as to where the priorities lie and what should be the relationship between Gemini, NOAO, and the independent OIR observatories. We discuss these components in turn.

4.3.1 Gemini

Gemini comprises two 8m diameter telescopes, completed roughly five years ago and located on excellent sites at Mauna Kea in Hawaii and Cerro Pachon in Chile (Fig. 9). Both telescopes are performing well after some initial performance problems. This is especially true at infrared wavelengths, for which the telescope designs were optimized. The early instruments include an impressive suite of imagers and spectrographs of which the most productive is the multi-object spectrograph on Gemini North. There is also a maturing AO capability that has produced impressive results. NSF paid $100M for a half

[34] 2001 Committee on Astronomy and Astrophysics report on Federal Funding of Astronomical Research.

share of Gemini's construction cost. An ambitious suite of new instruments has been proposed (see Sec. 5.2.1).

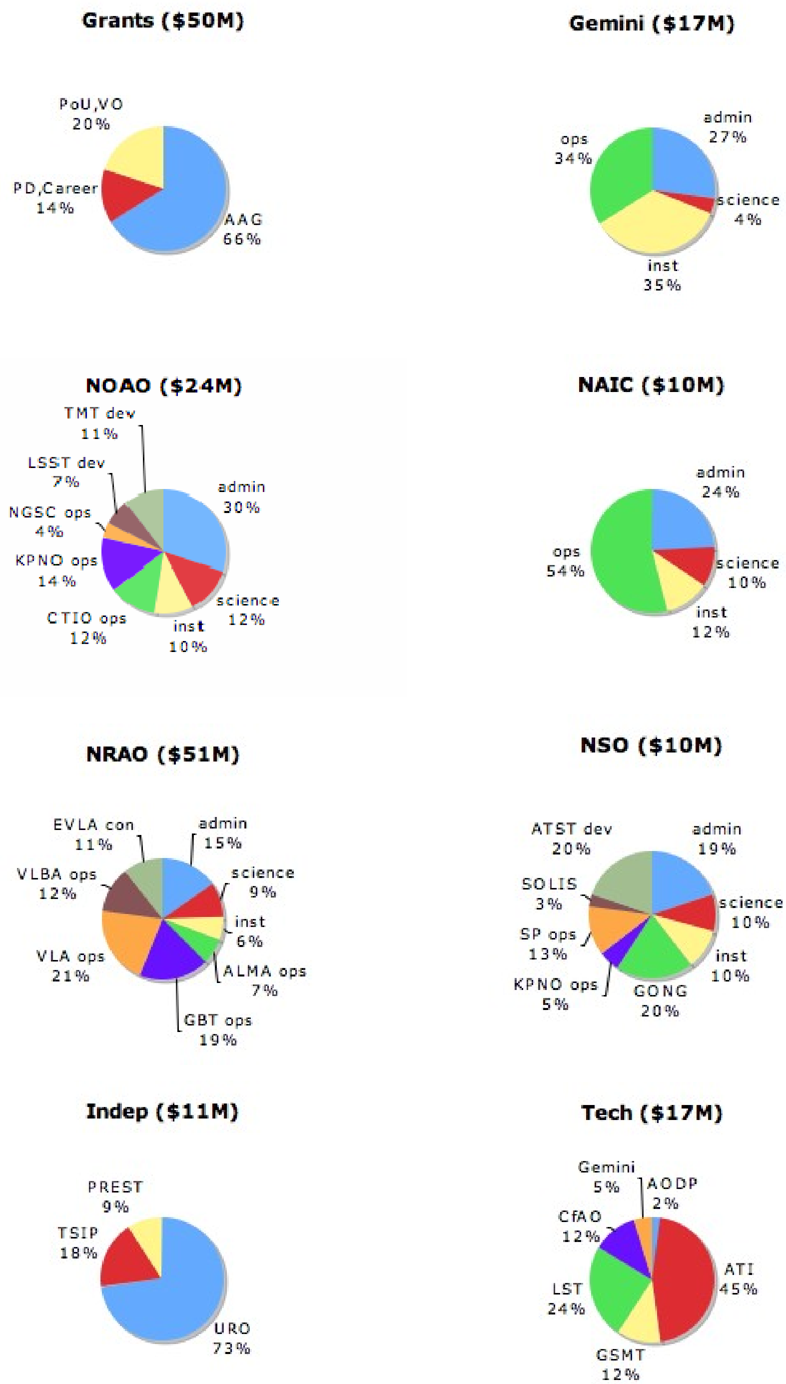

Figure 7. Division of the 2006 AST-only budgets for observatories and programs identified in Fig. 1. "Indep" denotes independent OIR and RMS observatories; "Tech" denotes technology development outside national observatories.

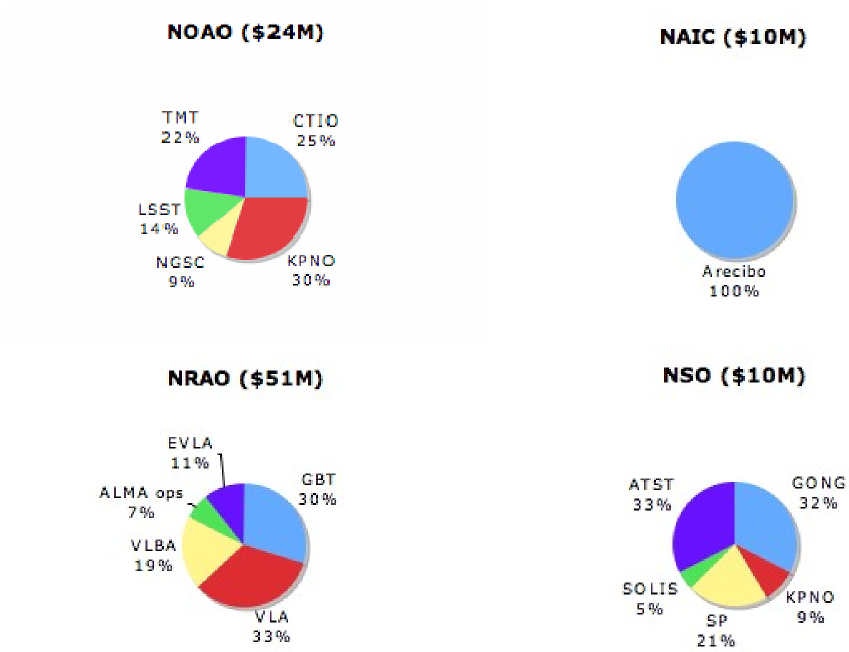

Figure 8. Burdened 2006 budgets for the four national observatories. These show the approximate costs of running the component sites, projects and telescopes including a share of the overall administrative, research and instrumentation costs and are a measure of the funds that would be liberated if this activity ceased and after all closure costs have been paid. ALMA construction costs are not included.

Gemini is a general purpose observatory designed to address many of the questions raised in Sec. 2.2 including, especially, the formation of the first galaxies and the search for extra solar planets. Over 200 papers have resulted from Gemini observations and the publication rate per telescope is approaching that of the Keck, Subaru and VLT telescopes at comparable stages in their histories.

Figure 9. Gemini North (left) and South (right) 8m optical-infrared telescopes on Mauna Kea, Hawaii and Cerro Pachon in Chile, respectively. The Gemini project is an international partnership managed by AURA under a cooperative agreement with NSF. [Image credit: Gemini Observatory]

The AST budget for Gemini is $17M (Fig. 2) and supports 85 FTEs. Equal support is contributed by the UK, Canada, Australia, Brazil, Argentina and Chile, combined. There is an international agreement to operate Gemini until 2012, which will be re-negotiated in 2010. The budgets are determined by the Gemini Board, on which AST is represented. In addition, the Gemini Science Center is run by NOAO for a cost of $1M and 8 FTEs. It is responsible for US time allocation and user support.

4.3.2 National Optical Astronomy Observatory

NOAO was formed in 1982 to consolidate the running of the many telescopes at CTIO and Kitt Peak National Observatory (KPNO) operated for the previous 20-30 years by AURA, including solar telescopes, which are now separately managed under the National Solar Observatory. NOAO operates telescopes in both hemispheres, on Cerros Tololo and Pachon in Chile and on Kitt Peak in Arizona, and maintains operations headquarters at La Serena (Chile) and Tucson (Arizona) (Fig.10). NOAO hosts the NOAO Gemini Science Center (NGSC) (Sec. 4.3.1) and it administers the TSIP program which provides community access to a number of independent observatory telescopes with apertures larger than 3m, in exchange for new instrumentation support at those facilities.

The largest NOAO telescopes are 4m in diameter. These telescopes have had long and distinguished careers in the study of star formation, stellar populations in our Galaxy and in nearby galaxies, motions within galaxies, and the evolution of galaxies, especially through interactions and mergers. Such studies continue today, often utilizing both hemispheric capabilities to identify and study large statistical samples with special characteristics. NOAO telescopes are also routinely used in conjunction with infrared and X-ray telescopes in space to study young stellar populations, to locate distant clusters of galaxies and to measure large-scale structure (Sec. 2.2.1). Up to 20 percent of the observing time available through NOAO at the KPNO, CTIO observatories, and via TSIP at the Multi-Mirror Telescope (MMT) and the Hobby-Eberly telescope (HET) may be allocated for major survey programs. To date, 20 survey programs have been approved by the NOAO peer review process. These surveys represent significant observational efforts that enable scientific investigations requiring large, statistically complete, and homogeneous datasets. The survey data are made publicly available and are a valuable resource to the community. The host galaxy of the most distant, powerful radio source has recently been found using data from two NOAO survey programs. Roughly 200-300 papers are written every year using data obtained using NOAO telescopes; in addition, the NOAO telescopes support the research of 26 new thesis students each year, or about 25 percent of the annual Ph.Ds awarded in astronomy.

NOAO administrative and scientific staff are distributed between La Serena and Tucson. There is also a major instrumentation group which recently has been downsized by a factor of two to employ approximately 30 FTEs, partially supported by external funding and a data products group (roughly 20 FTEs), whose role is changing to emphasize more data archiving and support of the VO. NOAO is also a partner in both LSST and TMT and is actively contributing to both projects (roughly 40 FTEs) (Sec. 6.1.3).

The total AST budget for NOAO is $24M (Fig. 2), supporting 250 FTEs. In addition there are about 60 FTEs that are externally funded.

Figure 10. (a) On the left is the CTIO site that is managed by NOAO in Chile. The large dome in foreground holds the Blanco 4m optical telescope. Four smaller domes near the Blanco contain 1.5m, 1.3m, 1.0m and 0.9m optical telescopes operated as the Small and Moderate Aperture Research Telescope System (SMARTS) led by Yale University in cooperation with NOAO. (b) The large dome on the right contains the Mayall 4m optical telescope operated by NOAO at the KPNO site outside Tucson, Arizona. The nearer dome on right is the KPNO 2.1m telescope. The intervening domes hold University of Arizona Steward Observatory telescopes. The multi-faceted dome on the left holds the 4m Wisconsin-Indiana-Yale-NOAO (WIYN) 4m optical telescope. Adjacent to WIYN's lab building is their 0.9m telescope. [Image credit: NOAO/AURA/NSF]

4.3.2.1 Cerro Tololo Inter-American Observatory

NOAO operates the 30-year old, 4m Blanco telescope at Cerro Tololo (Fig 10a). Among many important research discoveries made with this telescope was the demonstration that white dwarf supernova could be used to measure accurate cosmological distances, and this led to the discovery of dark energy (Sec. 2.2.2). The telescope has a number of OIR imagers and spectrographs, and there are plans to use a third of the Blanco time from 2009-2014 to conduct a "Dark Energy Survey" (DES) with a new wide-field 0.5 gigapixel Dark Energy Camera which will provide a catalogue of photometric redshifts for over 300 million galaxies out to redshift one. NOAO also has a 30 percent share in the SOuthern Astrophysical Research Telescope (SOAR) 4.2m telescope, which should be fully operational in late 2006. Just a year after its dedication, SOAR detected the afterglow of a gamma-ray burst with a record redshift of over six. CTIO also hosts four telescopes under 2m in size that were previously operated by NOAO but are now managed under the Small and Medium Aperture Research Telescope System (SMARTS) program with 25 percent of the time still available to the community. There are several other tenant telescopes on the mountain. The operating cost of CTIO is $3M and the burdened running cost is $6M.

4.3.2.2 Kitt Peak National Observatory

Kitt Peak has been an astronomical observatory since 1958. NOAO runs the 32-year old 4m Mayall telescope (70 percent share), the newer Wisconsin-Indiana-Yale-NOAO (WIYN) 3.5m telescope (40 percent share) as well as a 2.1m telescope (100 percent share) (Fig. 10b). NOAO also has small shares in two smaller telescopes operated by university consortia and maintains the infrastructure for many other independent observatories sited on the mountain, like those of the Michigan-Dartmouth-MIT Observatory and the University of Arizona's Steward Observatory. In total there are roughly 30 partner institutions with interests on Kitt Peak. The Mayall 4m telescope provides the widest field optical and near-infrared imaging capabilities in the northern hemisphere and also has OIR single and multi-object spectroscopic instruments. WIYN has multi-object optical spectroscopic capabilities and is expecting a one-degree optical imager next year. The operating cost of KPNO is $4M and the burdened running cost is $7M.

4.3.3 Giant Segmented Mirror Telescope

AST currently contributes to research and development on two GSMT candidates, the Giant Magellan Telescope (GMT) with a project-estimated cost of $500M and the Thirty Meter Telescope (TMT) with a project-estimated cost of $750M. GSMT was the top-ranked ground-based program in AANM and is intended to be the complement of and follow up telescope for the James Webb Space Telescope; it will study the evolution of galaxies and quasars from the earliest times as well as to contribute heavily to stellar and planetary astronomy (Secs. 2.2, 7.3.1.3). There has been considerable private investment in GSMT. The Gordon and Betty Moore Foundation has invested $35M in technology development for the TMT and GMT has received about $20M from private donors and its partner institutions. NOAO is a partner in TMT and supports it at the $3M level ($6M burdened). In addition, AST began separate funding of GSMT technology development in FY2005 through an award to AURA, amounting to $2M for 2006,[35] funding both GMT and TMT (Sec. 6.1.3).

In total, AST has contributed roughly $50M over seven years towards GSMT design and technology development through work carried out at NOAO and the Center for Adaptive Optics (CfAO), under the Adaptive Optics Development Program (AODP) and, more generally, though its support of Gemini AO research, laser development and individual university grants. All of this investment has led to impressive progress on both conceptual designs and the common challenge of ground layer and multi-conjugate adaptive optics (Sec. 4.3.6).

4.3.4 Large Survey Telescope

LST is planned to determine the properties of dark energy and dark matter through measuring the growth of structure in the universe and observing supernovae, to open up discovery space in transient astronomy, and to perform an inventory of Earth-crossing asteroids. The 8.4m LSST is one proposal for the LST project. It is a joint AST-DOE-Private venture with a project-estimated cost of $300M, of which NSF share would be about half. NOAO is supporting LSST at the $2M level ($3M burdened). In addition, AST is investing $14M in LSST technology development over four years and $4M is budgeted for 2006 (Sec. 6.1.3).

[35] Planned to increase to $5M in 2007.

