Investments in Critical Capabilities for

Geospace Science

2016 to 2025

A Portfolio Review of the Geospace Section

of the Division of Atmospheric and Geospace Science

Requested by the
Advisory Committee for Geosciences
National Science Foundation

Report submitted to

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Executive Summary

The Geospace Section (GS) of the Division of Atmospheric and Geospace Sciences (AGS) of the National Science Foundation serves a unique and important role in advancing the frontiers of knowledge of solar-terrestrial interactions, the Earth's space environment and the effects of the space environment on the Nation's technologies. GS investments in state-of-the-art instrumentation and facilities enable scientific discoveries of the physics, chemistry and dynamics of Earth's upper atmosphere and exosphere and the Sun. GS facilities provide crucial measurements that can only be obtained from ground-based instruments and that complement those from space-based platforms.

The GS grants programs are recognized within the space science community as a primary source of funding to support ideation, incubation, advancement and exploitation of new methods and concepts that have the capacity to transform our understanding of geospace, the interplanetary medium, the Sun and solar-terrestrial and solar-planetary interactions. The GS core grants program supports curiosity-driven research of the highest quality. It is complemented by an innovative targeted grants program which the geospace community uses to inform and guide collaborative research strategies for expanding the envelope of new knowledge. The GS CubeSat program is widely recognized as being in the vanguard of frontier science using instruments deployed on tiny satellite platforms.

GS led the original interagency effort that created the National Space Weather Program, a partnership between academia, industry and government. The National Space Weather Action Plan released in October 2015 by the Office of Science and Technology Policy assigns primary responsibility to NSF, in partnership with NASA, to prioritize and identify opportunities for research and development to enhance the understanding of space weather and its sources, including developing and testing models of the coupled sun-Earth system. In order to meet this challenge GS will need to augment its future investments for research into the science of space weather.

This Portfolio Review Committee (PRC) of the Geospace Section was charged by the NSF Advisory Committee for Geosciences to reconcile the most promising and essential science strategies and critical capabilities with the science goals of the 2013 Decadal Survey (DS) for Solar and Space Physics (SSP), and of the Geospace Section. Growth in future NSF budgets for geospace science would certainly make this assignment straightforward, with satisfying outcomes for practically every segment of the geospace research community. However, the committee charged with this review was given a more fiscally demanding constraint: Assume an inflation-adjusted, flat budget for GS over the next decade.

GS investments in facilities and grants programs, for the most part, are already well-positioned to enable significant progress in achieving the 2013 DS science goals. However, the Survey anticipated increasing importance and future emphasis on integrative and cross-disciplinary science, of which space weather is a prime example. Thus, the Portfolio Review gave particular attention to the alignment and balance in GS investments with this vector of the Survey.

After assessing the critical capabilities needed to make progress in achieving DS goals, the PRC examined in detail all GS programs and facilities, their balance and ability to provide the required capabilities. The committee finds that the Section's provision of critical capabilities for integrative and cross-disciplinary science must be augmented if geospace research is to intersect the future envisioned in the Decadal Survey. Doing so will require changes in the budgets of some program elements and facilities as recommended below. "Free energy" to implement new programs and facilities that better address DS goals is derived mainly from redirecting support from some current facilities into new facilities and programs.

Budget implications of the PRC recommendations are given at two snapshots in the future (Chapter 9). The first snapshot at 2020 shows the budgets of new program elements and facilities (together with unchanged program elements and facilities) that are made possible by reprogramming elements of the 2015 budget. The 2025 budget snapshot carries the 2020 budget forward with less specificity. PRC recommendations for various GS programs and facilities follow.

Core Grants Programs. Making progress on DS science goals would be impossible without vibrant research grants programs that support, sustain and stimulate a novel scientific enterprise. Together with the special GS program for **Faculty Development in Space Sciences** (FDSS), they are also essential in promoting a vital profession. The GS should maintain the existing budget share for the core research programs in Aeronomy, Magnetospheric Physics and Solar-Terrestrial Research and the FDSS program within the assumed inflation-adjusted 2015 level (or greater) for the next decade. It should use proposal pressure in concert with portfolio balance to determine an optimum distribution of investments across the three programs.

Targeted Grants Programs. The GS should maintain the combined current funding level for its three targeted research grants programs – Coupling Energetics and Dynamics of Atmospheric Regions (CEDAR), Geospace Environment Modeling (GEM) and Solar, Heliospheric and Interplanetary Environment (SHINE) – over the next five years. While doing so, it should monitor the nexus of cross-disciplinary collaborative and integrative research within these programs, including space weather research. Beyond 2020, or sooner if additional funding becomes available, the GS should reprogram a portion of the targeted research budget into a new program element, **Integrative Geospace Science** (IGS).

Space Weather Modeling Program. The GS should continue its current investment in space weather modeling (currently in collaboration with the NASA Living With a Star program), at least until 2020. Beyond 2020, or sooner if additional funding can be identified, and in concert with the recommended Grand Challenge Projects program (described below), the combined budget for space weather research and grand challenge projects comprising IGS should be increased significantly. Even in the assumed flat-budget scenario, growth in the IGS program by 60-70% is expected between 2020 and 2025 with the aforementioned reprogramming from targeted grants programs.

CubeSat Program. The GS CubeSat program has attracted national attention by demonstrating the feasibility of using tiny and relatively inexpensive satellite platforms for novel measurements in geospace. With the recent growing interest from other government agencies in CubeSat science, and from industry in the development and provision of standard CubeSat platforms, it may be too early to assess the long-term value proposition of conducting CubeSat science within the GS and its current mode of mission development. The GS CubeSat program has borne significant costs for CubeSat engineering, which detracts from the Section's primary scientific mission. However, development of CubeSat missions in universities has become a significant vehicle for generating interest among undergraduates in STEM studies. The GS should continue its CubeSat program with increased emphasis on CubeSat scientific mission concepts and instrument development and less emphasis on engineering of CubeSat buses and communication systems. With less engineering required, the recommended budget for the GS CubeSat program can decrease by one third. Interest in CubeSat science is expected to accrue more broadly across NSF in the Geoscience, Engineering and Education Directorates and at NASA and other agencies. The GS should pursue opportunities for CubeSat collaborations with the aim of leveraging its investment in this emerging capability.

Facilities Program. GS facilities, including Class 1 and Class 2 facilities (defined in Chapter 7), currently account for 38% of total GS investments. The facilities investment recommended by the PRC decreases to 36% by 2020 and stabilizes at this value from thereon. Although the decrement in the facilities budget is modest, a significant redistribution of funds within the facilities portfolio is recommended.

The currently supported GS facilities include:

Class 1 Facilities: Incoherent scatter radar facilities include Arecibo, Jicamarca, Millstone Hill, PFISR, RISR-N and Sondrestrom. The Consortium of Resonance and Rayleigh Lidars (CRRL) is also funded by the GS Facilities program.

Class 2 Facilities: These community facilities include data and modeling environments (AMPERE, CCMC, SuperMag) and a distributed array of coherent scatter radars (SuperDARN). They are currently managed by the program manager for space weather research.

The CRRL operates as a PI-led research project and does not meet the criteria used by the PRC for a facility. The PRC recommends that funding for the innovative science accomplished by **CRRL** be derived from the core or targeted grants programs through a standard competitive peer review process. The above noted 2% reduction in the facilities investment is mainly due to the redirection of CRRL funding to the grants programs.

Among the other facilities, **Jicamarca, PFISR, RISR-N, AMPERE, CCMC** (in partnership with NASA), **SuperMag** and **SuperDARN** provide critical capabilities that are deemed essential for making progress on DS science goals. All should continue to be funded at their nominal FY 2015 level, until 2020 or an interim Senior Review for facilities is convened (see below). **Millstone Hill** also provides a critical capability and its funding should be similarly continued, except for the portion of its budget dedicated to community data management. The small fraction (<10%) for data management should be added to a pool of funds (described below) for future competition to develop and manage community data systems, which eventually should also become separate Class 2 facilities.

The **Sondrestrom ISR** provides important diagnostics in the ionospheric cusp region, equatorward of the magnetic pole. This capability is needed to achieve DS science goals, but Sondrestrom's maintenance and operational costs, and its older Klystron-tube and dish technology, diminish its value proposition in the portfolio. The importance of international cooperation in observing typically fast-evolving, global geospace dynamics was well established even before the International Geophysical Year of 1957-58. It is recommended that the GS begin forging a new partnership with the **European Incoherent Scatter Scientific Association** (EISCAT) and terminate support for Sondrestrom when its current continuing grant is complete. The cost of full US partnership in EISCAT is less than half the cost of Sondrestrom, so GS resources will be significantly leveraged if ISR observing time and data access for US investigators can be adequately met by joining EISCAT. The location of the EISCAT-Svalbard ISR relative to PFISR and RISR-N offers some geographical advantages relative to Sondrestrom in diagnosing day-night flows across the polar cap. In addition, a new capability for auroral science, EISCAT-3D, is expected to become operational by 2020. Its volumetric imaging will leapfrog the AMISR phased-array technology developed with GS support two decades ago.

The world's most sensitive ISR at **Arecibo Observatory** (AO) provides capabilities primarily to address the DS science goal to "discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe", specifically in Earth's ionosphere and thermosphere. Provision of this capability required nearly 10% of the GS budget in 2015. The cost of this investment significantly distorts the balance in the GS portfolio and cannot be justified going forward if GS is to support activities that will optimally implement the DS recommendations. The PR recommends a 73% reduction in the GS contribution to AO to bring its cost approximately in line with proposal pressure and allocation of observing time for GS investigators relative to other AO users.

The recommended changes in GS investments in AO and Sondrestrom, discounted by the expected cost of joining EISCAT, open 10% in the GS budget for implementation of DS recommendations for NSF. This wedge falls short of the estimated 25% increase in the GS budget required for full implementation of DS recommendations (Section 3.2), but it does allow initiation of important new program elements that will provide critical capabilities.

These new program elements include a **Grand Challenge Projects** (GCP) program, new programs for **Data System**s and for **Distributed Arrays of Scientific Instruments** (DASI), and an **Innovation and Vitality** (I&V) program.

– The DS specifically recommended a GCP program to make progress on large cross-disciplinary problems. Such a program is deemed critical in addressing many basic science issues of geospace, the interplanetary medium and the Sun, as well as integrative science cutting across them.
– The DS identified the need for an advanced data environment that draws together new and archived satellite and ground-based SSP data sets and computational results. The recommended GS Data Systems program will support development of one or more new Class 2 facilities that exploit emerging information technologies for integrated software and data analysis tools, GS data mining and assimilation.
– DASI networks are essential to address the DS science goal to "determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs." The recommended GS DASI program emphasizes the importance of distributed measurement systems in geospace science. The peer-reviewed projects receiving support from this program are expected to become Class 2 facilities.
– In interviewing PIs of GS facilities the PRC heard repeatedly that funds for system upgrades, including software and data systems, have been stretched thin in recent years. Using a peer-review process to determine resource allocations, the recommended I&V program will maintain the state-of-the-art in GS facilities and models. In so doing, this program fulfills the DS recommendation to complete the current program.

Separate mid-decadal senior reviews of (1) the GS core and strategic grants programs and (2) the GS facilities program, including both Class 1 and Class 2 facilities, are recommended to evaluate continuing alignment of the programs with Survey, Section and Division goals and to identify and prioritize emerging opportunities for innovation in the programs.

In identifying gaps in proposal opportunities and funding levels that limit the effectiveness of SSP research, the DS recommended the addition of a midscale funding capability specifically for NSF. The DS-envisioned **Midscale Projects Program** would enable competition and support for high-priority midscale projects leading to next-generation ground-based observatories with individual project costs ranging from $4-30M (several candidates are listed in Section 7.7). This program does not fit into the budget envelope given to the PRC, nor do the full costs of DS recommendations for CubeSat, Space Weather and Grand Challenge Projects programs.

Should future GS budgets become more optimistic than current, a Midscale Projects Program would become a high priority together with more comprehensive implementation of these other programs. The recommended Senior Reviews would be an effective process for determining if, or the extent to which, additional investments might be adapted to accommodate more fully vested core and strategic grants programs together with new midscale projects and their future demand on the GS facilities budget.

Chapter 1. Introduction

Geospace science underwent a remarkable transformation in the decade between the last two Decadal Surveys for Solar and Space Physics (SSP). In 2003, a nascent though not quite articulated concept of geospace as a system appears as one of the Survey's top level science challenges. In the 2013 Survey, the domains comprising geospace are now recognized as elements of a coupled dynamical system extending from the upper atmosphere, through near-Earth and interplanetary space, to the Sun. The origins of solar variability, the predictability of space weather and fundamental plasma processes are common themes.

Today geospace science continues its arc of discovery into the basic physical and chemical processes that govern the dynamics of the Sun, the interplanetary medium, the magnetosphere and ionosphere and the upper atmosphere of Earth. We have learned during the recent, unusually quiet solar minimum that the thermosphere and ionosphere are strongly forced not only from above by the magnetosphere but also by the atmosphere from below. Escaping outflows of ionospheric ions, stimulated by intense electrodynamic forcing from the solar wind-magnetosphere interaction, modify fundamental properties of Earth's ionosphere and magnetosphere, including the important magnetic reconnection process. We have learned to interpret the geoeffective impacts of different interplanetary structures and can trace their origins back to dynamic events and regions at the Sun. Despite these successes, we are still unable to predict one of the most important properties of interplanetary disturbances that determine their geoeffectiveness – the north-south component of the embedded magnetic fields. We now realize that the geospace system behaves differently than a simple superposition of its constituent parts, and this key realization underpins our future ability to predict the impacts of space weather.

The National Science Foundation has endowed a vibrant and innovative community of space scientists with leading-edge tools for scientific investigation. Using new technologies geospace scientists are deploying increasingly sensitive ground-based instruments and observatories to discover previously invisible structures in the upper atmosphere and Sun. Widely distributed networks of ground-based instruments are helping to resolve space-time ambiguity in sparse measurements of the space environment. Complex and increasingly realistic numerical simulations performed on the most advanced supercomputers and combined with data assimilation enable exploration of regions such as the interior of the sun that are practically inaccessible to direct measurement; and novel numerical experiments are revealing the causal chain of events responsible for major disturbances in geospace such as geomagnetic and ionospheric storms.