4.3.5 Independent Optical-Infrared Observatories

The independent observatories provide the majority of the OIR observing capability in the US. There are two Keck 10m telescopes, two 6.5m Magellan telescopes, the 9m Hobby-Eberly Telescope, the 6.5m MMT and the imminent Large Binocular Telescope. AST is involved with each of these observatories through TSIP. This program, initiated in 2002, is administered by NOAO and helps fund instrumentation on these telescopes in exchange for community observing time. The current cost of this program is $2M.[36] In addition, there is a newer NSF program that supports research and teaching using smaller telescopes, the Program for Research and Education with Small Telescopes (PREST) $1M. There are also many smaller (<6.5m) telescopes, *e.g*. those associated with Lick, Lowell, McDonald, Palomar and Steward observatories, that are operated mostly without AST funding with annual budgets typically in the $1-5M range. Many students are supported through the funding of smaller telescopes (Secs. 3.2.1, 3.5.1).

4.3.6 Technology Development

AST also runs the Advanced Technologies and Instrumentation (ATI) program with a current budget of $8M, which supports detector and instrument development. The program supports any field in astronomy including OIR, RMS, solar astronomy and computing activity.

Major interest surrounds the development of ground layer and multi-conjugate AO A robust system will be needed by GSMT and will enhance the operation of most large telescopes operating today. AO was developed initially by the USAF. Following declassification, it was first implemented by independent observatories and has been successfully deployed in the near infrared on several 3m-10m class telescopes as well as on solar telescopes. AO, including research on the sodium lasers that are used to create artificial stars, is supported by the ATI and AODP with a budget of roughly $2M. CfAO at University of California, Santa Cruz is also managed outside AST as an NSF Science and Technology Center with an annual budget of $4M, of which roughly half supports astronomical applications and is credited to astronomy.

4.4 Radio-Millimeter-Submillimeter Facilities

The AST radio – millimeter – submillimeter system comprises telescope operations and technology development for observations operating over more than five decades of frequency from MHz to THz frequencies. AST plays a singular role in supporting world-leading observatories and grants for science programs focused on use of those observatories as well as technology development. Ten percent of the AAS membership self-identifies as RMS astronomers (excluding solar radio astronomers). The major facilities are run nationally but smaller, independent observatories are a vital part of the enterprise.

4.4.1 Arecibo

The NAIC Arecibo telescope is a 300m diameter radio telescope located in Puerto Rico (Fig 11a). Despite its limited steering, the telescope can access nearly 40 percent of the

[36] Planned to increase to $4M in 2007.

sky and it has an unrivalled sensitivity due to its large size. Cornell has operated Arecibo as a national facility since 1971 and has recently been awarded a cooperative agreement to continue operations until 2010. Over its 43 years of operation, Arecibo has been used to make many important discoveries about pulsars (including the first binary pulsar), planets, and distant galaxies along with major contributions to gravitational physics and atmospheric sciences. A project to upgrade the Arecibo telescope was carried out in the 1990's supported by $25M of NSF funding augmented by funds from NASA and Cornell University. It is now instrumented for observations up to 10 GHz. The Arecibo L-Band Feed Array (ALFA) allows the telescope to be operated efficiently in survey mode for three scientific foci: interstellar medium, galaxies, and pulsars. Twenty four percent of Arecibo users are graduate students. In addition, it operates the new, highly successful and self-supporting Angel Ramos Visitor Center.

Figure 11. (a) On the left is the 300m diameter Arecibo telescope in Puerto Rico operated from 3 MHz to 10 GHz by NAIC. A powerful radar and laser facility is used to probe solar system objects and the Earth's atmosphere. On the foreground hill is the popular Angel Ramos Visitor and Educational Center. [Image credit: NAIC] (b) On the right is the Robert C. Byrd Green Bank Telescope at Green Bank, WV, the world's largest fully steerable, single-dish antenna. Current observations extend from 290 MHz to 52 GHz and will eventually extend into the 95-GHz atmospheric window. Green Bank is centered in the National Radio Quiet Zone that provides considerable protection from man-made interference. [Image credit: NRAO/AUI]

The NSF budget for Arecibo is $12M, of which $10M is from AST and $2M is contributed by the Geosciences Directorate, Division of Atmospheric Sciences. There are roughly 155 FTEs, of which 15 are externally funded.

4.4.2 National Radio Astronomy Observatory

NRAO was founded in 1956 to develop radio telescope facilities in the US and has been managed by AUI since that time. Currently, NRAO operates the GBT at Green Bank, the

(Expanded) VLA and the VLBA at Socorro and is collaborating with ESO and the National Astronomy Observatory of Japan on constructing ALMA in northern Chile. The current AST budget of $51M supports roughly 400 FTEs.

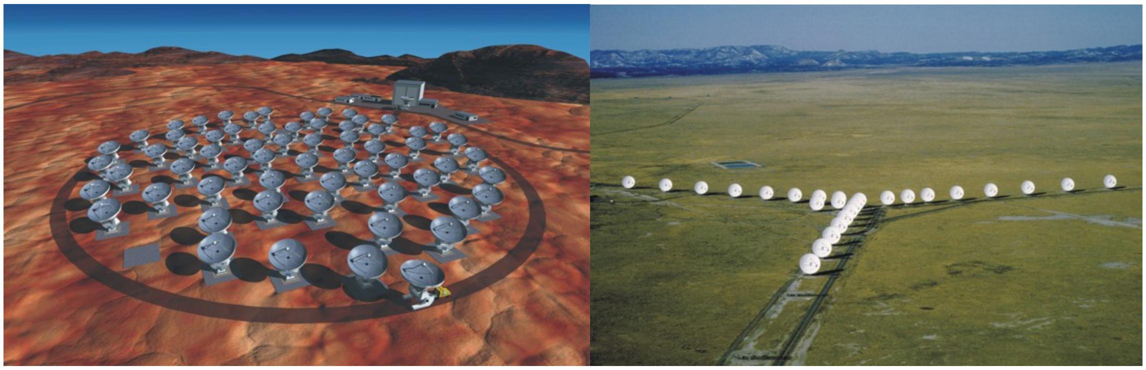

Figure 12. (a) On the left is an artist's conception of the ALMA compact configuration at Llano de Chajnantor, Chile. The US-Europe ALMA telescope will have 50 antennas of 12m diameter with frequencies extending to 720 GHz. Japan has joined as a third partner bringing additional capability. Early science is expected in 2009 and array completion in 2012. [Image credit: NRAO/AUI and ESO] (b) On the right is the VLA telescope, which is operated by the NRAO near Magdelena, New Mexico, in its most compact configuration. The VLA operates at radio frequencies between 74 MHz and 43 GHz and is undergoing a major upgrade called the EVLA that should be completed in 2010. [Image credit: NRAO/AUI]

4.4.2.1 ALMA

ALMA is an international collaboration, established to construct a 50 element interferometer, operating at millimeter and submillimeter wavelengths, in Chile by 2013 (Fig12a). The 6 milliarcsecond resolution that ALMA will achieve at its smallest observing wavelength of 300 microns will enable studies of planets in formation around nearby stars and measurement of spectral lines from cosmologically distant galaxies. ALMA should furnish transformational science and will be unrivalled for decades. A major design goal of ALMA is to make calibrated images and spectra readily available to all astronomers. Its total cost makes it the most expensive facility undertaken by NSF[37] and it is currently the centerpiece of the AST program. NSF will pay $500M, a half share of the total construction cost of $1000M. The 2006 NSF ALMA construction budget is $49M, paid for out of the MREFC line. The 2006 AST cost of ALMA operations is $4M and this is projected to rise to $30M by 2011, including a provision for an instrumental upgrade (Sec. 1.4).

4.4.2.2 Charlottesville Headquarters

The main administrative headquarters of NRAO are located in Charlottesville, VA. This is also the site of the Central Development Laboratory (CDL), which has a current budget of $2M. Charlottesville is home to many members of the scientific staff and will host the ALMA North American Science Center.

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[37] The total NSF contribution to Laser Interferometer Gravitational-wave Observatory will exceed that to ALMA, though.

4.4.2.3 Green Bank Telescope

The 100m Robert C. Byrd Green Bank Telescope (GBT), was completed in 2003 for a cost of $85M (Fig. 11b). It is the premier single dish facility in the world operating into the millimeter range. It currently operates at wavelengths as short as 5mm (and will eventually operate at 3mm) and is already contributing important discoveries on pulsars, cosmology, and interstellar chemistry. The annual operating cost of the GBT is $10M, ($15M burdened).

4.4.2.4 Very Large Array

The VLA is a 27-element radio interferometer located in New Mexico, completed in 1980 for a cost of $360M, operating at wavelengths as short as 7mm with an angular resolution of 0.1 arcsecond, as good as that achievable with Hubble Space Telescope (Fig. 12b). Remarkably, it remains the premier instrument for cm wavelength astronomy in the world, after 26 years of operation. It has made major discoveries about sources within our Galaxy, including normal stars, our Galactic center, the remnants of supernova explosions, and neutron star and black hole binary systems. It has also made comprehensive surveys of extragalactic radio sources, including gravitational lenses and used these to perform cosmological studies. Using standard bibliographic measures, for example, the cost per citation, it is the most scientifically productive major telescope supported by AST. The current EVLA upgrade, which should be completed by 2010 at a cost of roughly $93M (including a Canadian contribution of roughly $20M), will increase its sensitivity by a factor 10 and ensure its continued supremacy until SKA is completed. The annual operating cost of the VLA is $11M ($17M burdened) plus $5M for EVLA construction.

4.4.2.5 Very Long Baseline Array

The VLBA was inaugurated in 1993 for a cost of $130M (Fig. 13). It combines ten 25m radio telescopes separated by thousands of km to achieve an angular resolution of a few hundred microarcseconds, several hundred times better than the VLA. It is also regularly combined with telescopes on other continents and in space to achieve even greater resolution. The VLBA has made fundamental measurements of quasars, pulsars, astrophysical masers and planets. Two future satellites, NASA’s Gamma-ray Large Area Space Telescope (GLAST)[38], to be launched in 2007 and Japan’s VLBI Space Observatory Program (VSOP-2)[39], planned for a 2012 launch, are expected to be heavily dependent upon using the VLBA. The annual cost of the VLBA is $6M, ($10M burdened).

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[38] Many of the most prominent variable extragalactic radio sources are powerful gamma ray sources.

[39] Single small orbiting radio telescopes have to be combined with a large ground-based array to image their sources.

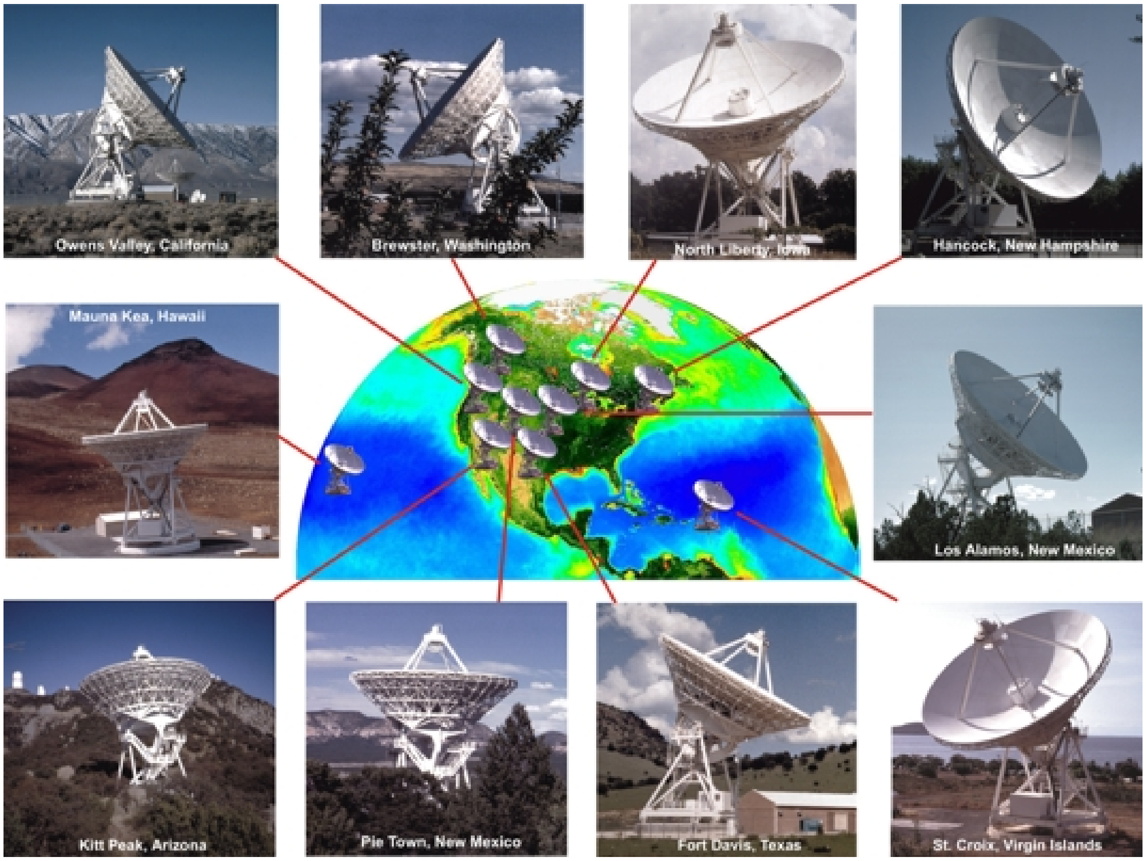

Figure 13. The Very Long Baseline Array (VLBA) is operated by NRAO and consists of ten 25m telescopes at sites that extend across the US from Hawaii to St. Croix, Virgin Islands. The VLBA often operates in conjunction with Arecibo, GBT, the VLA and other antennas for higher sensitivity and resolution. [Image credit: NRAO/AUI; Earth image courtesy of the SeaWiFS Project NASA/GSFC and ORBIMAGE]

4.4.3 Independent Radio-Millimeter-Submillimeter Observatories

The independent RMS observatories are all of smaller scale than the NRAO facilities but contribute essential and path-finding capabilities to the RMS system. These include developing the capability to perform interferometry with intercontinental baselines and at millimeter wavelengths. The major connection to AST is through the URO program which has recently supported CARMA, a Northern hemisphere millimeter array, the Caltech Submillimeter Observatory in Hawaii and the Five Colleges Radio Observatory, in support of the Large Millimeter Telescope. The Allen Telescope Array (ATA) has now started to receive some URO funding. The URO program has evolved, decade by decade, phasing out facilities as they become out of date, through a mini Senior Review process and adding new ones. AST funds are generally used for initial construction and operations and involve cost-sharing in various proportions with universities and other sources. They provide broad student exposure to telescopes and modern technology (Secs. 3.2.1, 3.5.1). NSF operations support leads to external user access to these facilities. The 2006 budget for the URO program is $8M. There are also some independent radio observatories that do not receive AST funding, such as the

Smithsonian Submillimeter Array. Several meter wavelength projects are under construction by university, federal laboratory and international collaborations.

4.4.4 Technology Development

The URO and ATI programs have both supported (successful) new technology development such as new receivers and correlators and the development of radio adaptive optics (c.f. Sec. 4.3.6) as well as SKA precursor research.

4.5 Solar Facilities

Approximately 11 percent of the AAS membership self-identifies as "solar" although this implied population size does not include solar physicists who do not belong to the AAS. The major telescopes are operated by the National Solar Observatory.

Figure 14. (a) On the left is the NSO's Global Oscillations Network Group (GONG++) facility at Udaipur, India. This is one of six such installations around the globe used for near-continuous observations of the sun. GONG is a fundamental instrument for the study of solar oscillations and subsurface gas flows and was one of the pioneer instruments in the field of helioseismology. (b) In the center is the NSO site on Kitt Peak near Tucson, AZ. The large tower and angled structure is the McMath-Pierce Telescope. With a 1.6-m aperture, the McMath-Pierce Telescope is the world's largest solar telescope. The vertical structure to the right is the former Kitt Peak Vacuum Telescope and is now the home of the SOLIS telescope. (c) On the right is the NSO site on Sacramento Peak near Sunspot, NM. The large tower houses the Dunn Solar Telescope (DST). The tower rises 41.5m above the ground and the optical system extends 67m below ground. The DST forms an image of the sun 51-cm across. The DST offers a routine adaptively-corrected feed and is the test bed for many of the instrument concepts that will be incorporated into the ATST. [Image credit: NSO/AURA/NSF]

4.5.1 National Solar Observatory

The NSO was formed in 1982 under the NOAO umbrella. Today it has its own Director but is still managed by AURA. It operates telescopes on Kitt Peak and Sacramento Peak as well as the international GONG stations. The USAF, NASA, NSF-ATM and other non-AST grants, also support solar astronomy. The AST budget for NSO is $10M (Fig. 2) supporting 90 FTEs.

4.5.1.1 Global Oscillations Network Group

GONG is an array of six small solar telescopes spread around the world designed to measure the spectrum of solar seismic oscillations (Fig. 14a). The network began operations in 1995. The high frequency resolution achieved in these long duration helioseismological measurements has been used to test and verify the standard solar interior model, which in turn indirectly contributed to the discovery of neutrino mass. Interest now centers on probing the subsurface foundations of sunspots, exploiting acoustic holography to image the far side of the sun (to aid space weather predictions), and exploring long term variations in the solar interior structure and flow fields in response to the sun's magnetic cycle. GONG was upgraded as GONG++ in 2003 to achieve higher spatial resolution and sensitivity, mainly through the use of an improved camera system. The annual cost of GONG++ is $2M ($3M burdened).

4.5.1.2 Kitt Peak/NSO/Tucson

NSO operates several solar telescopes on Kitt Peak and maintains a small scientific staff at Tucson (Fig. 14b). The McMath-Pierce facility has a 1.6m main telescope that can observe the solar surface and corona from infrared to near ultraviolet wavelengths. Over its 45 year lifetime it has contributed much of our fundamental understanding of solar astronomy and has driven new instrumental developments, particularly in extremely high resolution spectroscopy. The McMath-Pierce facility also has played an important role in studies of the inner planets of our solar system, and the iodine cells that have been used to discover two thirds of the known extrasolar planets were calibrated using the McMath-Pierce Fourier Transform Spectrometer. The annual cost, excluding the GONG++ station and including SOLIS, is $1M ($1M burdened).

4.5.1.3 Synoptic Optical Long-term Investigation of the Sun

Also on Kitt Peak is SOLIS, a relatively new and unique instrument designed to make highly precise vector magnetic measurements of the solar surface, to monitor small variations in the solar flux at high spectral resolution, and to chronicle chromospheric activity throughout the full 22 year Hale cycle.

4.5.1.4 Sacramento Peak Observatory

NSO also operates several telescopes at Sacramento Peak Observatory (Fig. 14c). The premier one is the 76cm Dunn telescope, which is evacuated to control internal seeing (the vacuum window transmits out to 2.5 microns), and is supplied with an advanced adaptive optics system, prototype for the ATST. The Dunn's instruments can perform simultaneous imaging and spectropolarimetric measurements with high spatial and time resolution, essential to study the dynamic and finely structured magnetized solar surface. Sacramento Peak also hosts an instrumentation group and a science staff. The annual operating cost is $1M ($2M burdened).

4.5.2 Advanced Technology Solar Telescope

ATST is the proposed major new initiative in solar astronomy. It is a 4m, off-axis, clear aperture telescope designed to perform adaptive optics imaging of the sun at optical wavelengths, detailed coronal studies, and infrared observations beyond the 2.5-micron cutoff of contemporary windowed vacuum solar telescopes. It will have six times the collecting area and 2.5 times the angular resolution of its closest competitor, the Swedish Solar Telescope on La Palma, enabling it to study the detailed interaction of “fibril” magnetic fields with turbulent plasmas in the solar photosphere, the root of the chromospheric and coronal activity of higher layers that is so conspicuous at ultraviolet and X-ray wavelengths. Most of the design and development is centered in NSO and the project schedule has 2009 as a start date for MREFC funding with first light in 2014. The annual cost is $2M ($3M burdened).

4.5.3 Independent Solar Observatories

In addition to AST-funded NSO, NSF-ATM supports the High Altitude Observatory of the National Center for Atmospheric Research. There also are several independent solar astronomy facilities, for example, Big Bear Solar Observatory in California and Mees Solar Observatory in Hawaii. For comparison, each of these has an annual budget of around $2M.

4.5.4 Technology Development

Most recent technology development has been in support of the ATST. Solar projects have also been supported out of ATI.

5. Recommended Base Program

The SR is charged with recommending which current activities must be preserved over the next five or so years as the new and proposed facilities (EVLA, ALMA, ATST, GSMT, LST and SKA) are developed. These elements represent the "base program" and enable the most productive and significant research and foster technical development that will be needed in the future to maintain the health of US astronomy. They are also needed to collect and curate data and to provide opportunities as well as challenges for the next generation of astronomers. Finally, as mentioned in Sec. 4.2, E/PO is an important feature of the base program which should be maintained at its present level, consistent with Principle 3.

5.1 Grants Program

5.1.1 Observations

Astronomy is conspicuous among scientific fields supported by NSF for the relatively low proportion of the total budget allocated to individual investigators. This reflects the community dependence upon large facilities; what remains for individual investigators must be protected against the demands of these facilities. The SR concurs with its charge that called out the grants program for continued protection. The reasons for this condition are simple. It is the grants program that enables most of the science from the facilities and it needs to be adequately supported if the nation is to get a proper scientific return on its investment in its observatories. Not only is the science at risk, but also the training of the next generation of astronomers. In addition, despite a recommendation in AANM that major projects support theoretical research, the AAG supplies almost all the support for this vital component of the research enterprise.

The pressure on the grants program has increased over the past three years and the proposal success rate has fallen from 35 percent to 24 percent. The SR believes that pressure on the program will continue to increase over the next five years, for four reasons:

1. An increasing number of graduate students, postdocs and junior faculty are taking up astronomical research.
2. NASA has decreased the support of its Research and Analysis program substantially in its 2006 and 2007 budget requests. This is already leading to increased pressure on the AST program as astronomers whose research primarily involved space missions are turning increasingly to ground-based telescopes.
3. The new, general purpose observatories that will come on line during the next decade, especially ALMA and ATST, are expected to stimulate much new research activity within the grants program. The annual science support recommended according to the AANM rules of thumb is $15M for ALMA and $4M for ATST (Sec. 1.4).
4. There is a growing demand for "mid-scale" (too expensive for the MRI program and below the MREFC threshold) telescope and instrumentation funding. In the absence of any other funding program within NSF, the responsibility for supporting this research will fall upon the grants program.

It is very hard to anticipate the level of future demand, but it will be high. The degree to which AST should be obligated to address this demand depends upon the quality of the proposals, judged according to criteria such as those embodied in Principles 1, 3 and 5. The SR expects this also to be high.

5.1.2 Recommendation 1

The Division of Astronomical Sciences should anticipate that pressure on the grants program will intensify over the next five years and should be prepared to increase its level of support to reflect the quality and quantity of proposals.

5.2 Optical-Infrared Base Program

5.2.1 Gemini

The Gemini submission to the SR described a “minimum” plan in which no additional instruments would be constructed, although there would be upgrades at the facility level, such as improving the acquisition and guiding units of both telescopes. The cost of this, including completion of the initial suite of instruments, ramping up to a higher percentage of queue scheduling, and developing a robust data pipeline for both telescopes, will require an annual budget falling from $17M in 2006 to $16M in 2011.

The discussion of Gemini must be different from that of the four national observatories because there is an international commitment to support operations at roughly the present level beyond the horizon of this report. AST can influence the detailed level of future funding through its representation on the Gemini Board, its role in deciding the future instrumentation program, and its participation in the negotiations of the next long term agreement scheduled to start in 2010. However, it cannot make unilateral changes to Gemini operations costs. Consequently, the Gemini minimum plan is simply adopted as the Base Program.

5.2.2 National Optical Astronomy Observatory

5.2.2.1 General Observations

For the past few decades, NOAO has been an organization that tries to accomplish much on behalf of many astronomers, with a diverse mission that currently includes activities related to telescopes ranging from 1m to 30m in size. It has received variable directions from the community and NSF that has made planning difficult. Despite their role in the development of our current view of the cosmos (Sec. 2.2), the telescopes operated directly by NOAO are relatively old and small. In its submission to the committee, NOAO described a future in which it maintains a level budget and staffing while evolving its data products and major instrumentation programs into LSST and TMT development programs and scaling back its direct support of small and mid-sized telescopes. NOAO proposes to enter into new partnerships for new telescopes, like the recent additions WIYN and SOAR, and to divest further the instrumentation and operation of existing mid-sized telescopes (including the Mayall and Blanco telescopes) and small telescopes, through partnership programs modeled on the SMARTS consortium.

In contrast to this plan, there was a strong message, delivered at the town meetings and through email by the many members of the US OIR community who do not enjoy privileged access to large telescopes, that NOAO should concentrate more of its resources on the support of small and mid-sized telescopes. There was ample evidence provided, which the SR corroborates, that the state of the public telescopes at CTIO and KPNO has been allowed to deteriorate and that, overall, the instrumentation is less competitive than it should be.

A third view was expressed at town meetings by representatives of the independent observatories, who compete for AODP, ATI and TSIP funding and have invested heavily in the proposed future program. They view continued operation of their observatories and development programs as being of higher priority, both scientifically and technologically, than supporting small and mid-sized telescopes through NOAO.

The SR is primarily concerned with the existing program. After considering the messages and submissions in detail, and examining the metrics relating to telescope usage and publication and citation rates, the SR concluded that there are three strong arguments for improved and assured community access to small and mid-sized telescopes.

1. There is a strong heritage of important, discoveries that have been made using small and mid-sized telescopes.[40] Indeed, the character of contemporary research, outlined in Sec. 2, suggests an increasing role for nimble and well-instrumented smaller facilities. There are ongoing small telescope (generally imaging) surveys, essential to understanding the statistical properties of stars and galaxies and these invariably lead to follow-up (generally spectroscopic) work on larger telescopes. This synergy has existed throughout the history of astronomy and is expected to continue into the GSMT era. The rise of organized, transient astronomy, with its enormous demands for follow up observations of supernovae, gamma ray bursts, and microlensing events, requires telescope networks that respond to alerts by immediately interrupting the background programs. Also, there are opportunities for making important discoveries from the systematic monitoring of known classes of variable objects – transiting planets, oscillating and binary stars, AGN etc.[41] What has become clear is that innovative ideas, advanced detectors and clever data handling can be more important than simply increasing collecting area for several of the highest priority investigations. Invoking the first Principle, there is therefore a strong scientific argument for investing in small and mid-sized telescopes.
2. Over half the OIR astronomers in the US have no access to ground-based facilities save through NOAO. This is especially important for graduate students. Fostering

[40] The Sloan Digital Sky Survey is being carried out on a 2.5m telescope. The Two Micron All Sky Survey utilized two 1.3m telescopes. The MACHO project was conducted on a 1.2m telescope. The first brown dwarf eclipsing binary was discovered using 1m class telescopes at CTIO and KPNO. The upsurge in the discovery rate of dwarf planets over the past five years has mainly come from 1-2 m class telescopes. Extrasolar giant planets have been discovered with a four inch telescope!

[41] Although LST will carry out some of this science more efficiently, it will not be in full operation for many years and, when it is, it is likely to spawn specialized research programs that will increase the net demand for small telescopes.

access to relatively small telescopes and modern instruments may be the best way to ensure a supply of astronomers with the necessary experience and skills to address the challenge of building and using the telescopes of the future. It is unreasonable to expect this cadre of scientists to emerge from the minority of students who have access to large telescopes at their home institutions. It is necessary to tap the potential not only of those who were attracted by the opportunity to train on private facilities, but of the entire student body undergoing scientific and technical education in the US.[42] This addresses our second Principle.

3. Small and mid-sized telescopes will continue to be the testbeds on which technology such as adaptive optics and interferometry is developed before being implemented on larger apertures. This is an important role which responds to the fifth Principle.

5.2.2.2 The NOAO Base Program

The SR was persuaded by the above three arguments and proposes a plan that is intended to maximize the scientific output while minimizing the changes that will be needed to NOAO's management and mission statement. Instead of further divestiture of the CTIO and KPNO telescopes, as proposed by NOAO, it recommends that NOAO should acknowledge a responsibility to lead the utilization of small and mid-sized telescopes in the public sector to address the new and emerging opportunities outlined in Sec. 5.2.2.1. The independent sector has risen to this challenge in several exemplary cases. NOAO has shown less leadership and initiative. In short, the SR recommends that NOAO's Base Program should include managing public access to small and mid-size telescopes economically, efficiently and productively, just as it is discharging its responsibilities for larger telescope access through the Gemini Science Center and TSIP. To be clear, the SR recommendation is for NOAO to provide US astronomers with the tools to contribute to some of the most exciting and productive astronomical research in the 21st century. It is not proposed that NOAO recover past capabilities simply to preserve old research communities or resuscitate existing subfields.

In order to achieve this goal, the first task is to perform essential, deferred maintenance at CTIO and KPNO. A one-time application of modest funds should make a big difference. The next is to take a hard look at the capabilities of the full suite of telescopes with which NOAO is involved and to work with the user community to consider new ways to use these telescopes more creatively and efficiently to execute better science programs than is likely to have been the case under the NOAO plan. In some cases this will mandate fresh arrangements with universities to build and maintain new instrumentation. The desire to engage more students in telescope operations can be met, for example, by having them involved in instrument maintenance and user support. In other cases it will require implementing more economical operating modes like robotic telescope operation, queue scheduling, and single instrument telescopes and not duplicating capabilities that are available elsewhere. In many ways this recommendation is similar to what NOAO has been doing in its partnership with university groups involving the WIYN and SOAR

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[42] The value of this exposure is not just limited to the future health of astronomy. Many accomplished scientists and engineers, now working in quite different areas, were first inspired by astronomy and its telescopes. This is particularly true for members of under-represented minorities as described in several submissions to the committee.

telescopes. Where the SR differs from the NOAO plan is that it recommends that NOAO continue to see managing the provision to the community of facilities to execute first rank science using small and mid-sized telescopes as a core part of its mission and one that cannot be divested[43].

If there is a need for providing more small telescope time than can be supplied economically at CTIO or KPNO, then it may be possible to purchase it from independent observatories. Although most independent observatories will see the challenge of serving the entire US community as too great to avail themselves of this opportunity, even one such arrangement might make a big difference, so this idea is worth exploring. New telescopes, perhaps on new sites, may also be needed.