The geospace science community's ambitious agenda for discovery and synthesis of new knowledge appears to have reached a limit in the Nation's ability to sustain it at an ever growing pace. This Portfolio Review (PR) of the Geospace Section (GS) of NSF's Division of Atmospheric and Geospace Science (AGS) reconciles the most promising and essential science strategies and measurement capabilities with the scientific aspirations prioritized in the 2013 Decadal Survey (DS).

Geospace phenomena are global in nature, in contrast with tropospheric dynamics, and they exhibit planetary-scale changes on time scales of an hour or less. Thus whether North America is affected by an ensuing space weather event is determined largely by the planet's rotation and the time of impact of the interplanetary driver. Since the state of geospace changes quickly and globally, simultaneous measurements are needed throughout its extensive spatial domain and over the entire surface of the planet. This fundamental feature has engendered a very active and collaborative international research community in geospace science. With judicious consideration of the synergies between US and international investments in the geospace scientific enterprise, the National Science Foundation (NSF) can substantially leverage its impact in this field. This review recommends a balanced portfolio of GS investments in critical capabilities, and it identifies natural synergies that can leverage NSF's current investments in geospace science to allow new initiatives in the next decade.

The Geospace Section's leadership of the past decade initiated innovative programs that have demonstrated their value to geospace science and to society. The Section's Space Weather Research and CubeSat programs are among the most outwardly visible of these programs. The CubeSat program was initiated at a time when inexpensive CubeSat missions and frontier science were considered incompatible. And yet NSF's Geospace Section led the charge in demonstrating viability when sound engineering practice is followed, for which it is now recognized as a pioneer in this area. The Section's efforts in forging a National Space Weather Program two decades ago, followed more recently with resources to focus the attention of geospace scientists on problems of significant national importance, are now culminating with the October 2015 release of a National Space Weather Action Plan by the Office of Science and Technology Policy. This action plan elaborates 18 actions for NSF, one with NSF having primary responsibility and seventeen to be undertaken jointly with other agencies. The Geoscience Directorate's Geospace Section is prepared to act, but new resources for space weather research are needed to meet the challenge.

The Geospace Section has been the idea innovator and entrepreneurial incubator for solar and space physics for many years. Will it continue to serve this important role?

The committee of thirteen prominent geospace and solar scientists charged to conduct this portfolio review has been tasked specifically with recommending an optimum, zero-sum distribution of GS investments that will enable significant progress in achieving the 2013 DS science goals in the next decade. In concert with this charge, the committee asserts for the geospace science community that NSF's Geospace Section must continue its crucial role as an entrepreneurial incubator for geospace science. The hard decisions of this review recognize the enormous value of previous generations of cutting-edge measurement techniques that led to many scientific discoveries. Yet this review is about the future of geospace science and about new measurement techniques, new simulation and data assimilation techniques, and new cyberinfrastructure capabilities for data exploitation of the growing database of heterogeneous, multi-scale measurements.

The Portfolio Review Committee (PRC) invites the Geosciences Advisory Committee (AC GEO) and the geospace research community to suspend its impressions of the status quo in reading this report and join the committee in envisioning a vibrant, forward-looking Geospace Section that melds the best current scientific practice with new program innovations to transform our understanding of geospace.

Chapter 2. Review Process and Guiding Principles

2.1 Committee Charge

The following boundary conditions were given to the PRC for its review (see App. A):

- All of the GS-funded activities should be considered together with the Decadal Survey recommendations: Core Programs of Aeronomy, Magnetospheric Physics, and Solar Terrestrial Research, focused programs CEDAR, GEM, and SHINE, elements of the new Space Weather Research & Instrumentation Program (CubeSat, space weather modeling, and other multi-user, space weather-related activities), components of the Geospace Facilities Program, such as the Incoherent Scatter Radar, Lidar Consortium, SuperDARN HF radars, and those activities specifically designed to enhance educational opportunities, diversity, and international participation.
- The review should be forward-looking, focusing on the potential of all funded facilities, programs, and activities for delivering the desired science outcomes and capabilities (while taking into account respective past performances) and considering the value of funded activities in terms of both intellectual merit and broader impacts.
- The review should assume budget scenarios (to be provided by GS) to encompass the period from 2016 through 2025, and consider the costs of (i) continuing the existing observing capabilities and science-funded programs, as well as of (ii) new facilities and programs, including those recommended in the Survey and others the Review Committee may wish to introduce.
- The Committee's deliberations should take into consideration the national and international Geospace Sciences landscape and the consequences of its recommendations for domestic and international partnerships.

With these guidelines, the PRC was asked to construct its recommendations around two themes:

1. Recommend the critical capabilities needed over the period from 2016 to 2025 that would enable progress on the science program articulated in Chapter 1 of the 2013 Decadal Survey for Solar and Space Physics. The recommendations should encompass not only observational capabilities, but also theoretical, computational, and laboratory capabilities, as well as capabilities in research support, workforce, and education.
2. Recommend the balance of investments in the new and in existing facilities, grants programs, and other activities that would optimally implement the Survey recommendations and achieve the goals of the Geospace Section as articulated in the AGS Draft Goals and Objectives Document (including NRC/BASC Review, 2014) and the GEO/Advisory Committee Document "Dynamic Earth: GEO Imperatives & Frontiers 2015-2020" (NSF, 2014). These recommendations may include closure or divestment of some facilities, as well as termination of programs and other activities, and/or new investments enabled as a result. *The overall portfolio must fit within the budgetary constraints provided to the Committee, given as the GS FY 2015 budget of $43.5M, extending out to 2025 with inflation adjustment but otherwise no augmentation.*

The Committee was further instructed to consider not only what new activities need to be introduced or accomplished, but also what activities and capabilities will be potentially lost in enabling these new activities and discontinuing current activities. The PRC was asked to prioritize elements of the recommended portfolio in sufficient detail to enable GS to make subsequent appropriate adjustments in response to variations in Federal and non-Federal funding.

Finally the Committee was asked to consider the effects of its recommendations on the future landscape of the U.S. Geospace community. The recommended portfolio and any changes should be viable and lead to a vigorous and sustainable future. In particular, the Committee should examine how the recommended portfolio supports and develops a workforce with the requisite abilities and diversity to exploit the recommended research and education investments.

2.2 Review Process

The Portfolio Review Committee was appointed and charged in late February 2015. Nominations for the PR committee membership were solicited from the GS staff and, upon identifying the Committee Chair, the GS staff worked with the Chair to identify the membership with the goal that the PR Committee will be highly respected and, to the greatest extent possible, regarded as equitably-constituted and fair-minded, by the broad geospace community.

The assembled committee includes a broad diversity of knowledge across geospace science theory, instrumentation, observation, computation and data. The Committee's research expertise includes aeronomy, magnetospheric physics, solar and solar-terrestrial physics, space weather research and instrumentation (including CubeSats), use of GS-supported facilities, as well as broad knowledge of educational and workforce development activities. The Committee members are in various career stages, balanced by gender, ethnicity, geography, and institution types. They have been vetted against NSF policy for conflicts of interest. A committee size of 12-14 was viewed as manageable while still maintaining the desired diversity.

The committee began holding regular biweekly telecons on March 4, 2015 initially to establish process and to identify key information needed to inform the review. Request for Information (RFI) was first directed to GS program officers to acquire an understanding of the programs and facilities GS currently funds. Each PI of the six Class 1 facilities and six Class 2 facilities[1] funded by GS was requested by GS program officers to provide a narrative or slide overview of their facility, along with information on science highlights, users and publications. This information was made available to the PR committee in late March, 2015.

The committee organized itself into six subcommittees along the lines suggested in its charge: 1) Aeronomy and CEDAR programs; 2) Magnetospheric Physics and GEM programs; 3) Solar-Terrestrial Research and SHINE programs; 4) Space Weather program; 5) GS Facilities program; and 6) Education and Workforce. These subcommittees were tasked by the committee with developing recommendations for consideration by the full committee on critical capabilities needed over the period from 2016 to 2025 that would enable progress on the science program articulated in the DS.

The committee met in person at NSF on April 6-7, 2015 to hear presentations from GS program officers on the scope, organization, administration and budgets of GS programs and facilities. It became clear at this meeting that additional information on the Section’s grants programs, funding

[1] Class 1/2 facilities are defined in Section 7.2.3

rates and facilities would be needed in order to understand current and, most importantly, future capabilities of the GS to make progress on DS science goals. Additional RFIs were submitted to GS program directors.

The committee considered the utility of site visits to key facilities. Since the charge of the PR committee differs from past GS facilities review committees, it opted for a more efficient mode of information gathering by developing targeted RFIs directed to the PI for each facility (Appendix C). Brief written replies were requested, followed by a one-hour telecon interview with each facility PI. The primary objective of this information gathering was to understand the value of each facility in providing critical capabilities needed over the period from 2016 to 2025 that would enable progress on the science program articulated in the DS. Gathering this targeted information on GS facilities took about 7 weeks to complete.

The PR committee also separately interviewed via telecon the Directors of NCAR's High Altitude Observatory, the National Solar Observatory, the Astrophysics & Geospace Sciences program of NSF's Polar Programs (Volodya Papitashvili, who was then acting as Head of the Geospace Section) and the EISCAT. The first three of these programs are sponsored by NSF. The EISCAT Director is responsible for overseeing the EISCAT incoherent radar system and the development of its new facility, EISCAT-3D. Developing recommendations on the science capabilities of these programs and associated facilities was not within the purview of the PR committee, but due diligence nevertheless suggested that the committee should understand the extent to which the scientific capabilities of these programs and facilities may enable progress on the DS science programs. These programs and facilities are sponsored by resources separate from GS. The committee especially wanted to understand the extent to which these other interests might be aligned with those of GS, and whether appropriate synergies might effectively leverage GS resources.

When the bulk of this information was in hand, a second in-person meeting was held at NSF on August 12-14, 2015. The PRC met in executive session during much of this meeting to develop initial recommendations, at times engaging the GS program managers, among them acting GS Head Janet Kozyra, the newly appointed GS Facilities Program Director, John Meriwether, and the AGS Director Paul Shepson for additional information and to clarify future constraints on recommendations.

Development of the written PR report occurred after this meeting. Subsequent weekly web conferences provided the committee with opportunities to refine and agree on its recommendations and coordinate report development. GS staff responded to additional RFIs from the PRC during this period, and this information was used to ensure accuracy of the PRC's findings.

A first draft of this report was delivered to AGS Director Paul Shepson and GS Head Therese Moretto on December 10, 2015 for "fact checking" by GS staff. Recommended corrections from GS were submitted to the PRC on January 9, 2016. A final draft was then developed by the PRC and delivered to AC/GEO on February 5, 2016.

2.3 Community Input

Announcement of the Portfolio Review and invitation to the Geospace Research community to provide input to the review via a special email address[2] were posted in all relevant community electronic newsletters and in the AGU journal Space Weather. The period for comment was

[2] geoagsgsportfolio@nsf.gov

provisionally posted as 60 days, from March 30, 2015 through May 29, 2015[3], but a soft deadline was imposed, and the committee accepted comments throughout June and July. The solicitation requested comments be limited to two pages or less, which was mostly followed in the responses. Announcement of the portfolio review and solicitation for community input was also made by the GS Acting Head, Volodya Papitashvili, at the annual Space Weather Workshop held in Boulder, CO on April 13-17, 2015.

Three Town Hall meetings were held at the NSF-sponsored GEM, CEDAR and SHINE summer workshops the weeks of June 14, June 21 and July 6, respectively. Several committee members participated in GEM and CEDAR Town Halls. Only one member of the committee was able to lead the SHINE Town Hall. One or more of the GS Programs Directors, the Acting GS Head and the AGS Division Director were also present at the Town Halls. Spirited discussions ensued at these open forums and many viewpoints were publically expressed and discussed by members of the community.

The solicitation for email comments yielded 47 written responses (with 62 signatories) that spanned all GS program elements. Each committee member was asked to read all email responses.

Figure 2.1. Wordl cloud of the most frequently used words in the 45 email comments received from the geospace research community. Size of a word in the cloud is a measure of its frequency of use. Some authors use a given word many times, so frequency of use in the concatenation of comments differs from the number of separate responses that use a given word at least once.

The written comments were analyzed to find common ideas. A first review searched for common threads and concepts in each of the 47 responses. As expected, a thread associated with Decadal Survey recommendations was pervasive. Equally dominate was a thread promoting system science or a system view of geospace. Space weather, science from incoherent scatter radars, and education of the next generation of geospace scientists were also common threads.

Because a common-idea search has a degree of subjectivity, a second objective analysis employing a computerized search for common words via the WORDL app was developed by submitting a concatenation of all email comments to http://www.wordle.net//. The result is an impression of

[3] http://www.nsf.gov/geo/ags/geospace-portfolio-review-2015/index.jsp

community input in the form of a word cloud as shown in Figure 2.1. In this graphical histogram the most repeated words are in the largest font. From such a graphic, one could conclude that the white paper respondents believe that: *NSF [should] provide new facilities, data, measurements [and] observations [to] support community research in geospace, atmosphere and solar science.*

The committee's more detailed review of the email comments grouped them into 4 broad themes (# indicates count): GS management and process (11); programmatics other than facilities (13); existing facilities, observatories and infrastructure (19) and new facilities, observatories and infrastructure (17). Some comments addressed multiple themes.

Themes within each category included:

1. <u>GS management and process</u>: GS funding priorities and review process (7); advocacy for a periodic senior review process (5); advocacy for a CubeSat program review (1).
2. <u>Programmatics other than facilities</u>: Strong advocacy for CEDAR, GEM and SHINE programs (4); advocacy for cross-cutting, system science and cross-agency science (4); advocacy for the Faculty Development in Space Science program (1); advocacy for the CubeSat program (1).
3. <u>Existing facilities, observatories and infrastructure</u>: Strong advocacy for incoherent scatter radars (7), but also concerns that ISR goals are fragmented and introspective (3) and some ISRs are no longer producing frontier science (1); advocacy for existing and new distributed ground-based observatories, synoptic observations and their data products (8).
4. <u>New facilities, observatories and infrastructure</u>: Advocacy for HAARP, a new Coronal Mass Ejection radar, magnetometer observatories as a component of the GS facilities program, neutron monitors, a pole-to-pole Fabry-Perot interferometer chain and a very large-aperture LIDAR observatory (11); advocacy for the FASR and COSMO solar facilities mentioned in the DS (3); and advocacy for use of advanced informatics in developing GS data products (3).

These thoughtful responses, the many comments made at the three Town Halls and individual exchanges among PRC and community members informed the PRC's considerations and recommendations.