The level and balance of OIR telescopes needed by aperture, instrumentation, and subfield is difficult to gauge at this time. The SR can see two mechanisms for establishing the optimal mix. The first is through the AAG grants program where there is competitive, peer review of research proposals involving telescopes of all sizes. The quality of the submitted proposals could provide a basis for assessing the relative importance of the science and thus influence decisions on whether or not to build new telescopes and instruments. The second is for the Director of NOAO to charge the Gemini and NOAO time allocation committees to compare the relative scientific benefit versus cost of observational programs on telescopes of all sizes. The end result would be a plan for strategic deployment of telescope/instrument capability that optimizes the science with limited resources, consistent with Principle 1.

Support of NOAO's education and public affairs operations should also be included in the Base Program, consistent with Principle 3.

5.2.2.3 Cerro Tololo InterAmerican Observatory

Cerro Tololo remains an excellent southern hemisphere site and there has been a large federal investment in infrastructure on the two peaks and in the La Serena headquarters. Despite this, there is an immediate need to address deferred maintenance on the Blanco and smaller telescopes. After this step has been taken, the primary goal should be to provide community access to modern telescopes according to the mechanisms outlined in Sec. 5.2.2.2.[44] If it is necessary to add additional telescopes in the southern hemisphere, then it is reasonable to suppose that they will be located at CTIO. The operations cost of CTIO is $3M, similar to that reported for comparable facilities elsewhere. (The SR did not attempt to compare the operations cost of CTIO with the capital cost of the facility because it is thirty years old and the telescopes have been modified too much to make this a relevant comparison. Also, non-uniform arrangements have been made for the tenant telescopes.)

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[43] The divestiture of telescope instrumentation and operations to university and other consortia does not necessarily reduce the cost to AST if the partners apply for and are successful in obtaining NSF support, independent of NOAO.

[44] There may be a need for more telescope access if the Blanco telescope is used for the DES (Sec. 4.3.2.1).

5.2.2.4 Kitt Peak National Observatory

The situation on KPNO is quite similar to that at CTIO, although the Mayall telescope has been refurbished and new instrumentation like NEWFIRM is being built. The smaller telescopes are reportedly not as well supported as in the past, and steps should be taken to perform the deferred maintenance on them, too. Looking to the future, although the site is no longer as dark as it once was, it supports too many tenants for it to be closed down now and much of the science, for example, in the infrared, is less dependent upon the sky darkness. However, new telescopes that require dark sites are unlikely to be located at KPNO. [45] Again the $3M budget for operations seems reasonable.

5.2.3 Independent Optical-Infrared Observatories

NOAO does not operate any telescopes with diameter greater than 4m. Instead it intends to continue to provide a link between these independently operated facilities and the larger US astronomy community. In this way, its role is quite different from that of NRAO which actually runs many of the premier RMS telescopes in the world. Providing access to larger telescopes is part of the base program. NOAO discharges its responsibility through running the Gemini Science Center (which allocates observing time to the US community) and administering the TSIP program.

Overall, NOAO's role in fostering unrestricted access to larger telescopes is seen by the community and the SR as a success. Concern was expressed about the recent reduction by AST of the annual TSIP budget to $2M. The SR echoes this concern given the success of the program and its large over-subscription.[46]

5.2.4 Technology Development

The SR regards AODP and ATI as part of the base program because they will greatly improve the performance of existing telescopes as well as develop technologies for future telescopes. Both of these activities have been successful. Several groups around the world have implemented AO systems using both natural and laser guide stars and the rate at which remarkable results are being published suggests that support of AO will be a vital investment for the future productivity of US large telescopes. The expansion of the technique to fainter magnitudes and shorter wavelengths is underway. There is also a clear path forward to OIR interferometry on progressively fainter sources observed at progressively shorter wavelengths. Investments made through the ATI program have led to substantial improvements and innovations in prototype and working detectors. The committee believes that these programs should continue to be supported at about their present level. Emphasis should be given to research that will develop systems that can be used on telescopes in which AST has a large investment. The committee notes that, as a practical matter, university instrumentation efforts need long term support to be viable and recommends that proposals for commitments of up to five years be solicited.

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[45] Other developed sites in the continental US as well as the Mexican National Observatory in San Pedro Martir should be considered as alternative northern hemisphere sites.

[46] The 2007 budget request is for $4M.

5.2.5 Recommendation 2

The Optical-Infrared Astronomy Base program should be led by the National Optical Astronomy Observatory. It should deliver community access to an optimized suite of high performance telescopes of all apertures through Gemini time allocation, management of the Telescope System Instrumentation Program and operation of existing or possibly new telescopes at Cerro Tololo Inter-American Observatory in the south and Kitt Peak National Observatory or elsewhere in the north. The balance of investment within the Base Program should be determined by the comparative quality and promise of the proposed science. In addition, there should be ongoing support of technology development at independent observatories through the Adaptive Optics Development and the Advanced Technologies and Instrumentation Programs.

5.3 Radio-Millimeter-Submillimeter Base Program

5.3.1 National Radio Astronomy Observatory

5.3.1.1 Atacama Large Millimeter Array

The highest current priority for all of AST is to complete and operate ALMA as economically and efficiently as possible, so as to optimize its science return while minimizing the impact of running this major new facility on the rest of the program. Indeed, the prospects for future large telescope projects in the US depend upon ALMA, which, in turn, depends upon the continued leadership of NRAO. There is concern about the adequacy of the estimated running cost (Secs. 1.4, 4.3.2.1), although there may be economies of scale in operating an interferometer relative to a monolithic telescope as appears to be the case in comparing the VLA with the GBT. NRAO estimates that it will be employing 70 FTEs seven years from now in the US to run ALMA and that there will be of order 300 FTEs working in Chile supported by all the partners. The SR strongly urges NRAO and AST to work together and with ESO now to limit the growth in operations staff and to develop operations modes that will be as inexpensive as possible without compromising ALMA's scientific potential.

5.3.1.2 Green Bank Telescope

The GBT is a new and highly promising telescope. It has already been used to discover the fastest spinning pulsar, with a frequency of 716Hz and several prebiotic organic molecules. It is expected that it will be operated as part of the base program beyond the horizon of this report. The SR recommends that its successful Visitor Center continue operations, consistent with Principle 3.

5.3.1.3 Very Large Array

In view of its current high scientific productivity relative to its operating cost and the promise of the upgrade, the (E)VLA should remain part of the RMS base program beyond the horizon of this report.[47] The SR believes that it should be possible to operate the VLA after the upgrade is completed with a similar budget ($11M operations and $17M burdened). There is some concern, discussed in Sec. 6.2.4 in the context of the

[47] The EVLA construction budget of $5M should revert to AST around 2010.

VLBA, about the roughly 50 percent fraction of foreign users. Although this is compensated by US access to international RMS facilities, consistent with the federal Open Skies policy, there is an implied lack of competitive involvement by US astronomers. There is also concern about the low percentage (ten percent) of student users.

5.3.2 Independent Radio-Millimeter-Submillimeter Observatories

The SR was impressed by the scientific and technical accomplishments of the URO program. Examples of techniques developed in university observatories leading a decade later to major instruments include Very Long Baseline Interferometry (VLBI) and millimeter interferometry which became the VLBA and ALMA, respectively. Bolometer arrays seem headed down the same path. The UROs have been heavily subscribed observationally and are very productive scientifically. They play vital roles in training students and providing testbeds for new instrumentation and techniques. They are supported very competitively and funding is not renewed when they are no longer able to contribute at the highest level. The URO budget has fallen from $10M to $8M.[48]

5.3.3 Technology Development

As with OIR technology, the benefit of the ATI program is apparent for RMS facilities. The CDL was also found to be performing well, particularly in implementing new technology at major facilities. NRAO will have to grow its expertise in mm astronomy techniques to meet the challenge of ALMA and it is recommended that it continue to strengthen its links with the university community to take advantage of outside expertise. The SR recommendation is to maintain ATI and CDL funding at present levels.

5.3.4 Recommendation 3

The Radio-Millimeter-Submillimeter Base program should comprise the Atacama Large Millimeter Array, the Green Bank Telescope and the Expanded Very Large Array operations together with support for University Radio Observatories and technology research and development through the Advanced Technologies and Instrumentation program.

5.4 Solar Astronomy Base Program

Development of ATST is a key part of the current solar astronomy base program. The remainder of the SR's recommendations in solar astronomy is predicated on ATST progressing in a timely manner through the MREFC process.

5.4.1 SOLIS

SOLIS is the one existing solar facility that is recommended for the Solar Astronomy Base Program. The SR supports the proposal (Sec. 1.3) to construct two additional copies of SOLIS in order to ensure more complete temporal coverage, and identifies this as another fine opportunity for international collaboration, consistent with Principle 6. The SR also notes that, with NSO's planned closure of their Kitt Peak facilities where SOLIS

[48] Planned to increase to $9M in the 2007 budget.

currently is deployed, a new home for the existing instrument will need to be found at a superior site that allows other possible SOLIS telescopes to be well-spaced in longitude. The transition will have to be completed fast so as to minimize the loss of synoptic data and to maintain continuity in the solar activity monitoring program. SOLIS should be redeployed early in the ATST construction phase.

5.4.2 Independent Solar Observatories

The SR was impressed with the integration into the national program of independent solar observatories like Big Bear Solar Observatory in California, which is operated by the New Jersey Institute of Technology and the High Altitude Observatory on Hawaii which is operated by the National Center for Atmospheric Research. In particular, the proposed solar program, centered on ATST, has broad and enthusiastic support throughout the solar community.

5.4.3 Technology Development

Solar astronomers should continue to have access to the ATI program in addition to carrying out design and development of ATST.

5.4.4 Recommendation 4

The Synoptic Optical Long-term Investigations of the Sun facility is the only, current solar astronomy facility that should remain in the Base Program in the Advanced Technology Solar Telescope era.

6. Recommended Transition Program

The base program that has just been outlined does not address the needs of future facilities. We now turn to transitional activities that relate to the proposed program. It is expressly not part of the committee's charge to revisit the exciting scientific imperatives identified by AANM, CQC and other studies; neither should it propose an implementation plan. However, it is part of the SR's purview to recommend investments for this program through technology development and precursor investigations and to find ways to expedite its completion. This is a major challenge because, as explained in Sec. 1.4, the combined cost of maintaining the current program and developing and supporting new facilities far outstrips any credible federal budget for ground-based astronomy. Consequently, it is also necessary to identify those parts of the current program which do not form part of the base program and which can no longer be supported at existing levels by AST. The investments and the reductions together constitute the transition program. The overall goal of the transition program is to position AST to continue its past record of accomplishment into the next decade.

These recommendations have direct implications for the workforce at all of the National Observatories and within the university community because a large fraction of the AST budget is taken up with salaries and benefits and it must be assumed that the budget will not grow. In other words, evolving the science program at fixed budget is roughly equivalent to employing the same total number of technical, administrative and scientific personnel to perform different jobs, as discussed under Principle 2. Of course these will not all be the same people. Although some employees will be re-trained and some will re-locate, others will leave or retire to be replaced by new hires. There will be severance and relocation costs which can be considerable and which will delay the realization of the savings from closing a facility. The implementation of these changes will present major managerial challenges and it will have to take place over several years, allowing the transitional effects to be mitigated by natural attrition and the growth of new programs.

In what follows, the SR recommends some actions and suggests targets for selective reductions that are designed to release funds to invest in the future program. Quantitative understanding of the savings that will ultimately be achievable will require individual cost reviews for all five observatories. The SR recommends that these be carried out soon. In each case, a small group of administrators, astronomers, instrument support staff and site managers familiar with the operation of other observatories should be charged to recommend detailed budgets and staffing targets in order to fulfill the base and transition programs described here.

6.1 Optical-Infrared Transition Program

The challenge to the OIR community is to transition to a future characterized by an optimal balance of access for the whole community to small, mid-sized and large private and federal telescopes, performing front rank science, while moving forward on the major new capabilities of GSMT and LST. The SR proposes a flexible plan that it believes can accomplish this.

6.1.1 Gemini

As described in Sec. 4.2.1, the two Gemini telescopes are maturing into effective and productive telescopes addressing a broad range of astronomical problems. The Gemini Partners have proposed an ambitious second generation instrumentation suite that goes beyond the minimum program, discussed in Sec. 5.2.1, and a contract has already been agreed for the Gemini Planet Imager designed to image solar systems around nearby stars. A Precision Radial Velocity Spectrograph, for finding planets, is at the conceptual design stage. A third instrument, the Wide Field Multi-Object Spectrograph (WFMOS), is being designed to perform major spectroscopic surveys of distant galaxies so as to refine our understanding of their evolution and the expansion of the universe. The scientific appeal of WFMOS is clear. However, it is to be deployed on the Subaru telescope and does not directly enhance the capability of the Gemini telescopes. It would therefore seem appropriate to review it competitively with other proposals to AST, not just as a Gemini instrument, consistent with Principle 1. The cost of all these new instruments is estimated to be roughly $75M and, in order to pay for the NSF share, the annual Gemini budget would have to rise to a peak of roughly $25M in 2011 before decreasing in subsequent years, until additional instrumentation proposals are accepted. The staffing levels would not change significantly under this scheme since the instrument development and construction would be sub-contracted outside Gemini. However, the SR notes that the opportunities and obligations associated with Gemini are likely to mandate an increase in AST support of Gemini over the coming years.

As already discussed in Sec. 1.2, Gemini is a relatively expensive facility. The cost of operations and proposed new instrumentation relative to capital cost is roughly double that of the more typical costs described by AANM. In addition, the cost per FTE is roughly 50 percent greater than the cost at the other national observatories. Furthermore, unlike other observatories, Gemini does not carry a large scientific staff. Some of this difference can be ascribed to the location of the telescopes and the additional overhead associated with a high profile, international collaboration. Other reasons derive from the sophisticated technology that is needed for modern OIR instrumentation. It urges AST to use the proposed cost review to understand the reasons for the large running costs and, if as it suspects is possible, to identify ways to operate Gemini with greater efficiency. As there are probably lessons to be learned here that could have an impact on the operation of future projects, it may be beneficial to have representatives of ALMA and GSMT participate in this review. The review may be completed in time to influence the ongoing negotiation over the second-generation instruments as well as the renewal of the international agreement in 2012 which will start to be discussed in 2010. The SR has considerable confidence that Gemini's performance and accomplishments will continue to grow and that it will remain at the center of the US program in large aperture OIR astronomy for a long while. The next four years will provide a long enough baseline to assess Gemini's performance relative to Principle 1.

6.1.2 National Optical Astronomy Observatory

The current NOAO budget discussed in Sec. 4.3.2 (see also Fig. 2) allocates $13M for administration, science and instrument development, exclusive of operations on the two mountain sites, GSMT and LSST support and the NGSC. The SR believe that it should be possible to execute the Base Program outlined in Sec. 5.2.2.2 with a much smaller budget, closer to half this value.[49] The following observations might be helpful to the cost review in identifying necessary economies and anticipating future needs.

- The cost of administration at NOAO seems high (30 percent) relative to NSO (20 percent). The SR is aware of some mitigating factors such as the inclusion of the Data Products Program and VO work (see below) in the NOAO figure. In addition, some AURA-wide functions may be book-kept under NOAO.
- The rules for overhead recovery from the various tenant telescopes sited at CTIO and KPNO need study.
- There may be some overlap between NOAO and Gemini responsibilities within Chile and, consequently, opportunities for savings.
- NOAO supports a significant scientific staff, roughly 36 FTEs, resident in both headquarters, with an annual cost of $3M. In the view of the SR, if NOAO were just to confine itself to its base program, then a much smaller scientific staff would suffice to support operations on smaller telescopes for a user community. If, conversely, there is a ramp up in either or both of GSMT and LST, then the scientific support staff should be associated with and grow with these projects.
- In its submission to the SR, NOAO proposed that its Data Products Program be phased out over a three-year timescale and replaced by growth in support of the VO, GSMT and LST. However, this proposal does not address the need to archive (and possibly pipeline reduce) data from existing telescopes in a VO-compliant manner. In addition, it may not meet the needs of users of a re-vitalized suite of small and mid-sized telescopes. Additional VO-, GSMT- and LST-specific tasks are likely to grow.
- It has been argued (Sec. 5.2.2.2) that the provision of new instrumentation for small and mid-sized telescopes (as distinct from the maintenance of existing instruments) is well-suited to the capabilities of university groups. It is recommended that NOAO's role should be in leading and coordinating this activity that may also involve NOAO personnel and facilities. There will be an additional need for major instrumentation associated with large telescopes, like Gemini. An NOAO instrumentation group could bid for these opportunities as they become available, perhaps in partnership with university groups. In the longer term, there will be much larger instrumentation needs for GSMT. It is appropriate for NOAO to aspire to lead and manage large teams involving industry, independent observatories and universities in constructing the $50-100M instruments that will be needed for GSMT. In the nearer term, though, the SR foresees further contraction (c.f. Sec. 4.3.2) in the NOAO instrumentation group to a level adequate to fulfill its existing obligations.

[49] This does not include the provision of additional small and mid-sized telescope access which would have to be competed as discussed in Sec. 5.2.2.2.

6.1.3 Giant Segmented Mirror and Large Survey Telescopes

As discussed in Secs. 4.3.3, 4.3.4, NOAO is participating in both of the large OIR projects under development, GSMT and LST. Although both projects originated within the independent community the NOAO participation is already significant. In its submission to the SR, NOAO has proposed that its staff transition to work on both GSMT and LST simultaneously and build up to 150 FTEs on these two projects by 2011, while maintaining the same overall NOAO FTE level as today. The SR sees three practical problems with this plan.

1. NOAO is currently partnering with only one candidate project for each initiative and there is no guarantee that these particular projects will be the federal choices.[50]
2. The advance of the two federal choices will be limited by the availability of technology development money, the MREFC queue, and activity by the different partners in each project.
3. The private-partner contributions to GSMT and LST are even less predictable than federal funding and come with expectations for telescope choice, location, financing (including operations) and schedule.

Of course, all three of these problems are strongly coupled. The SR has more to say on this matter in Secs. 7.3 and 7.4 but, for the moment, it invokes Principle 4 and recommends that the growth of both projects within NOAO should match the overall schedule for these projects and the level of federal investment in them. As explained in Secs. 4.2.3, 4.2.4, the federal GSMT and LST choices are also important factors. The SR believes that this approach to GSMT and LST optimizes federal resources for the creation of the exciting and ambitious OIR program envisaged by AANM and CQC and urges NSF to proceed to these decisions as soon as practical (c.f. Secs. 7.3.1.3, 7.3.1.4).

If the build up to these projects, as well as new, competitively-selected initiatives involving small and mid-sized telescopes, is rapid enough, then there will be opportunities for staff displaced by the proposed reductions in other NOAO activities. If it is slow or happens outside NOAO, then significant staff reductions will follow.

6.1.4 Optical-Infrared Summary

The Base Program proposed by Gemini, which includes no new instruments, leads to a $1M reduction in budget over five years. The SR recommends that the NOAO cost review focus on finding major economies from the $13M allocated annually for

[50] The planning for all four projects is relatively advanced. GMT is a 22m telescope to be sited in Chile with first light planned for 2016; the first of seven 8.5m mirrors has been poured. TMT has just passed a Conceptual Design Review and intends to choose a site soon. It is on a schedule for first light in 2016. LSST is in the detailed design phase and has chosen a site on Cerro Pachon, adjacent to Cerro Tololo with first light projected for 2013. Pan-STARRS will deploy its first 1.8m telescope on Maui this year and plans to combine four such telescopes on a single mount on Hawaii by 2009.

administration, science and instrument development leaving sufficient resources to execute the Base Program. This should position AST to support a vibrant observational program on existing OIR telescopes from 1m to 10m in aperture. The support for development of new instruments and telescopes should evolve at a rate that is matched to competitive selection in the case of small and mid-sized telescopes and a strategic plan in the case of large telescopes.

6.1.5 Recommendation 5

Gemini operations will continue through 2012. Decisions on new instrumentation and negotiations for operation beyond 2012 should be guided by a comparison with the cost, performance and plans of other large optical telescopes. The National Optical Astronomy Observatory should plan to reduce its major instrumentation, data products, administrative and science research staff over the next five years and concentrate on executing its base program, delivering access to high performance telescopes of all apertures in both hemispheres, more efficiently. Growth in support of a Giant Segmented Mirror Telescope and a Large Survey Telescope should be paced by Federal project choices and the schedule for Major Research Equipment and Facilities Construction account funding as well as progress by the partners in these projects.

6.2 Radio-Millimeter-Submillimeter Transition Program

The challenge to the RMS community is to transition to a future with a base program comprising ALMA, GBT, VLA plus selected university observatories and to build up its participation in the international SKA program.

6.2.1 Arecibo

The SR recognizes the significant and unique scientific contributions that the Arecibo Observatory has made to astronomy and astrophysics and it congratulates NAIC and Cornell on operating the facility so effectively. The current scientific program set out for Arecibo involving a combination of survey work and competed, smaller observing programs is very strong and is already producing important discoveries. The SR endorses its future discovery potential and archival value. Roughly 200 scientists from all around the world[51] are working with the three “ALFA” surveys (Sec. 4.4.1), all three of which promise important scientific results.

However, the committee was not persuaded of the primacy of the science program beyond the end of the decade and found that the case for long term support at the present level was not as strong as that for other facilities. Much of the survey work will be completed by 2010 when the current NAIC contract expires and the proposed extensions to higher Galactic latitude do not seem as likely as the current surveys to have a large scientific impact. The SR was advised that the minimum feasible operating cost for Arecibo is $8M, even when it is largely working in survey mode. Therefore, invoking Principle 1, the SR recommends a decrease in AST support for Arecibo to $8M (plus the

[51] Evidence of the international importance of Arecibo is provided by the large number of communications received in support of its continuing operation from astronomers not resident in the US.

$2M from ATM) over the next three years.[52] Roughly 20 percent of the observing time should be set aside for individual (non-survey) proposals in order to retain some discovery potential. This should permit a reduction in the scientific and observing support staff and a discontinuation of the future instrumentation program without compromising the main science program. Thereafter, the SR recommends that NAIC plan either to close Arecibo or to operate it with a much smaller AST budget. This will require that NAIC seek sufficient external funding to continue to operate it fully. This support might be coupled to Arecibo's status as one of the most important and visible high technology enterprises in the Commonwealth of Puerto Rico. An alternative possibility is to seek one or more foreign partners. This could have appeal to countries that wish to build up a capability in radio astronomy or communications technology. The SR recommends closure after 2011 if the necessary support is not forthcoming. It recommends that operation of the Angel Ramos Visitor Center continue, consistent with Principle 3.

If Arecibo is kept operating beyond 2011, it is expected that this will only be a limited term extension, pending the deliberations of the next decadal survey. In any case, Arecibo's longer term future depends upon progress with the SKA which will be fully steerable, have ten times the collecting area, will access more of the sky to higher frequency and will have the angular resolution of an interferometer, leaving Arecibo as a niche telescope. This raises the important question of the cost of decommissioning the telescope, which could be prohibitively large.[53] The committee concluded that there were no reliable de-commissioning estimates and recommends that AST engage an independent study to advise on the viability and cost of decommissioning the telescope. Obtaining this information is a pre-requisite to long term planning.

6.2.2 Green Bank Telescope Operations

The SR found that the GBT operations cost of $10M ($15M burdened) to be conspicuously large, especially as it is several years since the instrument was commissioned. The former figure is 12 percent of the construction cost, much larger than the seven percent rule of thumb and large in comparison with the proposed running costs for ALMA (six percent of capital costs minus the component set aside for new instrumentation). Based upon its analysis, the SR believes that there are opportunities for operating Green Bank significantly more efficiently and redeploying some of the existing personnel to help meet other NRAO responsibilities as has happened in the past, consistent with Principle 2. This should be considered in detail by the NRAO cost review.

6.2.3 NRAO Scientific and Administrative Staff

NRAO supports roughly 90 scientists - roughly 35 FTEs - with a budget of $5M. The composition of the scientific staff should evolve as the scientific focus of NRAO shifts from cm to mm astronomy. As there is much mm observing expertise in the university community, there should be less need for a scientific staff at NRAO in this area. The SR recommends that NRAO reduce the level of its scientific staff, taking advantage of

[52] Economies may be possible in the apparently large (20 percent of the total budget) administrative costs.

[53] In its submission to the SR, NAIC reported that the full cost of de-commissioning could be as high as $170M.

departures and retirements over the next five years and perhaps increasing the fraction of service work required.

6.2.4 Square Kilometer Array and Precursor Telescopes

SKA was planned from its inception, in 1990, as an international project to build a multi-purpose radio interferometer with a hundred times the collecting area of the VLA. The scientific goals include exploring the epoch of re-ionization in the early universe, seeking the origin of cosmic magnetic field, performing deep galaxy surveys using the 21-cm hydrogen line, measuring dark energy by seeking echoes of the microwave background fluctuations in the distribution of galaxies and studying tens of thousands of pulsars. Up to now, the development of SKA concepts and participation in the international organization involving the US has largely come from the community. This should continue. Eventually, the SKA will obviate many of the other large radio telescopes in the world. The SR expects that NRAO will play a larger role in SKA if and when this becomes a major US activity and that the level of support within NRAO will evolve to reflect a strategic plan to do this. AST is also supporting some university groups to participate in precursor telescopes like the Mileura Widefield Array – Low Frequency Demonstrator (MWA-LFD) and the ATA. These facilities could contribute several important scientific advances, such as finding the epoch of re-ionization and developing the techniques of wide field imaging and transient radio source detection. They will also help train the next generation of radio astronomers who will be needed to work on and with SKA.

6.2.5 Very Long Baseline Array

As outlined in Sec. 4.3.3.2, the VLBA is the premier scientific instrument for VLBI. It took many years to achieve its potential for two reasons. First, it had a low effective sensitivity, which limited the number of sources it could observe. Its sensitivity has recently been improved both through increasing the bandwidth and combining with larger apertures, which has greatly increased the number and type of source that are accessible to study and has expanded the range of problems that can be studied. Further improvements are technically possible. The VLBA is poised to produce its strongest scientific contributions. The second reason for its slow start is that the technique of VLBI often requires experienced observers and that community is small. Roughly 45 percent of the VLBA PIs are not resident in the US and the majority of new applications are being pioneered by foreign users. Furthermore the oversubscription rate, currently 1.5, the lowest for all major US facilities, is small and falling. To some extent this is a consequence of the university VLBI groups disbanding when their federal support was diverted to pay for the construction of the VLBA. However, it is also a tribute to the Open Skies policy and a testament to the international nature of the VLBI community. However, when combined with the observation above that roughly half the VLA PIs are foreign, it does raise the question of sharing the cost of operations of these premier facilities.[54]

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[54] The SR received many communications from members of the international radio astronomy community testifying to the uniqueness and future promise of the VLBA which demonstrates the international interest in preserving the VLBA.

Given this situation, and invoking Principles 1 and 6, the SR recommends that NRAO be directed to seek assistance in operating the VLBA for a finite time from the international user community and, perhaps, also from NASA and the Japanese Institute of Space and Astronautical Science where there is a strong synergy with its missions. The primary economy that is needed is in personnel cost and, in the case of VLBI, this assistance could be in the form of trained personnel who would work in the Socorro Operations Center and perhaps at the remote telescope sites, relieving NRAO staff. These astronomers and technical staff would be paid and supported by their home institutions and this would presumably be easier to negotiate than a straight currency transfer to pay the salaries of NRAO personnel. (Various consumables, such as recording media, may also be cost-shared.) Of course, there will be many difficulties to overcome, but if phased in over several years, this sharing of operations responsibility should lead to further strengthening of the global research community. The SR notes that the US intends to maintain its Open Skies policy with its share of ALMA time. The request for assistance in operations or indirect cost-sharing should be seen in this context. If an arrangement along these lines cannot be worked out over the next few years, then the SR recommends that this be taken as an indication that the future scientific importance of VLBI is not as characterized above and that the VLBA be closed in 2011. This schedule will still allow three years observing overlap with GLAST.

The current VLBA operations cost is $6M and the burdened cost is $10M so significant savings should be possible if operations are shared. (There should be opportunities for some of the displaced personnel to be employed by ALMA, the VLA and other NRAO facilities.) As with Arecibo, only a finite term extension of VLBA operations is anticipated, pending the recommendation of the next decadal survey. On the longer timescale, the SKA will include a VLBI capability but it is unlikely to achieve the full angular resolution of the VLBA and, if the VLBA is closed, a unique capability would likely be lost for decades.

6.2.6 Radio-Millimeter-Submillimeter Summary

The proposed RMS Base Program supports deployment of ALMA, GBT and EVLA plus the URO program. For the transition program, it is recommended that sufficient external financial or personnel contributions be found to operate Arecibo and VLBA with competitive scientific productivity after 2011 with an AST contribution not to exceed half the expected function costs ($4M and $3M, respectively). If these conditions cannot be satisfied, then the SR recommends that these facilities be closed with larger eventual savings. The SR recommends that additional savings be found from the $22M allocated annually for GBT operations, administration, and science and that this be a focus of the NRAO cost review.

6.2.7 Recommendation 6

The National Astronomy and Ionosphere Center and the National Radio Astronomy Observatory, which are heavily subscribed by other communities, should seek partners who will contribute personnel or financial support to the operation of Arecibo and the Very Long Baseline Array respectively by 2011 or else these facilities should be closed. Reductions in the cost of Green Bank Telescope operations, administrative support, and the scientific staff at the National Radio Astronomy Observatory should be sought. US *participation in the international Square Kilometer Array program, including precursor facilities, should remain community-driven until the US is in a position to commit to a major partnership in the project.*

6.3 Solar Transition Program

The solar community is committed to a future where it operates a fully functioning ATST in place of the current system of circa 1960's telescopes. NSO should be commended for recognizing that it would have to give up still productive solar facilities in order to free resources for ATST.

AST currently employs about 90 FTEs at NSO and there should be neither much growth nor much attrition with a phased transition from operating GONG++ and the Kitt Peak and Sacramento Peak telescopes to ATST (and SOLIS). If the NSO headquarters moves to follow the ATST construction, there might be significant loss of personnel who do not wish to re-locate.

6.3.1 Advanced Technology Solar Telescope

The cost of ATST, from the March 2005 cost review, is $195M, of which a quarter is hoped to come from foreign partners and $10M from the USAF. The project’s schedule for beginning construction under the MREFC program is 2009, with operations commencing five years later. The site proposed for the new facility is the west summit of Haleakala on Maui.