2.4 Guiding Principles

In developing recommendations for portfolio investments over the next decade, the PRC adopted the following principles:

Enable discoveries that transform our understanding of geospace. Discoveries in aeronomy, magnetospheric physics, solar-terrestrial physics and science applicable to space weather will continue unabated in the next decade, but, as indicated in the 2012 Decadal Survey, the importance of integrative geospace science will become increasingly prominent and inform future directions of disciplinary investigation and discovery. Thus the portfolio must 1) maintain state-of-the-art instrumentation, facilities and computational models that enable discovery in new physical regimes and new understanding of system-level behavior; and 2) include program elements that promote synthesis and integration of new disciplinary knowledge. Geospace science underpins important applications in space weather, and its trajectory must remain aligned with national needs in determining and predicting the impacts of space weather.

Align GS investments with decadal science goals. The Survey's top-level science goals are the primary touchstones for this review and the basis for the PRC's recommendations for a balanced GS portfolio. Throughout its evaluation process, the PRC avoided revisiting or modifying the Survey's science goals, which represent a broad consensus of the 85 solar and geospace scientists of the GS community that participated in the review. The Survey's recommended investments in facilities and programs relevant to NSF, at face value, exceed the current outlook for budget capacity of GS for the next decade. Consistent with its charge, this review strives to identify and prioritize the critical capabilities that *will enable progress* on the science program articulated in Chapter 1 of the Survey.

Achieve balance across the entire portfolio of activities. To maximize progress on the Survey's science program, GS investments must strike a balance across its science thrusts and among investments in infrastructure and facilities, workforce, core and targeted grants programs, and disciplinary and integrative program elements. These investments must continue to support time-tested and highly refined observational and modeling approaches while creating space for novel and sometimes unanticipated approaches and measurement techniques. The portfolio recommended for the next decade strives to achieve an optimal balance among these program objectives.

Maintain flexibility in adapting to new capabilities. Infrastructure for facilities and programs requires considerable time and resources to develop and maintain, and its value in ongoing scientific investigation is undeniable. However, when the cost of maintaining longstanding infrastructure and programs undermines the field's ability to pursue new opportunities for innovative science, the value proposition for the status quo may reach diminishing returns. In some cases, modest investments in existing facilities may improve the performance and sensitivity of the measurement techniques or even add important new capabilities. Understanding the trade space for new investments, reinvestments or upgrades and divestments is a crucial aspect of this review. Optimization of this trade space is essential in maintaining a flexible portfolio in a flat-budget environment.

Leverage GS investments. The Geospace Section is one of many US sponsors of solar and space physics research, but it has chosen to invest in program elements and facilities that are unique and complementary to those sponsored by other entities. Some of these investments are also complemented by similar investments by non-US sponsors of solar and space physics research. The scientific return on GS investments has been and should continue to be leveraged through resource sharing among broader NSF, commercial, cross-agency and international partners. In determining how to maximize progress on the Survey's science program, this review looked for nascent or existing synergies within the extended non-GS community that might allow more effective use of limited GS resources.

Value peer-reviewed competition. Peer review in awarding grants is a time-honored process for finding the best investments in science. This principle was central to the PRC's considerations of new program elements that would enable progress on the science program articulated in the Decadal Survey and how GS could best fund new modes of research, facility and model upgrades, and new instrumentation and instrument networks.

Promote open access to data and data standards. Open access to scientific data derived from an NSF grant is now a requirement. However, open access policies do not necessarily specify requirements for timeliness of access or usability of the data. Raw (level 0) data are straightforward to archive, but they are rarely usable without additional processing by instrument, model and/or data specialists. Making data open *and* readily usable by anyone with access to the data servers has enormous leveraging power in the scientific enterprise. Scientific investigations sponsored by non-GS resources significantly augment the scientific knowledge derived from GS-sponsored data. Although some GS program activities have been moving in this direction for some time, new program elements that direct modest GS resources to the development of higher level and more useable data products have the capacity to accelerate progress on the science program of the DS.

Provide excellent training and career opportunities. The quality of scientific achievements depends crucially on the intellectual capacity, creativity and dedication of participating scientists. Preparing the next generation of geospace scientists to discover and apply new knowledge in the field and preparing them for a broad range of career options are essential in maintaining the vitality of geospace science.

Inspire and inform public interest. The subtitle of the 2013 Decadal Survey, "A Science for a Technological Society", emphasizes the role and importance of geospace science in the national interest. To borrow recently publicized language from the US House of Representatives Science Committee, "funding priorities must ensure that America remains first in the global marketplace of basic research and technological innovation. Investments in basic research can lead to discoveries that change our world, expand our horizons and save lives." Public interest in geospace science depends crucially on our ability to provide clear, non-technical explanations of research projects that detail how each project meets intellectual merit criteria, is consistent with NSF's mission, and supports the national interest. All GS program elements must encourage participating scientists to communicate 1) the excitement of new discoveries in geospace science, enabled by state-of-the-art instrumentation and technology, and 2) the value to society of applicable geospace science leading to advances in prediction and understanding of the impacts of space weather and in understanding the influence on climate of downward coupling from geospace to Earth's atmosphere.

Promote transparency. Trust and understanding flow from transparency. The PRC strives to be transparent in this review. Portfolio review recommendations regarding management of NSF resources for geospace science aim for the same transparency from the Geospace Section.

Chapter 3. Budget Overview and Projections

3.1 Budget Summary for Current GS Portfolio

The GS portfolio has three primary science thrusts – Aeronomy (AER), Magnetospheric Physics (MAG) and Solar and Solar-Terrestrial Research (STR) – and a Space Weather Research (SWR) program, which spans and, to some extent, integrates across the three primary thrusts. The primary science thrusts include a core research program and a targeted research program in each area. The targeted programs include the Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) program, the Geospace Environment Modeling (GEM) program and the Solar, Heliospheric and Interplanetary Environment (SHINE) program. The NSF/DOE Partnership in Basic Plasma Science and Engineering is funded through one or more of the core programs.

The SWR program, as currently configured, is an umbrella administrative structure with responsibility for the NASA/NSF Collaborative Space Weather Modeling Program (SWM), a CubeSat program, the Faculty Development in Space Sciences (FDSS) program and Class 2 geospace facilities. It does not have a core research program, and its overall funding is small (13%) compared to the primary science and Class 1 facilities programs.

Class 1 facilities (see Section 7.2.3) include six incoherent scatter radars: Arecibo, Jicamarca, Millstone Hill, PFISR, RISR-N and Sondrestrom. Class 2 facilities (Section 7.2.3) include SuperDARN, AMPERE, SuperMag and the Community Coordinated Modeling Center (CCMC). A collaborative PI-led research project, the Consortium of Resonance and Rayleigh LIDARs (CRRL), is also funded by the GS Facilities program.

The budget allocations for these program elements are shown in Figure 3.1. The total GS budget for FY15 is $43.56M. The PRC was charged to assume that GS budgets would be flat out to 2025, capped at the FY15 value, with allowance for inflationary increases in future budgets.

3.2 Budget Implications of DS Recommendations

Chapter 5 of the DS offers specific guidance to NSF in implementing recommendations relevant to geospace science. DS Chapter 4 also concludes that maintaining and growing the basic research programs at NSF (and at NASA, AFOSR and ONR) are needed for a more effective transition from basic research to space weather forecasting applications, although no specific budget guidance is provided regarding growth. These recommendations have budget implications for NSF, some explicitly stated, others implied. Specific budget recommendations are listed below, along with PRC estimates (denoted with '?')

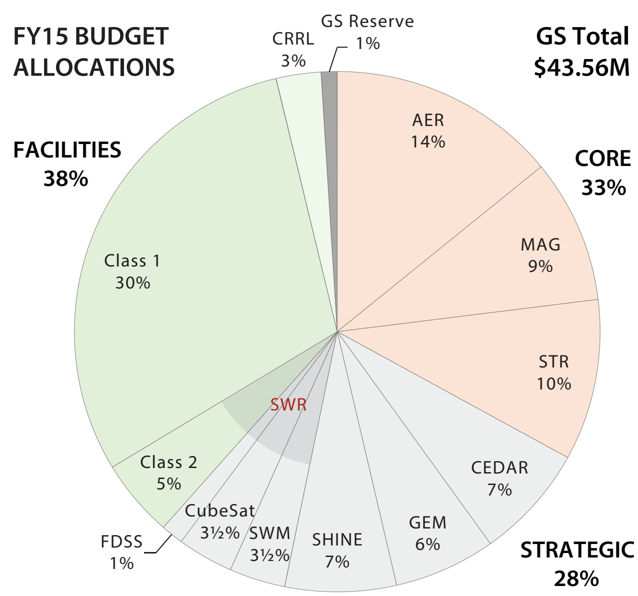


Figure 3.1. FY15 GS budget allocations for Core, Strategic and Facilities program elements.

for DS recommendations that did not specify target funding levels.

– Support key existing ground-based facilities and complete programs in advanced stages of implementation, e.g., RISR, PFISR, Sondrestrom, Millstone Hill, Arecibo Observatory, Jicamarca, SuperDARN | NRAO, WSO, NSO SP/KP, SFO, BBSO, MLSO, NSO DKIST (formerly ATST). The facilities after "|" are funded by NSF and other programs outside the Geospace Section and are not included in its FY 2015 of $43.6 M. But as discussed in Chapter 6 and 8, they are important data sources for solar and geospace science. In a flat-budget scenario, this recommendation implies, at face value, that the GS continue all of its existing programs and facilities, with a budget of *$43.6M per year* in 2015 dollars if none of recommendations for new facilities or programs listed below were to be implemented.

– Data Exploitation: Maintain and develop, as necessary, systems for accessing, archiving, and mining synoptic and long-term data sets, especially to facilitate synergies between ground- and space-based observations (*$0.5M per year?)*

– DS recommendations emphasize the importance of NSF in providing the DKIST with base funding sufficient for operation, data analysis and distribution, and development of advanced instrumentation for the DKIST in order to realize the scientific benefits of this major national investment. (It is not clear if this recommendation is addressed specifically to the AST or the AGS Division. DKIST is currently being developed by NSO and will managed by NSO with base funding from AST when it becomes operational.)

– Midscale project line for SSP (*$4-30M, e.g., a $30M project funded at $5-6M per year over 5 years or smaller midscale projects funded more frequently*).

– CubeSats ($2.5M per year, an augmentation *of $1M per year*)

– International collaborations, e.g., EISCAT-3D (*$1M per year?*)

– Multidisciplinary research: Encourage research that falls between NSF sections, divisions, and directorates. Implement "Heliophysics Science Centers" @ $1-3M per year for each center (e.g., NSF contribution to 1 or 2 centers at *$2M? per year*)

– Maintain and grow the SW research program (+*$1M per year?*)

– Education: Continue the GS program for Faculty Development in Space Sciences (FDSS) and support development of a complementary curriculum program. Four-year institutions of higher education should be considered eligible for FDSS awards as a means to further broaden and diversify the field. Maintain the various summer school offerings supported by NSF (as currently funded).

Guidance to NSF from the DS in implementing GS-relevant recommendations *imply an estimated budget augmentation above the current level of about $11M per year, a 25% increase.* Given its charge, the PRC was faced with 2 GS scenarios: Recommend a status quo program at $43.6M (i.e., complete the current program) or maintain a subset of the most productive, existing facilities and programs and phase-out or reduce funding for less productive elements to make room in the flat budget for new or augmented program elements and facilities. The PRC charge to recommend the critical capabilities needed over the period from 2016 to 2025 that will enable progress on the science program articulated in the DS was applied in deciding between these two scenarios.

3.3 Future Impacts of Past GS Budget Trends

Teasing out objective GS budget trends from 1999 forward is complicated by the addition of new programs and facilities (particularly Class 2) during this period. In some cases, the facilities and programs were initially funded either separately or jointly by base programs and then later were administered by the Space Weather Research (SWR) program created in 2013. In 2015, about 25 - 33% of the budget allocated to the SWR program supports clearly differentiated space weather activities (SWM), with this fraction being augmented by investments in Class 2 facilities and the CubeSat and FDSS programs, some portion of which supports space weather research. The budgets for these various program elements are kept in the SWR program primarily for administrative purposes. The PRC does not question the administrative utility of this organization, but it does note that this arrangement provides less than optimum transparency. As discussed in Chapter 7 on GS Facilities, funding for facilities and research is also somewhat blurred by the fact that research funding is embedded within awards to operate and maintain (O&M) facilities. Thus caution should be exercised in rigidly interpreting past GS budget trends. Nevertheless, the PRC identified several trends that, if continued, will impact GS capabilities to enable future progress on the science program of the DS.

1. The GS budget has been relatively flat for at least a decade when the bump from the American Recovery and Reinvestment Act of 2009 (ARRA) is subtracted in Figure 3.2. GS has added new programs and facilities during this time without terminating existing programs.

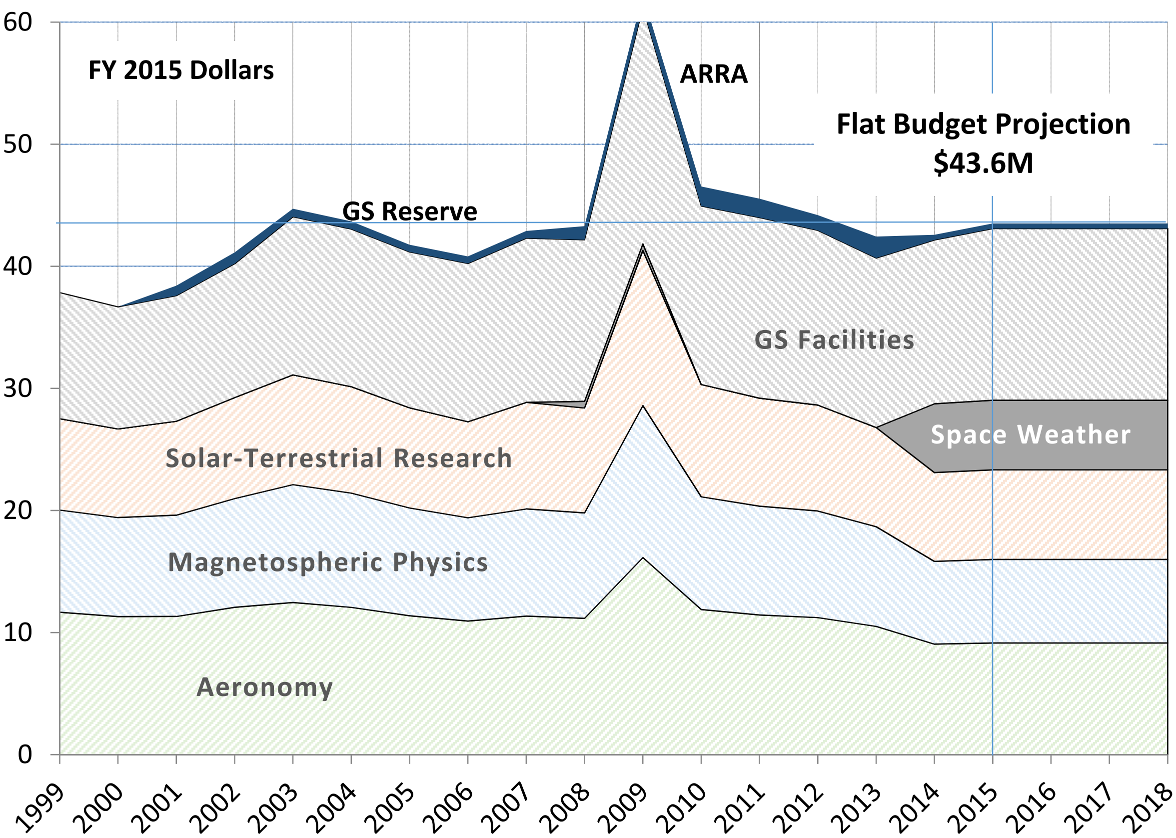


Figure 3.2. GS Budget from 1999 to 2015. Projected budgets are flat in FY 2015 dollars. The Space Weather Research program was created in 2013 from an amalgamation of existing program elements, such as FDSS and CubeSats, and activities that were previously funded via base programs.

This trend suggests that GS has adapted its funding strategies to the growing aspirations of the geospace science community. This practice tends to squeeze funds for all programs.

2. Funding for science grants administered by the combined core and targeted programs of AER, MAG and STR has been progressively decreasing. In the past, funding streams for facilities and grants programs were fairly distinct. The advent of Class 2 facilities, which were not in the GS facilities budget, has blurred this distinction. Education and workforce development previously and currently are accomplished by sponsoring students and postdocs via the base grant programs. Today, however, whole new GS program elements such as FDSS and CubeSats augment support for this core aspect of NSF's mission.

3. The number of GS facilities (Class 1 and 2) has increased over time. The budget for GS facilities has also increased over time but not necessarily at a rate needed to maintain the state-of-the-art in technical and scientific capabilities of the facilities. Adding new facilities while continuing to operate older facilities in a flat-budget environment requires reductions in other programs or sub-optimum funding of maintenance, operations and upgrades of GS facilities. This situation has been exacerbated by the redistribution of cost-sharing for M&O of Arecibo Observatory between AST and AGS. The GS investment in AO increased from $1.8M in FY 2008 to $4.1M in FY 2016, amounting to 32% of total AO funding at this time.

The PRC finds these trends to be problematic for achieving leading-edge science in the next decade. Future impacts include fewer or smaller grants for scientific investigations and a likely inability to advance facilities, instruments and simulation models to maintain the state-of-the-art in experimental, observational and modeling science. On the plus side, GS has improved its capacity for education and workforce development. However, a greater number of emerging researchers are now chasing diminished funding opportunities. Furthermore, GS does not have adequate resources to allow its research community to pursue new, innovative methodologies and observational techniques. These issues indicate that the status quo in the GS program cannot provide the critical capabilities to enable optimal progress on the science program articulated in the DS.

3.4 Additional NSF Investments in Geospace Science

The PRC reviewed NSF investments in programs and facilities external to AGS that also contribute to the advancement of geospace science. These programs include:

– National Solar Observatory (NSO): The AST division funds facilities administered by NSO at $13M per year. These facilities include the Dunn Solar Telescope and the Evans Solar Facility both on Sacramento Peak (phasing out by 2019), a special facility for Synoptic Optical Long-term Investigations of the Sun (SOLIS) and the McMath-Pierce Solar Telescope (recommended for divestment in 2017 by the 2012 AST portfolio review) both on Kitt Peak, the distributed Global Oscillation Network Group (GONG) and the Daniel K Inouye Solar Telescope (DKIST) with design and implementation funded by an MREFC grant with operations expected to begin in 2019. NSO also hosts a number of smaller solar observing projects and programs with AST support. The AST also supports the National Radio Astronomy Observatory (NRAO), which operates the Very Large Array (VLA), and the Green Bank Solar Radio Burst Spectrometer. The AST portfolio review noted that these facilities are joined by five public/private solar observatories, of which the Big Bear Solar Observatory (operated by New Jersey Institute of Technology) possesses the largest telescope (the New

Solar Telescope, or NST, a 1.6-meter off-axis clear aperture telescope with adaptive optics), but, as independent observatories, all have somewhat fragile funding streams. The PRC learned that grants to use data from these facilities for solar science is funded largely by the STR program of GS. Consequently, coordination between AST and AGS program officers is crucial in achieving the solar science and space weather programs advocated by the DS.

- High Altitude Observatory (HAO): The AGS cooperative agreement with the University Corporation for Atmospheric Science (UCAR) funds the National Center for Atmospheric Research (NCAR), and NCAR's FY 2015 budget included $6.2M for a variety of science activities at HAO. HAO operates the Mauna Loa Solar Observatory (MLSO) and supports a solar instrumentation group. A substantial portion of its budget supports research into long-term solar variability, solar transients and space weather, and geospace science (upper atmospheric, ionospheric and magnetospheric science). NCAR's Computational Information Systems Laboratory (CISL) operates the Yellowstone supercomputing facility and makes available to qualified NSF awardees high-performance computing allocations on this major facility.
- Division of Polar Programs: This separate division with the Geosciences Directorate sponsored Antarctic Atmospheric and Geospace Science (AAGS) in FY 2015 at $2.9M. It supports operations for two of the SuperDARN HF radars in the southern hemisphere along with instrument development, deployment, operation and science from an array of ground-based instruments on the Antarctic continent, including riometers, magnetometers, VLF/ULF receivers, all-sky cameras, gravity wave imagers, a Fabry-Perot Interferometer, an Fe-Boltzmann LIDAR and a neutron monitor.
- Cross-agency Programs: The Geospace Section has benefited from a variety of cross-agency funding opportunities. Substantial funding for interdisciplinary Geospace research been obtained through the EarthCube, Frontiers in Earth System Dynamics (FESD), Interdisciplinary Research and Education (INSPIRE), and Major Research Instrumentation (MRI) programs.

These additional facilities and programs augment the science accomplished with AGS investments. However, AGS does not control the budget allocations to or within these independent programs.

Chapter 4. Capabilities for a Vital Profession

Many factors enter an assessment of the vitality of geospace science as a profession. Two of the most important are the quality of the workforce and the resources available for frontier research. Advancing scientific knowledge requires innovative thinkers who bring a broad range of ideas and different perspectives to bear on key problems. NSF has a longstanding commitment to broadening participation in its programs for greater diversity. Many advantages accrue to organizations with a diverse workforce. In scientific endeavors diversity in the workforce brings diversity in scientific perspectives and approaches and, therefore, it broadens the pool of ideas for advancing science. In assessing capabilities for a vital profession, data on diversity have been included when such data are available. The very act of acquiring and posting data on diversity will usually encourage the program doing so to broaden its demographics of qualified participants.

4.1 Proposal Pressure

A review of the vitality of the profession starts with an assessment of the funds available to investigators to conduct the highest quality research. Common metrics typically include the fraction of highly ranked proposals in the annual pool of submissions, the likelihood that a highly ranked proposal will be selected and the average budget of an award relative to the average proposed budget. All of these factors influence what is commonly termed “proposal pressure”.

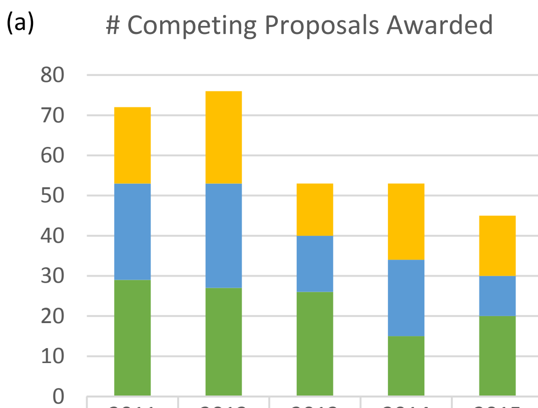
The GS budget has been relatively constant (in inflation-adjusted dollars) with less than 5% variation since 2003, with the exception of fiscal years 2009-2014 (Figure 3.2). The pulse of temporary funding from the American Recovery and Reinvestment Act of 2009 (ARRA) produced a 46% distortion in the budget in 2009 that did not fully subside until 2014 when all ARRA-funded projects were completed. This cash inflow significantly inflated the number and amount of GS awards, which complicates a longitudinal analysis of the GS grants profile in terms of number and size of awards.

The Geospace Section provided aggregated grant data from the NSF Office of Budget, Finance and Award Management (OBFAM) for the Aeronomy (including CEDAR), Magnetospheric Physics (including GEM) and Solar-Terrestrial Research (including SHINE) programs. The number of competing proposals awarded by fiscal year, the mean duration of the awards, the total of all obligated awards, and the annualized mean $ value of awards for proposal actions in the fiscal years 2011-2015 are given for each program in Figure 4.1. Grants for conferences are not included in these data, and *projects involving two or more proposals from participating collaborators are counted as one proposal and award by OBFAM in all data in the figure*.

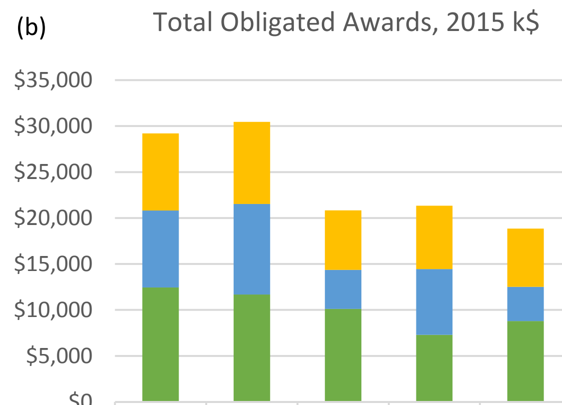
The precipitous drop in # competing proposals awarded and in total obligated awards in 2013 (Fig. 4.1a,b) are due mainly to a redirection of awards for Space Weather Modeling, AMPERE, SuperDARN, SuperMag, CCMC, CubeSats and FDSS into a then newly created SWR program (see Figure 3.2) that were previously funded from the core plus targeted (CEDAR, GEM, SHINE) grants programs. With this reprogramming the Section was able to provide a more transparent accounting of the actual funds available in the grants programs

Several trends emerge from these data.

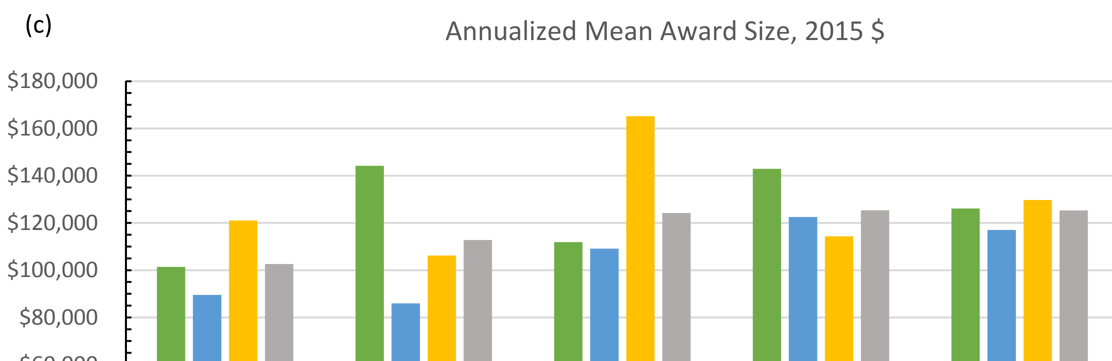
1. The number of core plus targeted GS grants awards has been progressively decreasing, even in the years after the redirection of projects into the SWR program. From 2013 to 2015 both the total value of obligated awards and the number of awards decreased by about 15%.



	2011	2012	2013	2014	2015
STR	19	23	13	19	15
MAG	24	26	14	19	10
AER	29	27	26	15	20



	2011	2012	2013	2014	2015
STR	$8,401	$8,926	$6,475	$6,895	$6,330
MAG	$8,374	$9,863	$4,246	$7,146	$3,714
AER	$12,436	$11,672	$10,119	$7,298	$8,798



	2011	2012	2013	2014	2015
AER	$101,388	$144,234	$111,874	$142,908	$126,130
MAG	$89,549	$85,937	$109,118	$122,504	$117,025
STR	$121,012	$106,224	$165,230	$114,320	$129,696
GS	$102,620	$112,787	$124,233	$125,345	$125,295

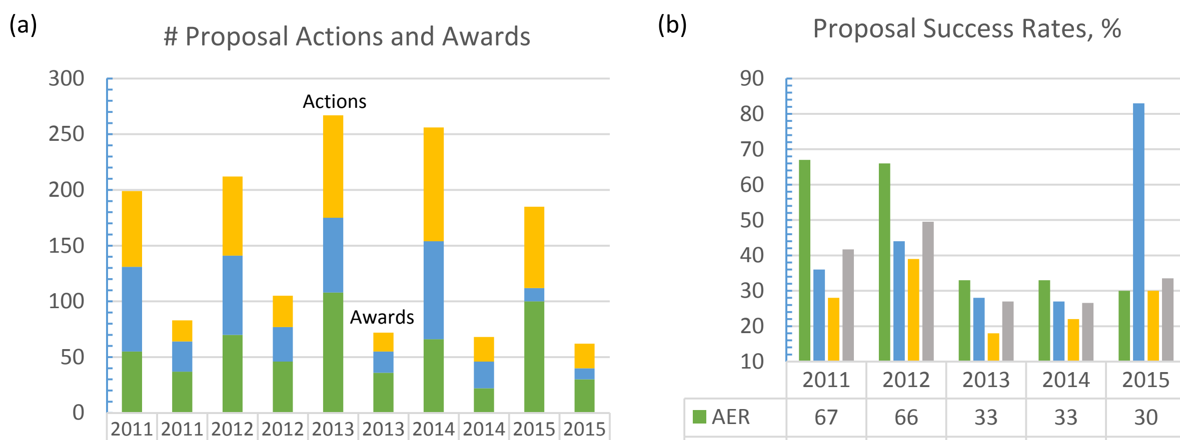
Figure 4.1 GS grant funding by program and overall for 2011-2015. All data refer to proposal actions in the fiscal year that resulted in an award. (a) Number of competing proposals awarded. (b) Total obligated awards is the total obligation value of all awards including all years of the awards in CPI inflation-adjusted dollars x 1000. (c) Annualized mean award size is the mean of annualized award sizes including all years for each in CPI inflation-adjusted dollars. CPI factors used for inflation adjustment: 1.04 (2011), 1.02 (2012), 1.01 (2013) and 0.99 (2014) of OBFAM data.