Although ATST itself must be considered part of the future program, as the construction phase has not yet been approved, we will assume that it will proceed through the MREFC process in order to understand the implications for the rest of the solar program. If this assumption turns out to be wrong, then the existing facilities will not be superceded and the proposed solar transition program must be revisited. Also, although ATST lies outside the purview of the SR, it was noted that the estimated total operations costs ($13M per year) are proportionately lower than for other comparable projects, being less than seven percent of the capital cost. This estimate should be scrutinized, particularly with regard to the adequacy of the budget for future instrumentation. Given the challenges of learning how to use ATST effectively, it is reasonable to maintain the scientific staff at existing levels. The SR recommends that the NSO headquarters, and the associated administration and support staff, be consolidated at a single location. Efforts should be made to plan ATST operations to be as economical as possible, with little or no growth in the overall NSO staff as it withdraws from operating the current Kitt Peak and Sacramento Peak facilities. At the same time, any costs associated with closing the Kitt Peak and Sacramento Peak facilities should be identified as soon as possible; as well as the costs of consolidating the existing management, engineering, and scientific staffs at a single location.

6.3.2 GONG++

GONG is an example of a project that has been extremely successful, but whose future science program might not have unique impact compared with other facilities supported by AST. In particular, many, though not all, of the capabilities of GONG will be duplicated, or exceeded, by the solar oscillation experiment on the Solar Dynamics

Observatory (SDO) after its launch in 2008. Although SDO currently is planned to be only a 5 year mission, much less than a solar cycle, a longer duration is a reasonable expectation (as has been the case with the Michelson Doppler Imager (MDI) experiment on SOlar and Heliospheric Observatory (SOHO)). Accordingly, the SR recommends that GONG++ be operated for at most one year following successful commissioning of SDO, to allow for intercalibrations. GONG++ should then be closed, unless international partners or the space weather community agree to take over the majority of the operations costs. In the interim, accurate termination costs for the facility (currently estimated at $3M) should be determined.

6.3.3 National Solar Observatory/Kitt Peak/Tucson

As acknowledged by NSO, the currently unique attributes of the McMath-Pierce facility will be fully supplanted by ATST. Ideally the McMath-Pierce telescopes should be operated until ATST becomes fully operational. However, this is not absolutely necessary scientifically, because some of the capabilities of the McMath-Pierce main telescope, for example, can be replaced in the near term by other national and international facilities. The SR recommends that the McMath-Pierce facility ramp down prior to the start of ATST construction, which would allow some staff to be transferred to work on ATST. Operation during the ATST construction phase should be subject to the constraint that there is no overall increase in manpower and operations costs. Managing this transition so as to maximize the availability of solar observation time will be a major challenge to NSO.

Because SOLIS currently is sited at Kitt Peak, provision will need to be made to move the experiment to a permanent location during the ATST construction phase. In addition, the recent decadal survey recommended an expansion of SOLIS to a three station network. The SR is supportive of that initiative but, consistent with Principle 6, any such extension should be funded and operated by non-AST partners.

6.3.4 Sacramento Peak Observatory

The SR recommends that the Dunn Solar Telescope and its user support should likewise begin ramping down prior to the ATST construction phase, to allow the NSO staff maximum concentration on the all-essential ATST effort (which might include, for example, use of the Dunn to test components of the ATST AO system). As far as the observational community is concerned, high resolution imaging and spectropolarimetric capabilities may be available at other solar telescopes. (One example is the Swedish Solar Telescope on La Palma. However, this facility is rather labor-intensive and therefore expensive to use in practice.) The full costs of divesting the Sacramento Peak site should be determined as soon as practical.

6.3.5 Solar Astronomy Summary

The solar astronomy base program comprises continued operation of SOLIS. The recommended transition program is to focus on rapid construction of ATST and consolidation of the headquarters, without expanding staffing. On paper these savings are almost the entire solar astronomy budget of $10M, though, in practice, they are proposed to match the growth in the ATST budget. They are also exclusive of any costs required to divest NSO of its two current observing sites or to relocate SOLIS. Any extension of the current SOLIS experiment to a multi-site network should be supported by non-AST sources.

6.3.6 Recommendation 7

The National Solar Observatory should organize an orderly withdrawal of personnel and resources, including the Synoptic Optical Long-term Investigations of the Sun telescope, from Kitt Peak/Tucson and Sacramento Peak and start to close down operations at these sites as soon as the Advanced Technology Solar Telescope funding begins. It should also consolidate its management and science into a single Headquarters. Support of the Global Oscillations Network Group project should cease one year after the successful deployment of the Solar Dynamics Observatory.

7. Future Program

The SR understands that if the Base and Transitional Program that it has recommended is implemented, it will result in the closure of productive facilities and the loss of unique capabilities. However, given the constraint of working with a fixed total budget, the re-investment strategy that it will permit will help to balance the program in ground-based astronomy and leave it in a stronger position in the future. The charge to the SR expressly excludes the nature and implementation of the future program, and the SR has no such plan to propose. The SR did, however, find it necessary to discuss the future of the field and has some reflections upon this future in the form of five Findings.

7.1 The Scientific Challenge

7.1.1 Reflections

As is abundantly clear from a reading of the summary in Sec. 2, the AANM and CQC, as well as the five observatory reports submitted to the SR, the potential for scientific discovery by astronomers supported by AST with the present and next generation of astronomical facilities is truly outstanding and the opportunity for further discovery will remain well beyond the five year horizon of the SR. However, as explained above, no credible, federal budget can meet the combined cost of the current and future programs. Consequently, the SR was charged with proposing changes constrained by a fixed budget in current dollars. It has respected this constraint in making its recommendations and found itself recommending the termination of programs of the highest quality while they still would be able to produce further great discoveries. Some important discoveries will also not now be made using those facilities that are recommended to receive reduced funding and the reductions in unique capabilities will retard progress in certain subfields of astronomy. The high quality of the science now at risk convinces the SR that additional investment in astronomy, shared between existing and proposed facilities, would have a large scientific payoff. This leads to its first finding.

7.1.2 Finding 1

Proper maintenance of current facilities while simultaneously developing and beginning operation of the proposed new facilities is infeasible under any reasonable expectations for federal budget support based on past funding levels .The cuts that are recommended here are as deep as they can be without causing irreparable damage and will only allow a start to be made on the new initiatives. The scientific promise of the proposed new facilities is so compelling and of such broad interest and importance that there is a strong case for increasing the overall AST budget to execute as much of the science as possible.

7.2 The Operations Challenge

7.2.1 Reflections

As explained in Sec. 1.4, one underlying motivation for the SR is the large operations cost associated with the major astronomical facilities supported by AST. Already these amount to roughly $120M, not including ALMA. This is two thirds of the total disposable AST budget. Astronomical telescopes have long, though finite, lifetimes during which the total operations and re-investment costs can far exceed the construction and commissioning costs. The costs of maintaining the telescopes and their sites, of support staff salaries, of administering the allocation of observing time, and of distributing and archiving observational data are crucial to the successful exploitation of the large capital investments needed for world-leading facilities.

Most facilities need to be continually upgraded with new instruments and expanded capabilities if they are to remain competitive throughout their operational lifetimes. The rule-of-thumb that we have adopted as a guideline is that the annual operating and re-investment cost is typically ten percent of the capital costs, after correcting for inflation. In many cases, the annual cost exceeds this estimate, especially if full economic cost accounting is adopted. If an adequate level of re-investment is not forthcoming, the facilities suffer, as was the case for the VLA and is currently true of KPNO and CTIO. Conversely, a running cost fraction closer to 20 percent, which, for example, is the case for Gemini, needs careful consideration.

We can illustrate the operations challenge by adopting an over-simple model. Suppose that facilities are all long-lived so that their costs are dominated by operations costing ten percent of capital costs. In a steady state, the total capital cost of all operating facilities cannot exceed ten times the annual budget for operations and new starts must await closure of existing facilities. The 2006 capital cost of currently operating AST facilities plus ALMA and ATST is $1.3B, more than ten times the operations budget of the current suite of facilities. Applying this simple model implies that AST, today, has already exhausted its capacity to begin new, large projects.

Equally important for the effective exploitation of astronomical facilities are the scientific users and, increasingly, the data and associated software tools which together create the innovative scientific outcomes that provide the reason for the investment in the first place. The user support costs for the exploitation phase of the observations is carried partly by the grants program and partly underwritten by universities and independent research organizations through scholarships, fellowships, and faculty salaries. When this support is not forthcoming, the research community is unable to exploit the facilities to best advantage when the opportunity is the greatest as happened with the VLBA (Sec. 6.2.4). We stress that there is vital need for a dynamic grants program which is appropriately matched to the capital investment (Sec. 5.1.1).

As noted in Sec. 2.1, the revolution in technology is driving profound changes in the way astronomical data are recorded and analyzed. The potential impact of astronomical facilities relies on the support for the tools and infrastructure for data processing in each facility. Support for the development of data and computational tools and standards must also be explicitly included in the life cycle planning for future facilities. This is a particular issue for LST and SKA. It should also be recognized that observatories are scientifically linked and that the data recorded at multiple facilities, when analyzed collectively, have the potential to extend the scientific reach of the individual facilities. Developing the capability to combine and exploit complementary datasets, as envisaged by the VO, is viewed as an important future program goal and this activity is likely to grow as astronomy becomes increasingly data-intensive.

Finally, the lifetime costs of the facilities need to include the prices of decommissioning telescopes. Leaving a telescope indefinitely in a mothballed state is not a zero-cost option and generally, because of safety and environmental issues, disassembly is the only possibility. Future telescopes should be constructed with a view to decommissioning them as inexpensively as possible and adequate provision for this phase should be included in the long-term budgets.

The pace of investment in new facilities should be informed by a realistic, long term strategic plan that balances new starts and operations against closures. The importance of conceiving and designing telescopes as operating facilities with finite lifetimes cannot be overstated. Finding creative ways to run them with lower staffing, upgrading and recurring costs may be even more relevant than identifying economies in the cost of construction.

7.2.2 Finding 2

Major astronomical observatories typically take at least a decade to plan, construct and commission. They are usually operated for several decades. The full costs of operating, maintaining, upgrading, exploiting, and decommissioning them are many times the costs of construction. Realistic life cycle costing for the observatories that are under construction or consideration is an essential part of planning.

7.3 The Strategic Challenge

7.3.1 Reflections

7.3.1.1 Planning a Viable, Stable, Balanced Program

Astronomers are proud of their decadal survey process. This has led to prioritized programs in ground-based astronomy every decade since 1960 and their process has been emulated by other fields. The last decadal survey, AANM, continued this fine tradition. However, many of its highest priority recommendations have turned out to be more expensive than originally estimated. This has led to unrealistic expectations and most of its proposed facilities will carry over until the next decadal survey when they will have to be re-considered. Others are starting but will be subject to descoping (as happened with ALMA) or outright cancellation if their costs grow unreasonably. This is a reason for undertaking the SR.

These considerations, and those of Sec. 7.2, imply that, in order to maintain a balanced program, there is an obligation to be as realistic and as economical as possible in planning for the future. Projects that are undercosted and contain too little contingency will not be adopted, however significant the potential scientific returns. A more strategic approach to buy down risk, including investing in technology development, as long advocated by AST and emphasized in the Brinkman report,[55] will be needed. Provision must be made for cost, schedule, and risk to become better defined as projects mature. These steps will be essential to carry out the largest and most expensive projects, whose execution depends upon defining a stable and realizable schedule for development,

[55] http://www.nap.edu/catalog/10895.html

construction, operation, exploitation and eventual de-commissioning. They will also provide international and independent partners with a well-defined strategic framework within which to collaborate with NSF with confidence that the programs will be executed in a timely manner. Furthermore, an exciting and stable program will attract the most talented scientists and engineers who will be needed to execute it.

The role of strategic planning within AST is currently unclear. While the principle that the community proposes while NSF, the White House and Congress dispose is appropriate for much of the Foundation, it is clearly inappropriate for handling MREFC facilities with multi-decade lifetimes. Coordinating design and technology development, expediting passage through the five MREFC stages - "Horizon," "Conceptual," "Development," "Readiness," and "Candidate" – prior to construction, and preparing for the operations and science phases, requires leadership and planning and this should come largely from NSF. A purely reactive NSF leads to community frustration and confusion.

Four major and moderate projects that were proposed in AANM should be considered in this context.

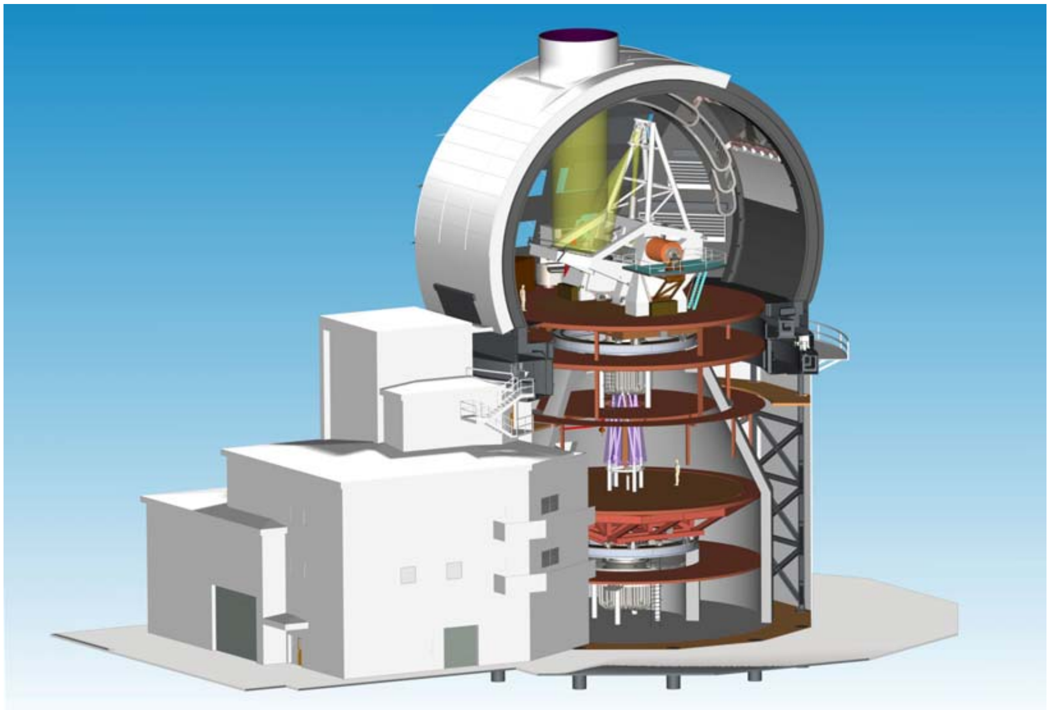

Figure 15. Artist's rendering of the Advanced Technology Solar Telescope (ATST) that was recommended in AANM. The ATST is an innovative 4m optical/IR telescope that will observe the sun at higher spectral, spatial, and temporal resolutions than are now possible. The all-reflective, adaptively-corrected design will deliver diffraction-limited performance from the visible through the mid-infrared and will incorporate a coronagraphic capability with extremely low scattering. [Image credit: NSO/AURA/NSF]

7.3.1.2 Advanced Technology Solar Telescope

ATST was the second-ranked moderate ground-based telescope in AANM (Fig. 15). It is currently proposed to start construction under the MREFC line in 2009 at a cost to AST of $135M. ATST is seen as an international project and it is vital to the AST program that the international contribution to the capital cost be at least as high as the estimated $30M and that this contribution be accompanied by a similar share of the running costs. Delay in completing ATST is likely to lead to delay in constructing other facilities.