2. The annualized mean award size for GS overall has been essentially flat from 2013 onward and is larger than the mean size in 2011 and 2012.[4] This stability in award sizes after 2012 can be traced to the fact that the number of awards and the total award obligations have been decreasing in tandem during that time. The increase in mean award size after 2012 is due in part to an increase in the number of large collaborative projects with multiple investigators. The award

[4] In fact, the total mean obligation per award for these combined grants programs (Total obligated awards/Number competitive awards) has been essentially flat at $406k ± 3% in inflation-adjusted dollars from 2011 to 2015.

size for these projects is typically greater than for a single PI research grant. Thus even though the award to individual PIs or individual CoIs in collaborative projects may be decreasing, OBFAM's practice of counting a collaborative project as a single grant records a larger mean grant size.

Data for proposal success rates in GS disciplinary programs are given in Figure 4.2 for FY 2011-2015. As in Figure 4.1, conference proposals are not included in these data. *In determining success rates, separate proposals that are part of collaborative projects are counted in the number of proposal actions and awards.* Thus the basis for success rates in Figure 4.2 is larger than the basis OBFAM uses to calculate mean award sizes, duration, etc. in Figure 4.1. (Compare # awards in Fig 4.2 to that in Fig. 4.1.) The PRC was unable to obtain data from NSF that uses the same basis for number of competitive awards in the calculations of mean award sizes and duration and in proposal success.[5] The basis for the data in Figure 4.2 is representative of the success rate individual PIs can expect regardless of whether their proposal is a single-investigator project or a large multi-investigator collaborative project. However, to the PRC's knowledge the success of large collaborative proposals relative to smaller single-PI proposals has not been studied.



	2011	2011	2012	2012	2013	2013	2014	2014	2015	2015
STR	68	19	71	28	92	17	102	22	73	22
MAG	76	27	71	31	67	19	88	24	12	10
AER	55	37	70	46	108	36	66	22	100	30

	2011	2012	2013	2014	2015
AER	67	66	33	33	30
MAG	36	44	28	27	83
STR	28	39	18	22	30
GS Avg	42	50	27	27	34

Figure 4.2. Number of GS proposal actions, awards and proposal success rates for competing proposals acted on in 2011-15. All data refer to proposal actions in the fiscal year that resulted in an award. (a) Number competing proposal actions is the number of decisions on competitive proposals made in the given fiscal year regardless of the year the proposal was submitted. This number includes carryover proposals from a previous fiscal year that are decided in the current fiscal year, but it does not include proposals that are submitted in the current fiscal year and that are decided in a future fiscal year. Number of awards is the number of actions in the fiscal year that result in a funded proposal. (b) Success rate is the ratio of awards to actions in the fiscal year.

Two observations are made:

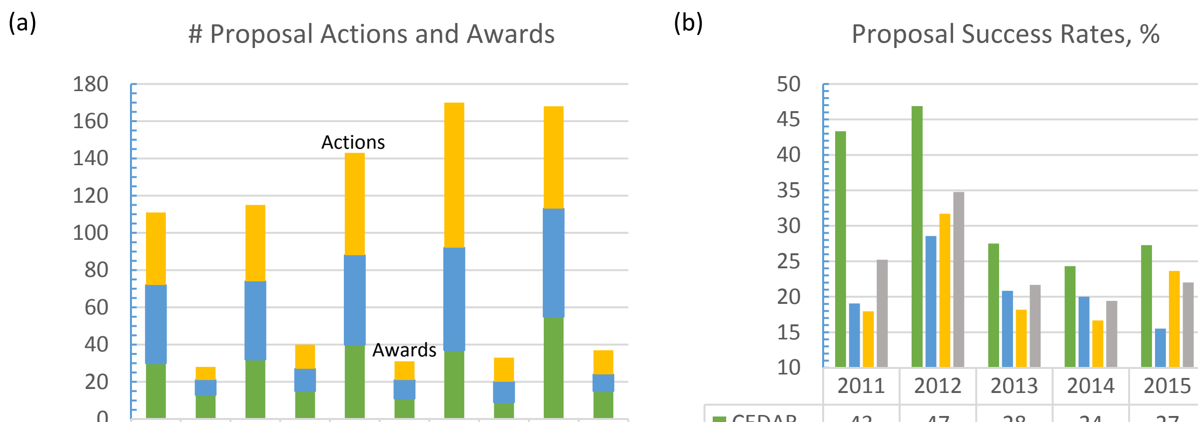
1. The unusually large uptick in success rate from 2014 to 2015 in the MAG program, with a modest uptick in GS overall, was due to short staffing in the Section in 2015. Although the bulk of MAG awards were processed in FY15, the declines were held until FY16, thus distorting the

[5] Suggestions for improving NSF's data collection for its grants programs are included in Section 9.6

fiscal year success rate. (Compare proposal actions for MAG in 2015 with the number in previous years.)

2. It is not entirely clear why the success rate decreased so much from 2012 to 2013. The proximate cause is the increase in the number of proposals submitted, with the average number submitted in 2013-2014 being ≈ 25% larger than the average in 2011-2012. An additional factor may be due to the transition of Class 2 facilities projects (to be discussed in Chapter 7) out of the core plus targeted programs into the new SWR program in 2013. Since facilities proposals have little-to-no competition, including them in the base programs probably produced some inflation, however modest, in success rates in 2011 and 2012. The ARRA bump (Figure 3.2) may have also temporarily reduced proposal pressure on grant program funds during the immediate post-ARRA years, with more typical proposal pressure starting to return in 2012.

Success rates have been even lower in the GS targeted grants programs (CEDAR, GEM, SHINE), which receive more than 50% of proposals to the GS grants programs (Figure 4.3). The proposal deadlines imposed on targeted grants programs may unintentionally encourage a higher rate of submissions.[6]



	2011	2011	2012	2012	2013	2013	2014	2014	2015	2015
SHINE	39	7	41	13	55	10	78	13	55	13
GEM	42	8	42	12	48	10	55	11	58	9
CEDAR	30	13	32	15	40	11	37	9	55	15

	2011	2012	2013	2014	2015
CEDAR	43	47	28	24	27
GEM	19	29	21	20	16
SHINE	18	32	18	17	24
Targ Avg	25	35	22	19	22

Figure 4.3. Number of GS proposal actions, awards and proposal success rates for competing proposals submitted to the CEDAR, GEM and SHINE targeted grants programs and acted on in 2011-15. The proposal basis and analysis are similar to those in Figure 4.2.

Many factors are at play in interpreting the data in Figures 4.1 – 4.3: Standard vs continuing awards; linked proposals vs sub-awards for collaborative projects; level of prior commitments from awards growing in the out-years; and delays in proposal processing due staff shortages. Large year-to-year oscillations tend to obscure trends.

A strategy for optimizing science advancement through the grants programs, in particular, for enhancing progress in achieving the science goals of the Decadal Survey, does not reveal itself in these data alone. The PRC did not acquire data on proposal quality (rankings). Highly ranked

[6] Report to the National Science Board on the National Science Foundation's Merit Review Process, Fiscal Year 2014 (NSB-2015-14) p. 48-49, Table 16. (http://www.nsf.gov/nsb/publications/2015/nsb201514.pdf).

proposals may be the most meritorious for selection, but the proposal ranking does not necessarily translate to quality of scientific advancement.

Several tensions are at play in the GS grants programs when the grants budget is flat or declining as in FY 2013-15:

1. Engaging the greatest number of researchers who submit highly ranked proposals increases the diversity of scientific ideas and new results and the likelihood of scientific breakthroughs. The number of PIs funded by the program can always be increased by decreasing the average grant size.
2. But when the average grant size does not fully fund the PI's proposed work, or only a portion of the PI's available time for research, the PI typically must develop and submit additional proposals to NSF or elsewhere. The effort in preparing additional proposals reduces the PI's research productivity. With more proposals chasing limited funding, the additional time researchers devote to the proposal peer review process also diminishes average productivity. [7]
3. PIs have a tendency to submit 'safe' science proposals when success rates are low and reviewers have a tendency to recommend them over high-risk, high-reward proposals.
4. The PIs', CoIs' and reviewers' efforts account for most of the cost in preparing and evaluating a proposal submitted to a funding agency.[8] As grant success falls, and proposal numbers increase, the community's overhead in seeking funding increases markedly.
5. Some misalignment in funding among sub-disciplines may be at play in the GS aggregate awards and success rates. The number of scientists affiliated with Space Physics and Aeronomy sections of AGU for 2015[9] were (primary/secondary affiliations) 262/874 for Aeronomy, 713/2477 for Magnetospheric Physics and 745/1811 for Solar and Heliospheric Physics, yet the GS historically has invested proportionally more resources in its Aeronomy and CEDAR grants program than in its other grants programs (less so in 2014 in Table 4.1). Some care must be exercised in interpreting these numbers, however, because if more support is available for Magnetospheric and Solar-Terrestrial research at other agencies, especially NASA, then the current number of scientists conducting research in these areas may be correspondingly larger. Comparable funding portfolios from other agencies were not available to the PRC.
6. Finding an optimum balance between the average value of a research award, the number of proposals awarded and highest scientific return for a given budget and population of researchers certainly deserves further study by social scientists.[10] The problem is compounded when multiple funding agencies are involved, e.g., changes in grant award policy for geospace science at NASA impacts submissions at NSF and vice versa.

This analysis of the grant portfolio is an important aspect of due diligence of the portfolio review. The PRC has no recommendations to offer on this complicated issue and concludes its

[7] P. Cushman et al. (2015). Impact of Declining Proposal Success Rates on Scientific Productivity, draft AAAC report at http://www.nsf.gov/attachments/134636/public/proposal_success_rates_aaac_final.pdf

[8] T. von Hippel and C. von Hippel (2015). To Apply or Not to Apply: A Survey Analysis of Grant Writing Costs and Benefit, http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0118494

[9] http://spa.agu.org/spa-section-newsletter-volume-xxii-issue-71/

[10] NSF Report on Efficiency of Grant Size and Duration at http://www.nsf.gov/pubs/2004/nsf04205/mathematica_nsfrptfinal6.pdf

analysis with the following finding:

Finding. *Total award obligations in the core plus targeted grants programs have progressively decreased in the past five years, most markedly from 2012 to 2013. GS program managers have adapted to the reduced investment in these programs by accepting lower proposal success rates on average so as to maintain a more or less constant total mean obligation per award (Total obligated awards/Number competitive awards) irrespective of award duration.*

The PRC finds the decision to maintain healthy award sizes in inflation-adjusted dollars, even though it has the undesirable effect of reducing proposal success rates when the overall budget is flat or declining, to be preferable to reducing award sizes so as to maintain higher proposal success rates. In this regard, the GS has recently been bucking an NSF-wide trend wherein the average number of months of salary support per grant decreased by roughly 50% from 2002 to 2014.[11] Recommendations for increasing the relative investment in GS strategic grants programs are offered in subsequent chapter.

4.2 FDSS and CAREER Awards

Important exceptions to the erosion of grant sizes are the FDSS and CAREER awards, which are designed to enhance, and fully support, a new faculty line in a college or university (FDSS), or a major multi-year grant to an early career scientist (CAREER). These programs are extremely effective in allowing the recipients to develop a respectable research profile (and earn tenure) and subsequently to be more competitive in securing sponsored research funds. The number of awards in these programs is limited, but they make a huge difference in the lives of the recipients. The faculty hiring and tenure process in universities is usually very effective in ensuring that award recipients meet high professional and scientific standards.

Finding. *An FDSS announcement of opportunity has been offered twice, in 2005 and 2014. Eight FDSS awards have been made (Table 4.5) and all but two professors were tenured. One of the appointments left before achieving tenure but was replaced with a tenured professor; another one did not pass tenure evaluation. More importantly, this program has helped two institutions achieve a "critical mass" of researchers.*

Table 4.5. FDSS Awardees

Demographic	Number awarded	Now tenured
Women	2	1
Hispanic	1	1
Other Minority	0	0
White Male	5	5

In addition to funding the career development and research of early-career faculty in the space sciences, the program has the broader impact of establishing bulwarks for space science in university departments. This impact includes the transmission of knowledge of the space environment of the Earth and solar system to students in astronomy and general science courses, which often do not incorporate such knowledge.

The DS recommended expanding the FDSS program to four-year colleges, to help improve the pipeline of students educated in space physics. A counterargument is that those teachers are frequently required to devote much of their teaching to subjects that do not include space physics

[11] See Fig 12 in the NSF report to the NSB on Merit Review in FY 2014 at http://www.nsf.gov/nsb/publications/2015/nsb201514.pdf

topics. Astronomy classes include a section on the Sun but rarely include more than a brief introduction to the magnetospheres or auroras of the Earth and planets. The PRC fears that without adequate institutional support for research and relief from the large teaching load typical of four-year colleges, these faculty will have difficulty succeeding in an increasingly competitive research funding climate.

Finding. *In the past ten years, 80 GS-relevant CAREER proposals were submitted of which 45 were selected.*

Of these, thirteen reported "women involvement" but only three checked "minority involvement" (Table 4.6).

Recommendation 4.1. The FDSS and CAREER programs should be continued as resources allow.

Table 4.6. AGS CAREER Awardees 2005 - 2015

Type	AER	MAG	STR	Total
Women	4	5	4	13
Minority	1	1	1	3
Neither	11	8	10	29
Total	16	14	15	45

4.3 AGS Postdoctoral Research Fellowship Program

The AGS Postdoctoral Research program is an excellent way to support and encourage postdoctoral researchers. With proposal writing, teaching, and committee work in abeyance during the appointment, post-docs can broaden and deepen their experience in preparation for the next career step. As a competitive program, the most qualified and self-directed candidates are funded to pursue a research agenda largely of their own design.

Recommendation 4.2. The AGS Postdoctoral Research Fellowship should be continued as resources allow. All such funded programs should continue to keep metrics on the diversity of the participants and report them annually.

4.4 NSF Graduate Research Fellowships Program

Similarly, the NSF Graduate Research Fellowship program directly funds the research of graduate students in the field. The PRC did not acquire data on the diversity of the graduate student population in this program. The PRC certainly recommends continuation of the Graduate Research Fellowships program, but this program is funded at the Foundation level rather than Section level, so a recommendation for the GS is not included here.

4.5 Graduate Summer Schools and Workshops

Summer school programs and workshops bring graduate students together from a variety of institutions for comprehensive education in a single subject area. In addition, like the REUs reviewed below, they provide students with informal opportunities to make important research connections with future mentors and employers.

Summer schools in solar and space physics are an excellent way to provide breadth in basic science topics and research techniques, especially for students from institutions that do not offer many advanced courses in solar and space physics. In addition, since the students meet researchers and many other students in the field at the summer school, the interaction encourages the students to remain in the field by learning about career and employment opportunities.

The GS-sponsored summer school from the legacy Center for Integrated Space Weather Modeling (CISM) provides participants with an introduction to the phenomenological and modeling aspects of space weather. It fills an important niche among the many summer school opportunities open to graduate students and upper level undergraduates. It has become increasingly popular and now receives more applications for participation than it can accommodate.

The GS also supports a summer school in the use of Incoherent Scatter Radars (ISRs) and interpretation of data from ISRs. These summer schools provide an important service to the community.

Finding: *The DS recommended that a suitable replacement (or continuation) of the NSF Center for Integrated Space Weather Modeling summer school (p 92 of the Survey) be competitively selected. As of this date, the GS has continued to support the summer school and has satisfied the DS recommendation.*

Recommendation 4.3. The CISM summer school and the ISR summer school should be continued, periodically assessed and competed for renewal. Metrics on the diversity of the student participants should be kept and reported annually.

The GS targeted grants programs reviewed in Chapter 6 include student support to attend the GEM, CEDAR and SHINE community workshops.

Finding. *The DS recommended that NSF should enable opportunities for focused community workshops that directly address professional development skills for graduate students (DS p 92). This activity takes place to a large extent at the GS-sponsored CEDAR, GEM and SHINE summer workshops. Student participation in these workshops is very popular and provides a more research oriented educational experience for students than summer schools.*

Recommendation 4.4. GS support for graduate and advanced undergraduate students to attend the GEM, CEDAR and SHINE summer workshops should be continued as resources allow. Metrics on the diversity of the student participants receiving support should be kept for each workshop and reported annually.

4.6 Research Experiences for Undergraduates

NSF's Research Experiences for Undergraduates (REU) program provides college students between their junior and senior year with travel and stipend support for a summer research experience at a university other than their home institution. This experience has been successful in helping students gain confidence in their scientific knowledge and skills and in learning about research and career opportunities in fields of potential interest. It also helps them make connections and acquire relevant research experience so that they can choose a graduate school best aligned with their talents and interests.

AGS has supported five REU grants at three institutions over the past ten years. (In addition, some REU grants from other NSF divisions have supported student research in AGS science). The Program in Solar and Space Physics at the University of Colorado Boulder is one of the most popular REUs and attracts about 30 undergraduates every summer. It allows students to work with scientists at one of the many space science organizations in Boulder: University of Colorado's Laboratory for Atmospheric and Space Physics (LASP), NCAR's High Altitude Observatory (HAO), NOAA's Space Weather Prediction Center (SWPC), the Southwest Research Institute (SwRI), North West Research Associates (NWRA) and Atmospheric and Environmental Research (AER) or Atmospheric & Space Technology Research Associates (ASTRA). Summer projects span the field of solar and space physics, from instrument hardware to data analysis to modeling of the Sun-Earth system. The number of participants in the CU REU program by year appears in Table 4.7 along with diversity data. Participation by women and other underrepresented groups is significant.

Table 4.7. Colorado REU students 2007-2015

Year	Males	Females	White†	Hispanic	Black†	Asian	Native American
2007	12	2	12	0	2	0	0
2008	9	5	11	0	1	2	0
2009	6	5	9	0	1	1	0
2010	7	9	15	0	0	1	0
2011	7	9	13	1	0	2	0
2012	2	12	12	1	1	0	0
2013	7	10	12	2	0	2	1
2014	7	10	15	0	1	1	0
2015	6	10	12	1	1	2	0
Totals	**63**	**72**	**111**	**5**	**7**	**11**	**1**

† Non-Hispanic

The NASA/NSF sponsored Community Coordinated Modeling Center hosts the Space Weather Research, Education and Development Initiative (SW REDI) which provides educational opportunities for high school, undergraduate and graduate students. The program's objectives are to: promote space environment awareness as an important component of the new millennium core education; facilitate establishment of space weather programs at universities worldwide; and provide undergraduate student internship opportunities at CCMC/SWRC to develop skills beneficial for any future career pursuit. The high-school and college-oriented program supports both two-week educational "boot camps" and internships. With 23 internships hosted in 2014-15, the SW REDI program appears to be both popular and successful in meeting its goals. It also appears to be doing well in facilitating gender and ethnic diversity in the field (Table 4.8).

***Finding**. The NSF-sponsored REU program and SW REDI program provide undergraduates with opportunities to experience research in the space sciences and to make better informed career decisions. These programs are also doing well in promoting gender and ethnic diversity while training the next generation of researchers.*

Recommendation 4.5. NSF support for REU programs in solar and space physics should be encouraged. The SW REDI program should be continued as resources allow. Metrics on the diversity of participants should be kept on all such funded programs and reported annually.

4.7 Workforce Diversity

The fraction of women participating as undergraduate students in the Colorado REU program is quite large, mirroring the undergraduate population that is now more than 50% women. However, the number of female graduate students drops to around 30%, as suggested by data for student participation in the SHINE summer workshop (Table 4.9).

Table 4.8. GS-supported CCMC interns†, 2014-15

Type	Number	Fraction
Women	6	0.26
Hispanic	0	0.00
American Indian	1	0.04
African-American	2	0.09
White Male	9	0.39
Asian (male)	5	0.22
Total	**23**	

† Two of these interns were graduate students.

The fraction of women falls still further in later career stages, with less than 30% CAREER awardees being women (Table 4.6), and only 25% as FDSS recipients (Table 4.5). The fraction of female GS PIs is significantly less. Diversity data for GS grant awardees are included in Appendix D. We expect the number of women in geospace science to increase, as this new generation of researchers "move up the ranks". The fraction of other minorities (excluding Asians) is much less. Participants in student conferences such as SACNAS (Society for Advancement of Chicanos/Hispanics and Native Americans in Science) show that far more Hispanics and Native Americans are drawn to the biological sciences than the physical sciences, perhaps for cultural reasons and perhaps because these fields are considered less mathematical, or just because of a lack of role models.

Finding. *The GS has been reasonably effective in funding competitive proposals from underrepresented groups. However, the number of proposal submissions from diverse PIs is still quite low.*

Table 4.9. SHINE students supported by NSF, 2006-2009

Type	2006	2007	2008	2009	2011	2012	2013	2014	2015	Total	%
Women	8	14	15	16	15	15	16	16	14	129	31
Hispanic (M/F)ᶧ	0	0/2	0/1	1/1	1/1	0/3	0/2	0/4	1/2	3/16	1/4
Other Minority	1	0	0	0	0	0	0	0	0	1	-
White Male	29	23	21	39	34	34	27	38	40	285	68
Total	**38**	**37**	**36**	**56**	**50**	**49**	**43**	**54**	**55**	**418**	100

ᶧ Hispanic female students indicated here are included in the count of women in the line above.
Data for 2010 was not available

Recommendation 4.6. The GS and the GS community should be in the vanguard of NSF initiatives to promote engagement of women and under-served populations in all aspects of geospace science from school to research proposal writing to leadership in GS activities.

4.8 PhD Employment Opportunities

The numbers of PhDs in space science has increased from ~35 per year in 2000-2005 to ~55 per year in 2006-2010[12] (Figure 4.4). The same study saw the typical research and faculty job listings decline in real numbers over the same period. Part of the decline in the numbers of jobs posted

[12] Moldwin, M. B., J. Torrence, L. A. Moldwin, C. Morrow (2013), Is there an appropriate balance between the number of solar and space physics PhDs and the jobs available?, *Space Weather 11*, 445–448, doi:10.1002/swe.20075.

is likely related to recent reductions in sponsored research for geospace science as discussed in Section 4.1. Many of these recent graduates are going into other fields or to industry, or, among international students, returning to their home country. These students advance new knowledge of geospace science while earning a PhD, even if they do not continue in geospace science post-PhD. The subset of graduates who are pursuing successful careers in industry is testament to the broad utility of an education in geospace science. International students who pursue AGS-related research after returning to their home country become international collaborators and facilitate a much needed global network of geospace scientists.

Finding. *AGS appears to be serving as an excellent platform for training a highly skilled workforce. In so doing, it contributes to the economy and technical productivity of the Nation.*

Recommendation 4.7. Where possible, the first employment step of geospace PhD students should be tracked to determine and demonstrate how the skilled workforce is being utilized. This information could be entered in a data-information box in the final grant report.

4.9 GS CubeSat Program and Education

An extensive review of the GS CubeSat program follows in Section 6.6. Since this chapter addresses the vitality of the profession and workforce issues, the significant role of university CubeSat programs is also emphasized here. University CubeSat programs in general and the GS CubeSat program in particular have been very effective in stimulating interest in STEM education and in aerospace-related careers. In doing they contribute to the development of a highly skilled workforce.

Finding. *CubeSat projects are an excellent vehicle for training students on spacecraft instrumentation and systems. As described in Section 6.6, GS CubeSat projects to date have generated more engineering than science publications and have garnered participation from 6 high school students and more than 250 BS and MS students. They have provided the basis for 15 Ph.D. theses.*

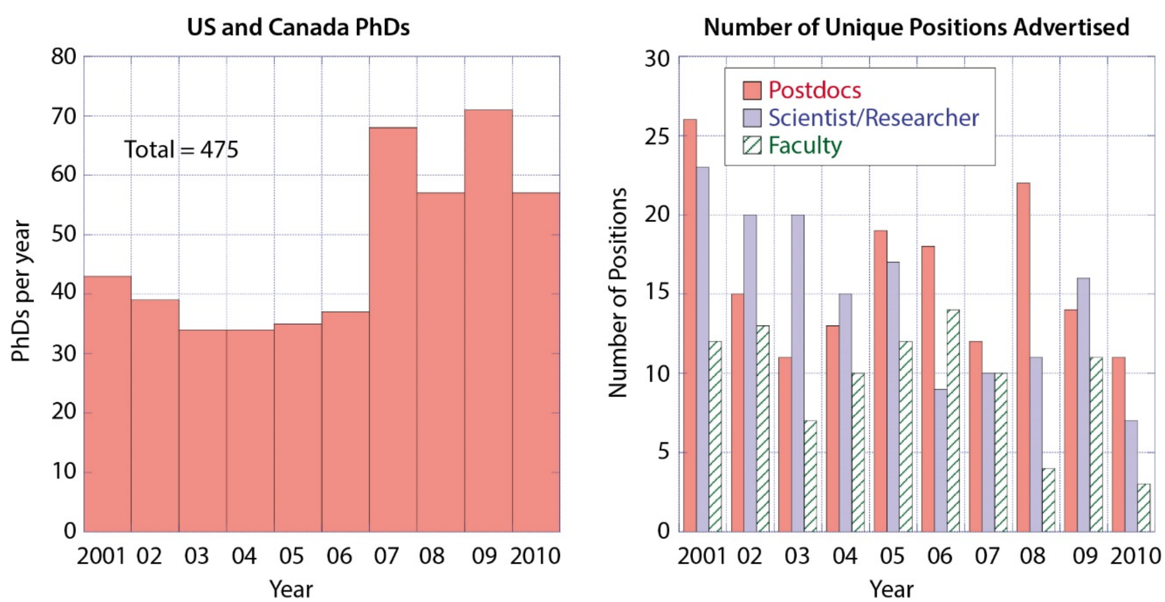


Figure 4.4. *Left:* Production of PhDs in Solar and Space Physics. *Right:* Job advertisements in Space Physics and Aeronomy and the Solar Physics Division for US institutions.[12]

Recommendation 4.8. The GS should continue its CubeSat program at the funding level recommended in Sections 6.6 and 9.3. Given the educational and engineering successes of the CubeSat program, the GS should cultivate partnerships with the NSF Engineering and Education Directorates to broaden NSF investment in CubeSat programs and expand their reach across NSF.

4.10 Public Outreach

The role of outreach in inspiring youth is crucial in creating and maintaining interest in STEM subjects and STEM careers. NSF requires statements of "Broader Impacts" in all new proposals; however, many of these efforts have been limited in scope and/or regional in impact. Similarly, CAREER grants also require an outreach component. Science centers such as CISM have included comprehensive education and outreach programs but have now expired. The NSF Informal Science Division has sponsored a number of excellent planetarium shows that showcase Heliophysics science, and these venues can reach millions. Until recently, NASA missions were "taxed" 1 to 3 percent to support outreach efforts. This practice was recently rescinded by the Committee on Science, Technology, Engineering, and Mathematics, and NASA outreach funding will be concentrated in fewer programs but with a more integrated approach. Thus outreach efforts from NSF programs may be increasingly important in the future.

GS funds two noteworthy projects in this regard. Its SuperMag data center engages K-12 teachers in its activities. Its "Aurorasaurus" project is an excellent citizen science program to monitor the real time aurora. These novel programs for engaging and informing "teacher science" and "citizen science" improve visibility of the field.

Recommendation 4.9. Continue modest investments in projects and programs that involve teacher research and citizen science and inform public interest in geospace and solar science.

4.11 Survey of Earned Doctorates

A significant difficulty for solar and space physics is its invisibility in the NSF-sponsored "Survey of Earned Doctorates". The recent study of PhD graduates referenced above[4] used key words in abstracts to identify relevant theses, but some space science theses may have been missed. Most undergraduates have never heard of solar and space physics as an option for graduate study. Students applying for NSF Graduate Research Fellowships to study geospace science may be at a disadvantage in the review process without a clear category for their proposed work.

Finding. *The Decadal survey recommended having NSF immediately implement a category of "solar and space physics". It is likely that other compendia would follow suit. This proposal for a separate listing can even be found in one of the first decadal reports: "Solar Terrestrial Research for the 1980's" [NRC, 1981].*

Recommendation 4.10. The GS should work with the NSF office that maintains "Survey of Earned Doctorates" to implement immediately the category "Solar and Space Physics" (or another name to be determined) into the Survey.