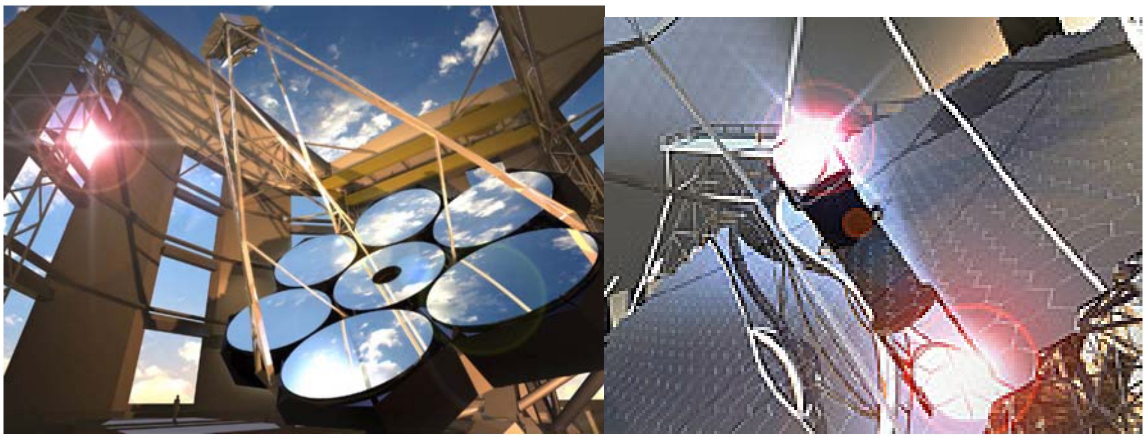

Figure 16. (a) On the left is an artist's renderings of the Giant Magellan Telescope (GMT). The GMT design incorporates seven 8.4-m primary mirror segments to yield a resolving power equivalent to a 24.5-m telescope. The GMT Consortium is led by the Observatories of the Carnegie Institution of Washington and includes eight additional, including international partners. [Image credit: Giant Magellan Telescope – Carnegie Institution] (b) On the right is a rendering of the Thirty-Meter Telescope (TMT). The TMT design utilizes roughly a thousand small mirror segments. The TMT Corporation includes California Institute of Technology, University of California, NOAO and the Association of Canadian Universities for Research in Astronomy. [Image credit: TMT Project] These are two concepts for an optical-infrared Giant Segmented Mirror Telescope (GSMT) as recommended in AANM.

7.3.1.3 Giant Segmented Mirror Telescope

There has been much work directed towards defining GSMT and attacking the technological problems that must be solved to implement it. The development and construction costs of either GMT (Fig16a) or TMT (Fig. 16b), estimated by the projects to be $500M and $750M, respectively, are close to the limit of what can be achieved through federal or private funding or, more likely, both.[56] The expectation is that the capital cost will contain a large fraction of private funding and that a federal contribution

[56] Building a GSMT for these costs will require considerable discipline. For comparison, in very rough numbers, two 10 m Keck telescopes cost $200M, a single 8m Subaru telescope cost $300M, two 8m Gemini telescopes cost $200M and four 8m VLT telescopes including the interferometric capability cost roughly $850M. As the accounting conventions are quite different in each of these projects, these figures should be used with caution. However, collectively, they demonstrate the challenge to GSMT.

would be sought from the MREFC account of NSF as soon as this becomes possible (Sec. 4.3.3). Furthermore, the considerations of Secs. 1.4 and 7.2 suggest that the full operating and re-investment costs of GSMT, adopting the projects' cost estimates, will be in the range of $50-150M per year (Sec. 1.4), depending upon the choice made and whether or not the observatory operations costs follow the ten percent rule of thumb or scale as Gemini. Such operations costs would need to be sustained over several decades. Even a figure at the low end of this range is well beyond the current capacity of AST.

Faced with these challenges and uncertainties, the SEUOIF Committee recommended that, as a first step, a choice should be made between the two GSMT projects around 2008 and that the optimal funding timeline would lead to construction beginning in 2010. The project not chosen was expected to pursue purely private funding. The SR finds that this proposed schedule is infeasible and has created unrealistic expectations in the community. It believes that the timing must now be fixed by the timescale on which confident costs and schedules can be determined and partnership arrangements, including AST, can be organized. There are so many possibilities here that it is premature to set any schedule. We return to this issue in Sec. 7.4. Whatever the outcome, it is evident that long-term operating costs are likely to be a determining factor in the fraction of the project that can be supported by AST within a balanced program.

ESO is developing its own plans for an ELT. Originally this was to be a 100 m "Overwhelming Large Telescope." At the time of writing, the aperture under consideration is in the 30 – 40 m range and so international collaboration can now be contemplated. Although every country desires its own telescope, the challenging new era of large construction projects and these long-term operating costs may make this infeasible henceforth.

7.3.1.4 Large Survey Telescope

LST was endorsed by AANM, NFSS and CQC. Two approaches were considered by SEUOIF. LSST is a monolithic 8.4 m telescope for which the total development and construction costs are estimated by the project to be $300M to be funded as a joint NSF-DOE-Private collaboration involving over 20 institutions. It is planned to operate for ten years with no new instrumentation and an annual operating cost to AST of $14M out of $22M total. This estimate is consistent with the rule of thumb as no instrumental upgrades are envisaged. The Pan-STARRS project is currently commissioning a single 1.8 m wide field telescope. The PS-4 proposal is to operate four similar telescopes on a common mount for a total construction cost of $60M, of which $35M has been secured from the USAF. AST is not supporting development of Pan-STARRS at this time.

The relevant figure of merit for the LST is the product of the aperture, the field of view and the duty cycle. This is at least an order of magnitude greater for the LSST than for PS-4, but LSST would be more expensive and take longer to complete. The SEUOIF Committee recommended that a federal LST choice be made as soon after 2008 as practical.

Figure 17. LSST and PS-4 are two concepts for a Large Synoptic Telescope (LST) that was recommended in AANM. (a) On the left is LSST, an 8.4m optical telescope being designed by a corporation including US universities, NOAO and national DOE labs. The site selected for LSST is Cerro Pachon, Chile. [Image credit: LSST Corporation] (b) On the right is the 1.8m diameter Pan-STARRS-1 which is under construction on Haleakala on the island of Maui in Hawaii. This is the precursor to the four telescope PS-4 project. [Image credit: Institute for Astronomy, Brett Simison]

7.3.1.5 Square Kilometer Array

There has been much international progress on the SKA. It is intended to make a choice between several designs and two candidate sites in Australia and South Africa over the next year with a view to completing the instrument in 2019. Several SKA pathfinder, or precursor, telescopes are currently being constructed, including the ATA, the Long Wavelength Array and the MWA. The EVLA may also be considered as a SKA precursor. Several foreign research organizations have already provided significant seed funding for SKA, including such major investments as the Netherlands LOFAR project. The results from these telescopes will undoubtedly influence the full SKA which may comprise two (or more) telescopes, a cheaper, low frequency array followed by a more challenging and more expensive high frequency instrument.

The US role in SKA has been understated so far, largely because of the large investment that is being made in ALMA. NAIC and some university groups have provided leadership within the US and NRAO has recently become more involved in the project. The complete SKA is a billion dollar plus facility. If the US is to have a large role in what will become the premier radio telescope in the world, superceding essentially all of the major centimeter and longer wavelength radio facilities available today, it will have to develop plans for ALMA-level investment in SKA. At present, though, AST is looking to the radio astronomical community to self-organize and develop a plan for transitioning from the various SKA precursor facilities to involvement in the full international project. Clearly, this will be a topic for the next decadal survey.

Figure 18. The Square Kilometer Array (SKA) is being planned by an international group of scientists and engineers as a next-generation facility for observations from 30 MHz to 30 GHz. This artist's conception shows aperture array (front) and small telescope (back) designs that are currently being considered to cover this broad frequency range. Sites in Australia and South Africa are under consideration. [Image credit: Xilostudies]

7.3.1.6 Summary

We have highlighted the cases of ATST, GSMT, LST, and SKA since they all figure prominently in the last decadal survey and represent the US community and world-wide consensus on large programs which offer most potential for advancing our understanding of central astrophysical and cosmological problems. They also bring into sharpest focus the challenges of supporting such large projects in the long term. It is currently hoped that ATST will proceed to construction in 2009 and be completed in 2014. Going beyond 2014, it seems unlikely for AST to have a significant role in GSMT, LST, and SKA simultaneously without dominant contributions from private, agency or international partners to the construction and operations of these facilities. These strategic considerations together with life cycle planning, as emphasized in Sec. 7.2, will feature prominently in the next decadal survey. As emphasized in Secs. 6.1.3, 6.2.3, there is an immediate need for AST to provide guidance to its potential partners on the plausible scope and schedule of its participation in these projects.

7.3.2 Finding 3

Construction on the Advanced Technology Solar Telescope may begin as early as 2009 (so as to be operational in 2014) and there is a strong scientific case for proceeding with the Giant Segmented Mirror Telescope, the Large Survey Telescope and the Square Kilometer Array projects as soon as feasible thereafter. A realistic implementation plan for these projects involves other agencies and independent and international partners.

Some choices need to be made soon; others can await the conclusions of the next decadal survey. Much work is needed, scientifically, technically and diplomatically, to inform this plan.

7.4 Towards a Coherent National Astronomy Enterprise

7.4.1 Reflections

7.4.1.1 Optical-Infrared Facilities

As is evident from the preceding discussion, astronomers are pursuing similar science goals with different proposed implementations in the case of both GSMT and LST. In some respects this is very healthy, as the competition has led to a better understanding of the scientific issues and to many new and creative approaches to solutions of the technical problems. At the same time, this has also led to a degree of fractionation of the optical astronomy enterprise and decoherence in the overall US effort making it potentially less effective than might otherwise have been the case. In particular, despite lengthy on-going discussions, AST, NOAO and the independent observatories do not share a common understanding of the available federal resources and realistic schedules for these major new projects.

This issue is most pronounced for GSMT. As discussed in Sec. 3.4, there have been longstanding tensions between universities and the national optical-infrared facilities that have weakened the national astronomical enterprise. As a consequence, NOAO has not been in a position to provide the leadership of the US OIR community and it was further diminished when it was excluded from Gemini construction and operation. Today, NOAO's primary role is to run 4m telescopes in an 8-10 m telescope era. As discussed in Sec. 5.2.2.2, the SR recommends that managing the provision of observing time on well-instrumented small and mid-sized telescopes in both hemispheres is an essential part of NOAO's mission and that this should constitute its base program. The question then is "What is NOAO's future role in large telescope science?"

Recognizing this challenge, the present NOAO management has developed a forward-looking plan with fixed level of effort which is discussed in its submission to this review, and for which it should be commended. The essence of this plan is to transition over half of its employees from supporting moderate size telescopes, instrumentation, and data products to working on the GSMT and LST projects. The problem facing NOAO is that, as explained in Sec. 6.1.3, it is neither guaranteed that the GSMT and LST projects will proceed on the schedule envisaged in the NOAO plan nor that the projects NOAO is currently supporting will be chosen by AST. In addition, Gemini has ambitious instrumentation plans, which, if implemented, will affirm it as the *de facto,* premier, national OIR facility at least until construction begins on the next national OIR telescope.

If the federal government were to become the major contributor to the life-cycle costs of GSMT, then this would be able to place a completely re-organized NOAO in a position to lead US OIR facilities. This is a role analogous to that of Goddard Space Flight Center and the Jet Propulsion Laboratory within the NASA system. If, however, the involvement of AST in GSMT does not flow through NOAO (as happened with Gemini), or if the private sector is able to proceed, largely independently of AST (as happened with the

Keck and Magellan telescopes), NOAO is likely to shrink further and play no more than a minor role, purchasing and distributing GSMT time on behalf of the national community. This ambiguity is making it almost impossible for NOAO to make coherent plans.

The independent observatories involved in GSMT are faced with no less of a quandary. They would naturally prefer to construct and to operate GSMT independently. However, even if they can raise the full construction costs outside of AST, it seems quite unlikely that the much larger running costs can be found over the long-term without considerable federal assistance.

Given the immense financial and technical challenges of a GSMT, the SR believes that it will take the combined material and intellectual resources of the national and the independent OIR observatories, the larger national community and, perhaps, the even larger international community to plan, construct, and use a GSMT effectively. This implies that these parties will have to find common cause with AST and work together to propose a radically different approach to developing GSMT. If this does not happen, the SR doubts that GSMT will be constructed. Although the SEUOIF recommended that the losing partnership be encouraged to proceed independently, the SR is skeptical that this will happen. Instead, it suggests that consideration be given to merging the existing, separate GSMT development efforts behind a single, preferred design. The next step might be for NOAO to oversee the creation of an integrated GSMT management organization through combining existing structures. Its nature and composition would reflect the balance of the public and private commitments to the project. A considerable challenge to this organization would be to reconcile public and private funding schedules and to determine appropriate levels of contingency as well as to agree upon the assumption of risk in the event that the construction and running costs increase from their current estimates. No less a challenge would be to harness and sustain the expertise and enthusiasm to be found already in the GSMT community so as to build and operate it as cleverly and as efficiently as possible.

There is also an immediate need to rationalize the planning of LST. The recent inter-agency, Dark Energy Task Force (DETF) report recommends a four stage approach to investigating dark energy, with DES and PS-4 included in the third stage and LSST (and SKA) in the fourth stage. AST and other stakeholders will have to respond soon to the DETF so that research on dark energy is coordinated and paced appropriately. The sequencing of GSMT and LST is also a critical issue for AST, as recognized by SEUOIF.

The SR suggests that AST should take the next step and establish a high-level commission with membership drawn from AURA, the two federal optical observatories, senior administrators of representative institutions currently associated with GSMT and LST projects. The AAS might represent the larger, university-based user community. This commission could be charged with bringing together the main stakeholders and finding a way ahead through the many conflicting issues to propose a new organizational structure for managing US OIR astronomy. Clearly, one outcome could be a recommendation to rebuild NOAO into a position of leadership in US OIR astronomy after the current management contract expires in 2007. If NOAO does not earn this opportunity, other outcomes are possible. Such a commission could go a long way toward creating a genuine OIR system that would ensure a strong US future in OIR astronomy, close to its historical strength.

7.4.1.2 Radio-Millimeter-Submillimeter Facilities

The situation in RMS astronomy is quite different. NRAO and NAIC are recognized for their record in managing the construction of internationally pre-eminent observatories, specifically VLA, VLBA, GBT, and Arecibo. NRAO is now an equal partner in an even larger project, ALMA. NAIC and the university observatories, while of smaller scale, provide unique observing capabilities and a fertile environment for innovative technical and instrumental developments. Many of the techniques and methods used in the national facilities were first developed at university observatories which also perform an essential role by producing astrophysicists highly trained in radio instrumental techniques.

Within the RMS system, it makes sense for the leadership to remain centered at NRAO as it is, by far, the largest radio astronomy organization in the world. It will be necessary, however, to ensure that NRAO continues to strengthen its partnership with NAIC as it evolves over the next decade as well as with the university community and to treat them as vital and essential parts of the RMS system.

7.4.1.3 Solar Astronomy Facilities

The solar astronomy community appears to be the most cohesive of the three considered in this report. In its submission to the SR, NSO recognized the need to close productive facilities in order to proceed with ATST. In addition, there appears to be a good integration between ground- and space-based solar astronomy as well as a synergistic relationship between AST-supported and other independent solar facilities.