Chapter 5. Science Goals and Capabilities for SSP

Building on the extraordinary advances in solar and geospace science of the previous decade, the Decadal Survey (DS) for Solar and Space Physics (SSP) recommended a comprehensive program of research to "improve understanding of the mechanisms that drive the Sun's activity and the fundamental physical processes underlying near-Earth plasma dynamics; to determine the physical interactions of Earth's atmospheric layers in the context of the connected Sun-Earth system; and to greatly enhance the capability to provide realistic and specific forecasts of Earth's space environment that will better serve the needs of society." The overarching DS recommendations crystallized with four key science goals in Chapter 1 of the DS report:

Key Science Goal 1. Determine the origins of the Sun's activity and predict the variations in the space environment.

Key Science Goal 2. Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.

Key Science Goal 3. Determine the interaction of the Sun with the solar system and the interstellar medium.

Key Science Goal 4. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

These key science goals were further parsed in Chapter 2 of the DS report into 12 science challenges. The flow down from key science goals to science challenges – in effect science objectives – can be used to determine the critical capabilities required to achieve DS goals and thereby meet charge (1) of the portfolio review. These challenges are listed in Table 5.1. Other chapters of the DS report provide more specific guidance on various aspects of this review. DS Chapter 4, *Recommendations,* outlines program elements needed to accomplish the key goals; Chapter 5, *NSF Program Implementation*, provides specific guidance to NSF in implementing enabling program elements; and Chapter 7, *Space Weather and Space Climatology: A Vision for Future Capabilities*, describes the enhanced capabilities required to provide realistic and specific forecasts of Earth's space environment. The PRC also used the three DS panel reports on Atmosphere-Ionosphere-Magnetosphere Interactions, Solar Wind – Magnetosphere Interactions and Solar and Heliospheric Physics, and their imperatives for NSF initiatives, to further inform its review and assessment of critical capabilities.

The PRC formed four science sub-committees to identify critical science capabilities. Three of the sub-committees addressed capabilities for science challenges listed in Table 5.1 for Atmosphere-Ionosphere-Magnetosphere Interactions, Solar Wind-Magnetosphere- Ionosphere Interactions and Solar and Heliospheric Physics. The fourth sub-committee focused specifically on Space Weather and Prediction, and, in keeping with DS directives for advancing integrative science, gave special attention to the capabilities needed to address science challenges that span across the traditional disciplines and that involve interactions occurring within the connected Sun-Earth system. These four sub-committees identified the subset of critical capabilities, within the broader landscape of support for SSP, that lie within the purview of the current or future GS portfolio. With the assessments of these sub-committees in hand, the PRC as a whole reviewed and ranked the critical capabilities for advancing the DS scientific agenda using observations, instrument techniques, data analysis, theoretical and modeling approaches and laboratory measurements.

TABLE 5.1 Science Challenges for Solar and Space Physics from the 2012 Decadal Survey

Atmosphere-Ionosphere-Magnetosphere Interactions (AIMI)	
AIMI-1	Understand how the ionosphere-thermosphere system responds to, and regulates, magnetospheric forcing over global, regional, and local scales.
AIMI-2	Understand the plasma-neutral coupling processes that give rise to local, regional, and global-scale structures and dynamics in the AIM system.
AIMI-3	Understand how forcing from the lower atmosphere via tidal, planetary, and gravity waves influences the ionosphere and thermosphere.
AIMI-4	Determine and identify the causes for long-term (multi-decadal) changes in the AIM system.
Solar Wind-Magnetosphere Interactions (SWMI)	
SWMI-1	Establish how magnetic reconnection is triggered and how it evolves to drive mass, momentum, and energy transport.
SWMI-2	Identify the mechanisms that control the production, loss, and energization of energetic particles in the magnetosphere.
SWMI-3	Determine how coupling and feedback between the magnetosphere, ionosphere, and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind.
SWMI-4	Critically advance the physical understanding of magnetospheres and their coupling to ionospheres and thermospheres by comparing models against observations from different magnetospheric systems.
The Sun and Heliosphere (SHP)	
SHP-1	Understand how the Sun generates the quasi-cyclical magnetic field that extends throughout the heliosphere.
SHP-2	Determine how the Sun's magnetism creates its hot, dynamic atmosphere.
SHP-3	Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate through the heliosphere.
SHP-4	Discover how the Sun interacts with the local interstellar medium.

The DS science challenges and the critical capabilities required to address them are summarized in the next four sections.

5.1 Atmosphere-Ionosphere-Magnetosphere Interactions

AIMI-1: Understand how the ionosphere-thermosphere system responds to, and regulates, magnetospheric forcing over global, regional, and local scales.

This science challenge embodies the recognition that the magnetosphere, ionosphere, and thermosphere respond as a coherently integrated system to solar forcing. To understand and predict variability within this system requires a deep understanding of solar wind forcing, energy storage and release, feedback pathways, preconditioning, and regulation mechanisms. The AIMI-1 challenge serves as the "Aeronomy" complement to SWMI-3, which casts this challenge from the magnetospheric perspective. The shift of the Aeronomy and Magnetospheric communities toward the "system science" paradigm is a direct consequence of the vast expansion of collaborative measurements from ground and space over the preceding decade, coupled with commensurate advances in assimilative and first-principles modeling. Further progress will require initiatives and capabilities that transcend traditional programmatic boundaries within the Geospace Section.

A unifying theme under AIMI-1 is the geospace system response to geomagnetic storms and substorms, which are known to have global effects on the AIMI system extending from pole to equator, and are a major component of space weather. Structuring of the conductance field by particle precipitation patterns affects the partitioning and efficiency of energy transfer into the I-T system. Transmission and reflection of wave power from the magnetosphere offers a complementary view into these issues. The resultant thermal expansion, ambipolar diffusion, and structured convection patterns constitute an effective system of mass redistribution within the geospace system. Free energy arising from stormtime interactions also drives a rich variety of instabilities (e.g., Langmuir turbulence, Farley-Buneman waves, Rayleigh-Taylor instabilities, gradient-drift instabilities) which adversely impact ground-space communications and further affect energy and momentum transfer within the AIMI system through cross-scale coupling. Progress has been made in addressing these issues, both in terms of global observational measurements and in the development of coupled, large-scale physics-based and assimilative numerical models; however, a full understanding and predictive capability of stormtime effects on the near-Earth space environment remain to be achieved.

Geospace science should aggressively continue its trend toward distributed measurements coupled through multi-scale physical models. DASI-type measurements and coordinated observations (e.g., TEC maps, ISRs, SuperDARN, ionosondes, passive optical networks, and satellites) with the international community are necessary to assess the temporal and spatial changes in the AIM system during the course of a magnetic storm. In particular, the direct connection between solar wind parameters (density, velocity, and magnetic field) at 1 AU and the ensuing dynamics within the AIM system. Additionally, fully global models of the AIM system need to be developed within the 'system science' approach, that is, to determine the complex nonlinear relationships between the different components of the system as a function of space and time. In addition to considering the essential physical processes involved, there is a need for high spatial and temporal resolution in computational models that is lacking in most models today. For example, the development of ionospheric irregularities on scale lengths of a few kilometers needs to be modeled to assess their impact on space-based navigation and communication systems during magnetic storms, yet most global models have a grid resolution of a few hundred kilometers.

Important questions that need to be addressed include the following:

1. How do solar wind disturbances propagate through the magnetosphere and impact the ionosphere?

2. How do ionospheric storms develop, evolve, and recover?

3. What physical processes control the spatial and temporal extent of storm-time penetration electric fields in the low- to mid-latitude ionosphere?

4. How do neutral wind dynamics impact the electrodynamics of the global ionosphere during

ionospheric storms?

5. How do sub-auroral ion drifts (SAIDs) and sub-auroral plasma streams (SAPS) form and develop?

6. How do AIMI interactions affect mass redistribution within the geospace system?

Critical capabilities. The critical capabilities needed to address this challenge entail synergies between measurement and modeling. Distributed measurements of flows, temperatures, and compositions of the plasma and neutral gases are needed for ingestion into assimilative models, and as constraints on first-principles models. Provision of these capabilities ultimately includes collaborative measurements from ground-based and space-based platforms.

Specific high-priority observational capabilities relevant to GS include: (1) density and composition of the neutral atmosphere from 0 to 1000 km altitude, (2) measurements of ionospheric flows at 10 km and 10 s resolution, (3) maps of ionospheric conductance at space-time scales inherent in the phenomenon (context dependent, but 100 m and 1s variations are possible), and (4) cyberinfrastructure capabilities to optimally exploit the growing database of heterogeneous, multi-scale measurements.

Modeling capabilities include: (1) A multi-scale modeling effort is needed in concert with these observational capabilities. (2) Both regional (transport, flux-tube) and global (multi-fluid, MHD, GCMs) models of first principles physics are needed to test our physical understanding and to predict unobservable parameters in the system (e.g., neutral abundances, ion composition). (3) A global model of the electrodynamics of the ionosphere that self-consistently includes the major drivers: the high-latitude Region 1 and 2 current systems and the neutral wind. (4) Assimilative models are needed to evaluate self-consistency of heterogeneous distributed measurements, and to make real-time predictions of space weather effects on the geospace system.

AIMI-2. Understand the plasma-neutral coupling processes that give rise to local, regional, and global-scale structures and dynamics in the AIM system.

Although ionized species in the outer atmosphere are a minor constituent in terms of mass density, they have a significant impact on neutral dynamics owing to the efficacy with which they may be driven by free energy in the magnetosphere and solar wind. Conversely, neutral motions influence the effective conductivity and electric fields projected into the magnetosphere, as well as serving as the reservoir for ionospheric plasma production. Our understanding of plasma-neutral interactions is incomplete at best, based in large part on the difficulty of observing the neutral gas.

Until recently, the role of the neutral atmosphere on the geospace system has received inadequate attention. In a great many studies, the reliability of the Mass Spectrometer and Incoherent Scatter Radar model (MSIS) is accepted as a baseline assumption for studies driven by observations of plasma phenomena. This practice is followed not because MSIS is reliable, but because its parameters are difficult to quantify experimentally. The forthcoming NASA missions ICON and GOLD include substantial focus on plasma-neutral interactions. Recent efforts to develop imaging Fabry-Perot interferometers (FPIs) and deploy such instruments in networked configurations alongside plasma diagnostics will also contribute substantially.

Perhaps the dominant ion-neutral coupling issue in the AIMI system is the generation of the global dynamo electric field associated with thermospheric winds in the *E* and *F* regions. This electric field is the dominant transport mechanism of plasma transverse to the geomagnetic field via the $\mathbf{E} \times \mathbf{B}$ drift, and is responsible for the generation of the Appleton anomaly peaks in F region as well as the enhancement of the upward plasma drift at sunset which is a major factor in the generation of equatorial spread F (ESF). Another important issue concerns the interplay of plasma and neutral species in controlling the ion outflow. The mechanical transfer of electromagnetic power to the neutral wind dynamo at high latitudes is also poorly quantified.

Important questions that need to be addressed are the following:

1. What is the dominant neutral wind structure that controls the strength of the post-sunset pre-reversal enhancement?

2. What changes occur during periods of low solar activity that cause a post-midnight enhancement of the upward plasma drift and lead to pre-dawn density depletions?

3. What role do thermospheric drivers play in regulating the day-to-day variability of the neutral wind and low-latitude electric field?

4. What are the primary processes that control the longitudinal variability of the global low-latitude electric field?

5. How does thermospheric composition, temperature, and bulk motion affect plasma production and outflow?

To answer these questions requires knowledge of the global thermospheric wind. However, measurements of the wind are relatively sparse compared to measurements of ionospheric properties, and a global system of observations is needed (e.g., Fabry-Perot interferometers). The upcoming NASA ICON mission is designed to make measurements of the neutral wind in the low-latitude ionosphere and will provide an important new data set.

Aside from observations, first-principles physics-based models are being used to determine the thermospheric wind (e.g., TIEGCM, TIMEGCM, WACCM-X, WAM). It is important that this type of model development be continued and validated to provide critical wind data in the absence of measurements.

Critical capabilities. In addition to the general framework for modeling and distributed measurements previously discussed, progress in understanding plasma-neutral coupling requires the following capabilities: (1) coordinated measurements of neutral and plasma dynamics. This capability includes distributed ground-based measurements of neutral winds and temperatures, and coordinated global-scale observations from space, (2) improved hybrid fluid-kinetic models capable of capturing magnetosphere-ionosphere-thermosphere-mesosphere interactions, (3) experimentally driven methodologies by which small scale processes may be used to drive GCM and MHD modeling efforts.

AIMI-3. Understand how forcing from the lower atmosphere via tidal, planetary, and gravity waves influences the ionosphere and thermosphere.

In recent years there has been a growing recognition that the geospace system can be effectively and significantly driven through "coupling from below." The full implications of lower atmospheric forcing are still being explored. During the recent extended solar minimum period, the occurrence of equatorial spread F (ESF) occurred more frequently in the post-midnight period than the post-sunset period—a marked departure from 'normal' ESF. Although not entirely understood, it is conjectured that the changes in the thermospheric wind because of low solar irradiance and various tidal and gravity wave motions altered the global electric field to favor post-midnight *F*-region irregularities to develop (as noted in AIMI-2). This result becomes more important to the geospace community in light of predictions that solar activity will continue to decline and possibly reach solar conditions similar to the Maunder minimum in 2030.

There has also been considerable interest of late in the impact of sudden stratospheric warmings (SSW) in the Polar Regions on the global ionosphere. For example, changes in the ionospheric drift velocities have been observed at Jicamarca following a SSW suggesting a global coupling of the polar stratosphere to the equatorial ionosphere associated with altered atmospheric wave patterns.

Lastly, non-migrating tidal motions generated in the troposphere have been convincingly linked to the so-called '4 wave' pattern observed in ionospheric optical emissions and TEC patterns. Subsequent simulation studies have been able to reproduce this behavior.

The NASA Ionospheric Connection Explorer (ICON), to be launched in 2016, and the Global-scale Observations of the Limb and Disk (GOLD) mission to be launched in 2018, will contribute to this challenge. ICON, in particular, is specifically dedicated to exploring connections between Earth's weather and space weather. New modeling efforts, such as the Whole Atmosphere Community Climate Model (WACCM) are emerging to make quantitative predictions. These efforts are particularly important owing to the unprecedented changes of Earth's intrinsic magnetic field.