7.4.1.4 An Integrated Astronomical System?

As was made clear in Sec. 2.2 the various subfields of astronomy are becoming intellectually inter-dependent. This drives a need for multi-facility scientific investigations, which, in turn, has strengthened the relationship between the independent and federal observatories. However, OIR, RMS, and solar astronomy have addressed, in different fashions, rather similar challenges in supporting the university observatories with federal funds. AST supports instrumentation at large, independent OIR telescopes by buying observing time for the national community through the TSIP program. It also supports technical development for future facilities through the ATI and AODP programs. In contrast, the URO program provides direct operations support to a few, competitively-selected radio observatories with unique and complementary capabilities to each other and to the national facilities. They, in turn, provide community access and technical innovation. Solar astronomy has evolved to a system where independent observatories are now supported largely outside AST but are scientifically integrated into the proposed program centered on ATST. In principle, all three programs could learn from each other and evolve towards a more parallel organization that combines explicit purchase of observing time with an expectation that the universities concentrate on advanced technology research while the national facilities emphasize its development and implementation.

It is instructive to compare the US arrangement to the situation in Europe. ESO runs the leading optical-infrared telescope in the world, the VLT, and is planning its successor. There is no US organization that provides a suitable match to ESO. Despite its origin as an optical observatory, ESO was the natural organization to lead European involvement in the ALMA project and, through the international nature of its operations, obtained the resources to match NRAO in constructing and operating ALMA.

In considering these differences, it is tempting to consider a natural convergence in the roles of national OIR, RMS, and solar facilities. Such a convergence could provide a rational framework for tackling some serious questions such as the sequencing of SKA relative to GSMT and the utility of changing the existing programs that support independent observatories to accommodate the best features of the three separate arrangements. Alternatively, it could stifle innovation. Ultimately, the benefit, or otherwise, of NSF creating a single national observatory should be debated. The SR offers no opinions here but trusts that these questions will be seriously considered by the next decadal survey. In the meantime, the responsibility for managing the aspirations of the five observatories and their operating organizations rests with AST.

7.4.2 Finding 4

In order to meet the challenge of (multi-)billion dollar, ground-based optical-infrared and radio observatories, there will have to be strong collaboration between the federal and independent components of the US astronomical enterprise and firm leadership by AST. A high-level commission addressing optical-infrared facilities provides one way to start to bring together the diverse components of the national program to realize the full potential of the US system.

7.5 Summary and Future Reviews

Presented with the challenge of identifying a target of $30M, approximately a quarter of the combined budgets of the four national observatories, the SR developed a set of criteria for comparing facilities and programs and examined in detail how AST resources are, in practice, used. As a consequence of this study, the SR identified Base and Transition programs for OIR, RMS, and solar astronomy. It recommends a savings plan which includes downsizing NOAO to concentrate on managing US access, either finding partners to operate Arecibo and the VLBA, or closing them entirely,identifying efficiencies wihtin NRAO, and closing down most of the public solar telescopes on a schedule linked to ATST construction.

Despite its scientific and budgetary analyses, the SR has chosen not to give a final tally of recommended savings for five reasons.

1. The precise level of savings that is prudent and achievable can only emerge from the five proposed cost reviews. This report identifies where the committee believes savings will be found and it has supplied AST with its best estimates of what is achievable. The reviews will need to make an independent and more authoritative examination of the observatory budgets starting with the recommendations of the SR.
2. There are several contingencies in the SR recommendation. For example, the savings from Arecibo and VLBA will depend upon how successful are the quests for partnership. The extent to which NOAO is downsized depends upon choices made concerning GSMT and LST.

3. There are considerable uncertainties over termination costs which have mostly not been reliably estimated.
4. Whether or not to characterize a change as a saving depends upon the context. For example, associating support of projects like ATST and GSMT with the future program is formally a SR saving although no additional funds may be liberated. Contrariwise, the EVLA construction budget should be available for re-investment after 2010 but does not count as a SR saving.
5. There are already international obligations to ALMA operations and Gemini instrumentation which must be included in future budgets.

The SR estimates that, based upon a minimal interpretation of these issues, real savings of at least $15M are achievable if its recommendations are adopted; a maximal interpretation gives savings well in excess of $30M.

Finding these potential savings has been extremely difficult. In none of the proposed actions can the facilities targeted be seen as redundant to the scientific enterprise. Instead, the SR is recommending reduced AST funding or closure of telescopes that could be unique and productive for decades. Further savings could, in principle, have been recommended, but they would have so weakened the US program as to do irreparable harm whatever new projects are started.

If the premise of the SR - that the federal funds available for ground-based astronomy will not grow over the next five years – is accepted, then some of the ambitious recommendations of the last decadal survey will have to be put on hold and re-evaluated in the next survey. It is incumbent upon the national and international astronomical communities to come to terms with these realities and to work together to optimize the program. Simultaneously it will be necessary for AST to continue to be proactive and to adopt a leadership role in bringing the stakeholders in future major projects together to find a common implementation approach. The traditional, reactive stance of NSF is ill-matched to the development of major projects and leads to frustration in the astronomical community and wastage of human and material resources.

These findings, which go beyond the SR's charge, may appear defeatist to some. However, the SR developed the more optimistic view that, in combination with the SR recommendations, they provide the best opportunity US astronomers have to realize the promise of the next generation of major telescopes of all types. Patience, cooperation and wise planning will be needed to move forward.

The Senior Review is an experiment, not just within AST but for the whole of NSF. Time will tell if it was well conceived and sensibly executed. Independent of the shortcomings of the present exercise, it is the committee's unanimous view that facilities must regularly close to enable more powerful replacements to be constructed and operated. The SR process must be a feature of the next decadal survey and should be repeated roughly every five years thereafter.

7.5.1 Finding 5

Balancing the demands of the current program against the aspirations of the future program is an ongoing obligation. The Senior Review process should be implemented as *a standard practice within the Division of Astronomical Sciences and to be a consideration included in the next decadal survey.*

Appendix A. Acronyms

AAG – Astronomy & Astrophysics Research Grants Program

AANM – NRC 2001 Decadal Survey *"Astronomy & Astrophysics in the New Millennium"*

AAS – American Astronomical Society

AGN – Active Galactic Nuclei

ALFA - Arecibo L-Band Feed Array

ALMA – Atacama Large Millimeter Array

AO – Adaptive Optics

AODP – Adaptive Optics Development Program

AST – Division of Astronomical Sciences

ATA - Allen Telescope Array

ATI – Advanced Technologies and Instrumentation program

ATM – Division of Atmospheric Sciences, Geosciences Directorate, NSF

ATST – Advanced Technology Solar Telescope

AUI – Associated Universities, Inc

AURA – Association of Universities for Research in Astronomy, Inc

CAREER – Faculty Early Career Development Program

CARMA - Combined Array for Research in Millimeter Astronomy

CDL - Central Development Laboratory

CERN - European Organization for Nuclear Research

CfAO - Center for Adaptive Optics

CMB – Cosmic Microwave Background

CQC – NRC report *"Connecting Quarks with the Cosmos"*

CTIO – Cerro Tololo InterAmerican Observatory

DARPA – Defense Advanced Research Projects Agency

DES – Dark Energy Survey

DETF - Dark Energy Task Force

DOE – Department of Energy

DST – Dunn Solar Telescope

ELT – Extremely Large Telescope

E/PO – Education and Public Outreach

ESO – European Southern Observatory

EVLA – Expanded Very Large Array

FASR - Frequency Agile Solar Radio Telescope

FTE – Full Time Equivalent

GBT - Robert C. Byrd Green Bank Telescope

GLAST - NASA's Gamma-ray Large Area Space Telescope

GMT – Giant Magellan Telescope

GONG – Global Oscillations Network Group

GSMT – Giant Segmented Mirror Telescope

HET – Hobby Eberly Telescope

KPNO – Kitt Peak National Observatory

LOFAR - LOw Frequency ARray

LSST – Large Synoptic Survey Telescope

LST – Large Survey Telescope

MACHO – Massive Compact Halo Object

MDI – Michelson Doppler Imager

MMT – Multiple Mirror Telescope

MPS – Directorate of Mathematical and Physical Sciences

MREFC – Major Research Equipment and Facilities Construction

MRI – Major Research Instrumentation

MWA-LFD – Mileura Widefield Array - Low Frequency Demonstrator

NAIC – National Astronomy and Ionosphere Center

NASA – National Aeronautics and Space Administration

NEWFIRM – NOAO Extremely Wide Field InfraRed IMager

NFSS – NRC report *"New Frontiers in the Solar Systems: An Integrated Exploration Strategy"*

NGSC – NOAO Gemini Science Center

NOAO – National Optical Astronomy Observatory

NRAO – National Radio Astronomy Observatory

NRC – National Research Council

NRL – Naval Research Laboratory

NSF – National Science Foundation

NSO – National Solar Observatory

OIR – Optical-Infrared

OSTP – Office of Science and Technology Policy

Pan-STARRS, PS-4 – Panoramic Survey Telescope and Rapid Response System

PoU – Physics of the Universe

PREST - Program for Research and Education with Small Telescopes

R&A – Research and Analysis

RMS – Radio-millimeter-submillimeter

RMSPG - Report of the Radio, Millimeter and Submillimeter Planning Group

SDO – Solar Dynamics Observatory

SEB – NRC report *"The Sun to the Earth - and Beyond: A Decadal Research Strategy in Solar and Space Physics"*

SEUOIF - Strategies for Evolution of US Optical/Infrared Facilities

SKA – Square Kilometer Array

SMARTS - Small and Medium Aperture Research Telescope System

SOAR - SOuthern Astrophysical Research Telescope

SOHO – SOlar and Heliospheric Observatory

SOLIS – Synoptic Optical Long-term Investigations of the Sun

SPST - South Pole Submillimeter-wave Telescope

SPT - South Pole Telescope

SR – Senior Review Committee

TMT - Thirty Meter Telescope

TSIP – Telescope System Instrumentation Program

URO – University Radio Observatory

USAF – U. S. Air Force

USNO – U. S. Naval Observatory

VERITAS - Very Energetic Radiation Imaging Telescope Array System

VLA – Very Large Array

VLBA – Very Long Baseline Array

VLBI – Very Long Baseline Interferometry

VLT – Very Large Telescope (ESO)

VO - Virtual Observatory

VSOP-2 - Japan's VLBI Space Observatory Program

WFMOS - Wide Field Multi-Object Spectrograph

WIYN - Wisconsin-Indiana-Yale-NOAO

Appendix B. Senior Review Committee

THOMAS R. AYRES, University of Colorado

DONALD C. BACKER, University of California, Berkeley

ROGER D. BLANDFORD, Kavli Institute for Particle Astrophysics and Cosmology, Stanford University (Chair)

JOHN E. CARLSTROM, University of Chicago

KARL GEBHARDT, University of Texas, Austin

LYNNE HILLENBRAND, California Institute of Technology

CRAIG J. HOGAN, University of Washington

JOHN P. HUCHRA, Harvard-Smithsonian Center for Astrophysics

ELIZABETH LADA, University of Florida

MALCOLM LONGAIR, University of Cambridge

J. PATRICK LOONEY, Brookhaven National Lab

R. BRUCE PARTRIDGE, Haverford College

VERA C. RUBIN, Department of Terrestrial Magnetism, Carnegie Institution of Washington

Appendix C. Charge to the Senior Review

Background

This review, a recommendation of the most recent Decade Survey,[57] is motivated at this particular time by a confluence of the current flat outlook for the Federal budget, the increased cost (relative to previous programs) of the ambitions of the astronomical community as evidenced in the Decade Survey and other reports such as "Connecting Quarks with the Cosmos," and by the growth in the Division of Astronomical Sciences (AST) budget over the past five years, which provides ~$60M a year more to spend on astronomical research than was available in FY2000.

This review is designed to examine the balance of the (AST) investments in the various facilities and selected other activities that we support. The primary goal of the review and the resultant adjustment of balance is to enable progress on the recommendations of the Decade Survey, including such things as operations funds for ALMA, and other priorities such as those recommended in "Connecting Quarks with the Cosmos". At the same time AST seeks to preserve, indeed grow, a healthy core program of astronomical research. Possible reinvestment of some of the Division's resources in the highest priority components of the existing facilities and programs is therefore an important consideration.

The following boundary conditions should be adopted for the review:

- The review will assume that the AST budget will grow no faster than inflationary increases for the remainder of the decade
- AST will not use resources from the unrestricted grants programs (AAG) to address the challenges of facility operations or the design and development costs for new facilities of the scale of LSST, GSMT, SKA, etc.
- The Committee will not revisit the priorities and recommendations of community reports such as the Decade Survey; the committee will not consider proposals for future individual projects nor will it determine how funds are to be distributed among individual ongoing development efforts, but rather identify resources that can be distributed to these future efforts through AST's normal review and priority setting processes.
- The adjustments in balance that may result must be realistic and realizable; the committee should recognize that savings will not be immediate and additional costs may be associated with reprogramming.
- The committee's deliberations should take into consideration systemic issues such as U.S. scientific leadership within a global context, the ability to complement

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[57] AANM: " Cross disciplinary competitive reviews should be held about every 5 years for all NSF astronomy facilities. In these reviews, it should be standard policy to set priorities and consider possible closure or privatization."

observations at other wavelengths, filling critical niches in the overall U.S. system, and the needs for training and technical innovation.

- Recommendations should be based on well-understood criteria established by the committee and articulated to the community.
- There should be ample opportunity for community input.

The Charge

The committee is asked to examine the impact and the gains that would result by redistributing ~$30M of annual spending from Division funds. These funds would be obtained by selective reductions in the operations of existing facilities and instrumentation development programs, possibly in combination with opportunities to deliver scientific knowledge at reduced cost to NSF or increased efficiency through new operating modes. Near-term needs for new investment lead us to conclude that we must try to generate the $30M in annual redistributed funding by the end of FY2011. The $30M (annual) would be used to bolster the highest priority components of existing facilities, to begin to cover ALMA operations costs, and as a source of support for implementation of Decade Survey recommendations.

In short, the committee is asked to trade progress on new and enhanced programs against the preservation of existing capability by proposing changes that are viable and that lead to a vital and sustainable future.

The committee is asked to provide its recommendations by 31 March 2006, if possible, so the report can be presented to the MPS AC at its April meeting and considered in formulating the FY2008 budget.

Appendix D. Meetings of Senior Review

The committee held four face to face meetings and six plenary telecons.

FACE-TO-FACE MEETINGS	TELECONS
October 19-21, 2005, Arlington, VA January 12-13, 2006, NSF. February 26-28, 2006, Boston, MA April 17-18, 2006, NSF.	February 6, 2006 February 24, 2006 March 22, 2006 June 23, 2006 July 3, 2006 July 18, 2006

Appendix E. Town Meetings

Boston, Massachusetts - 29 September 2005
Boston University

Minneapolis, Minnesota – 7 October 2005
University of Minnesota

Washington, DC – 14 October 2005
Sponsored by the AAS, held at the Carnegie Institution of Washington

Clemson, South Carolina – 15 October 2005
Clemson University

Boulder, Colorado – 24 October 2005
University of Colorado/High Altitude Observatory

Berkeley, California - 15 December 2005
University of California at Berkeley

Washington, DC, AAS meeting - 10 January 2006