Critical capabilities. The scientific efficacy of these space-based and modeling efforts will be greatly enhanced through ground-based measurements traditionally sponsored within the NSF Aeronomy and Facilities Programs. Of particular interest are (1) optical techniques, such as Fabry-Perot interferometers and LIDARs and (2) neutral airglow monitors, which remain the principal diagnostic of the neutral state of the outer atmosphere, (3) radar systems (incoherent scatter, MF, meteor) which can use backscatter from ionized species as tracers of neutral dynamics, coupled with (4) collaborative measurements of lower atmospheric phenomena (forcing from orographic, geological, anthropogenic, and weather system sources).

AIMI-4. Determine and identify the causes for long-term (multi-decadal) changes in the AIM system.

Understanding long-term trends in the lower atmosphere has been at the forefront of research in the Geoscience Directorate for decades. Climate change has immediate global societal consequences. Similar efforts aimed at understanding climatological effects in the upper atmosphere may provide crucial additional insights into our understanding of how our home in space interacts with our parent star.

Critical capabilities. Although investments in long-term measurements are needed, the community is still debating which measurements are highest priority and viable given the substantial variation in cost depending on diagnostic technique. Candidates include: (1) Calibrated long-term globally distributed magnetometer measurements (available from the mid 1800's to present); (2) Optical measurements (desirable but expensive and challenging in terms of long-term calibration); (3) A 50-year database of ISR measurements remains largely untapped at present and is expensive to maintain. The new AMISR radars have the promising capability of "low duty cycle operation." Emerging networks of optical instrumentation are achieving similar cadence, albeit subject to weather and observing conditions. These electronically steerable systems can sample ionospheric state parameters at a regular cadence (typically 10's of seconds to minutes) with reasonable operating cost. These measurements will need to be supported by appropriate database, cyberinfrastructure, and modeling methodologies, as discussed previously.

5.2 Solar Wind-Magnetosphere-Ionosphere Interactions

SWMI-1. Establish how magnetic reconnection is triggered and how it evolves to drive mass, momentum, and energy transport.

While the broad view of how reconnection takes place and drives convection in the magnetosphere is now well established, the underlying physics of magnetic reconnection in the collisionless regime of the magnetosphere is not yet understood well enough to enable prediction of when, where, and how fast this process will occur and how it contributes to mass, momentum and energy transport. NASA's Magnetospheric Multiscale Mission (MMS) was launched after the 2012 Decadal Survey was completed and is now conducting measurements inside reconnection diffusion regions to resolve the collisionless microphysics of reconnection in Earth's magnetosphere.

MMS *in situ* measurements will determine how reconnection occurs, but prediction of its onset and spatial distribution is influenced by both local microphysics and nonlocal effects of magnetosphere-ionosphere coupling. Reconnection also impacts the magnetosphere-ionosphere system. The spatial variation in ionospheric conductivity regulates the ionospheric load on the solar wind dynamo and the closure of electric currents couples reconnection regions to the ionosphere. The transport of ions from the ionosphere to the magnetosphere becomes especially intense during magnetic storms and can modify local reconnection rates by changing the mass composition of reconnecting plasmas. The reconnection process exhibits different dynamics in different regions of geospace. Magnetotail reconnection produces bursts of high-speed flows in narrow channels. Dayside reconnection generates localized flux transfer events that produce bursts of particle precipitation, auroral light and flow channels in and poleward of the low-altitude cusp region. Reconnection produces structured ionospheric signatures in plasma flows and density, vertical transport, Alfvénic activity and charged-particle precipitation, and these signatures are primary diagnostics of the regional and global distributions of reconnection occurring at the magnetospheric boundary. Thus measurements and models of low-altitude signatures are needed to understand reconnection well enough to be able to predict when and where it will occur and how it evolves to drive mass, momentum and energy transport.

Critical capabilities. Data and observational capabilities include: (1) basic research and analysis of data from spacecraft and GBOs relevant to reconnection processes; (2) measurements near the dayside and nightside convection throats in the ionosphere of ionospheric flows, precipitation inferred from ground-based imagers, magnetic field perturbations from GBOs and low-altitude spacecraft (e.g., AMPERE constellation) to resolve current systems; (3) coherent scatter radar measurements for resolving global convection patterns; (4) cyberinfrastructure capabilities to exploit the growing database of heterogeneous, multi-scale measurements;

Modeling capabilities include: (1) large-scope 3D kinetic simulations to study the microphysics of reconnection diffusion regions; (2) regional flux tube simulations to study Alfvén wave dynamics, charged-particle precipitation and ionospheric outflows on and near reconnection flux tubes; (3)

global MHD simulations to study nonlocal processes controlling where and when reconnection occurs and the influence of MI coupling in regulating it.

SWMI-2. Identify the mechanisms that control the production, loss, and energization of energetic particles in the magnetosphere.

Wave-particle interactions (WPIs) are key drivers of particle energy gain and loss in the radiation belts. WPIs and mixing of energetic and low-energy plasmas promotes and sustains the various modes of wave turbulence that permeate the ring current and radiation belts. It is now understood that storm-time particle dynamics are the result of a delicate balance between acceleration and loss of relativistic particles mediated by waves produced by local plasma instabilities. The efficiency of WPIs depends critically on the cold plasmaspheric population that undergoes erosion during geomagnetic storms and exhibits prominent longitudinal asymmetries that are poorly resolved by spacecraft measurements. NASA's Van Allen Probes Mission has been conducting measurements in this critical region since the completion of the Decadal Survey and has observed local acceleration and radial diffusion.

Magnetic reconnection in the magnetotail drives convection that carries energetic particles earthward, where they are injected and trapped in orbits around Earth to form the extraterrestrial ring current, a region overlapping the radiation belts. Energetic ions and electrons are found at distances of 1 to 7 R_E from Earth's center. The inner extent can overlap LEO while the outer extent of energetic particles can overlaps the orbital radius of geostationary satellites (6.6 R_E) where the vast majority of communications and Earth-monitoring spacecraft reside. These satellites can be damaged by energetic radiation belt electrons whose flux is strongly enhanced during intense solar and geomagnetic activity. Understanding charged particle acceleration, scattering, and loss, which control the intensification and depletion of the radiation belts, and developing capabilities to predict their dynamics are priorities for solar and space physics.

Critical capabilities. Basic research and analysis of data from spacecraft and GBOs relevant to energization and loss processes are of highest importance; loss processes are understood empirically, but better theoretical understanding is needed. *In situ* measurements of both particles and wave fields are critical in determining local properties of energetic particles in the inner magnetosphere, understanding the mechanisms that control their production, loss, and energization. Full understanding also requires distributed complementary ground-based measurements of precipitation (from riometers and VLF networks), particle-scattering by ultralow frequency wave fields extending up to the ion cyclotron frequency (from magnetometer networks), ionospheric convection controlling the location of the plasmapause (from mid-latitude ISR measurements), and Total Electron Content (whose variations have been shown to map to the plasma density changes in the magnetosphere that control WPI). Low-altitude polar orbiting CubeSats and balloon-borne measurements of energetic particle precipitation can play a complementary role and are desirable. Observations are needed for a variety of solar wind conditions and throughout the entire solar cycle; it is also essential to have observations in the solar wind in order to characterize the external drivers, although provision of this data is not within the GS purview.

Modeling capabilities include: (1) bounce-averaged transport models that include pressure anisotropy and effects of WPI; (2) hybrid simulation codes to study growth and propagation of waves and their interactions with charged particles; (3) global MHD codes to simulate ULF wave variability and the structure of magnetospheric electric and magnetic fields in response to interplanetary drivers; and (4) Assimilative models of 3D diffusion (in energy, pitch angle and L*) that ingest boundary data to constrain the solution.

SWMI-3. Determine how coupling and feedback between the magnetosphere, ionosphere and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind.

The SWMI-3 science challenge intersects with, and is complementary to, AIMI-1, both of which address fundamental aspects of Key Science Goal 2. The past decade has seen tremendous advances in understanding how the magnetosphere and ionosphere respond to storm-time disturbances, but the nonlinear linkages that control the coupled system are relatively opaque and not readily determined from observation alone. Addressing this challenge requires a concerted effort. Data from widely distributed observations, *in situ* and ground-based, must be integrated and assimilated into increasingly realistic dynamic models and computer simulations of geospace to understand cause and effect.

Examples of the underlying complexity include: Electrodynamic coupling between the magnetosphere and ionosphere modifies the simple dissipative response of the coupled system in dramatic ways. Dynamic charged-particle precipitation changes the distribution of ionospheric conductance and thus the patterns of electrical current flow and Joule dissipation in the ionosphere. The magnetospheric dynamos that power dissipation in the ionosphere-thermosphere must therefore dynamically adapt to the evolving sites of dissipation, and ionospheric dynamos feedback on the magnetospheric plasma. The interaction of the ring current with the ionosphere severely distorts inner magnetospheric convection, which feeds back on the ring current itself, skewing its peak toward dawn. Duskside flow channels arising from ionospheric coupling remain long past periods of peak solar wind driving. Outflows of ions from the ionosphere into the magnetosphere are so intense during magnetic storms that ionospheric O^+ can dominate the ring-current ion pressures. Outflow of heavy ions also alter magnetospheric dynamics by modifying magnetic reconnection on both the dayside and the nightside. Since the feedback of the ionosphere and thermosphere as a source of plasma and dissipation for the magnetosphere has such profound effects, the evolution of the ionosphere and magnetosphere must be studied as a globally coupled system.

Critical capabilities. Basic research and analysis of data from the multitude of ground- and space-based measurements is essential. Distributed synoptic measurements of the following variables at high- and mid-latitudes are critical: (1) Electric currents flowing into and through the ionosphere and associated magnetic perturbations (from magnetometers at GBOs and on low-altitude satellite constellations); (2) convective electric fields (from radar measurements); (3) energy and flux of charged-particle precipitation (and ideally their phase space-density), obtained either from direct measurement or optical techniques (from ISRs, low-altitude satellites and ground-based imagers); (4) associated ionospheric conductivity and ionospheric plasma density (from ISRs and model inversion techniques); (5) flux and density of upflowing and outflowing ionospheric ions and ideally their phase space density (from ISRs); and (6) the frequency and wavenumber spectrum of turbulent fluctuations of electromagnetic fields and plasma variables (from low-altitude satellite measurements). All are within the purview of GS sponsorship. Distributed measurements of turbulent spectra is currently and will continue to be a very challenging diagnostic problem for many years to come. These low-altitude data should be complemented by *in situ* data obtained from other sources, especially upstream solar wind data and magnetospheric state variables derived from measurements on NASA, NOAA and DoD satellites.

Modeling capabilities include: (1) increasingly detailed empirical models (dynamic statistical); (2) global simulations of the coupled solar wind – magnetosphere – ionosphere – thermosphere interaction, extended to include the generalized Ohm's law and drift kinetic effects and coupled to high-resolution global I-T models that include field-aligned mass transport between the magnetosphere and ionosphere: (3) regional models to study dynamics of active regions in the outer magnetosphere (magnetopause, magnetotail), generation of waves in such regions, and wave propagation to and interaction with the ionosphere; and (4) Local and regional three-dimensional kinetic and hybrid simulations to determine the mechanisms responsible for field-aligned acceleration of electrons and ions and transverse acceleration of ions.

SWMI-4. Critically advance the physical understanding of magnetospheres and their coupling to ionospheres and thermospheres by comparing models against observations from different magnetospheric systems.

Jupiter's moon Io is a copious source of neutral gas, which, upon ionization, is a dominant drag force on the rapidly co-rotating magnetic field of the planet. Similarly, the moons of Saturn, particularly Titan and Enceladus, are major sources of plasma that affects the dynamics of Saturn's magnetosphere, and aspects have been studied with data from the Cassini and Voyager spacecraft, though much remains unexplained. The magnetospheres of Uranus and Neptune are largely unexplored but present unique cases that will likely further challenge scientific understanding. Finally, the tiny magnetosphere of Mercury is an extreme example of a magnetospheric system because it possesses no ionosphere. In such a situation the coupling processes that operate are radically different. These other systems present a suite of vastly different configurations and the opportunity to test current theories and models on these widely varying systems.

Critical capabilities. The capabilities within the purview of GS sponsorship required to address this science challenge include (1) development of theoretical models and (2) application of empirical and first-principles simulation models adapted to the special circumstances that make other planetary magnetospheres different from Earth's.

5.3 Solar and Heliospheric Physics

SHP-1. Understand how the sun generates the quasi-cyclical magnetic field that extends throughout the heliosphere

The first Solar-Heliospheric (which is essentially equivalent in scope to the GS concept of Solar-Terrestrial) challenge raised by the Decadal Survey addresses both the *origins* and the *impacts* of cycling magnetic activity throughout the heliosphere. We have broken the challenge into these two components in order to focus on the capabilities and requirements distinct to each.

How is the cycling solar magnetic field generated? Dynamo models range from mean-field parameterizations to global convective simulations. These models have had significant recent success in explaining magnetic field generation, cycling fields, and even "grand minima" (i.e., extended periods of low solar activity interrupting otherwise quasi-regular solar cycles). Observations of solar oscillations (helioseismology) and surface flows have provided new details about both global and local structures within the Sun, and high-resolution observations and numerical simulations of magnetic flux emergence have revealed the physical processes at work in sunspot fine structure. Along with recent stellar measurements of the properties of solar analogs relating rotation, convection, magnetism, and cyclic activity, these observations and simulations have been a rich resource for inspiring theory and constraining models.

However, fundamental questions remain as to the roles played by the various physical processes potentially involved in generating magnetism -- e.g., convection, circulation, rotation, and flux emergence -- and how these vary within and across solar activity cycles. For example, patterns of meridional circulation with latitude and depth, and the degree of diffusivity of flows are essentially unknown parameters. Similarly, uncertainties remain about how local dynamo effects may impact the global dynamo which generates the cycling solar magnetic field, and of how sunspots form and to what extent they contribute to the operation of the global dynamo. Until and unless these questions can be resolved, our ability to predict future solar activity levels is severely limited.

Critical capabilities. (1) Basic research and development pertaining to dynamo theory and models remains a high priority. (2) Observational analyses of helioseismology and surface magnetic fields and flows continue to be essential, and (3) efforts in data assimilation to directly incorporate these observations into models are of growing significance. (4) Analyses of observed Sun-like stars provide an excellent means of testing the physicality and generality of dynamo models.

In what way and to what effect does the solar cycle vary throughout the heliosphere? The impact of the recent prolonged solar minimum was felt throughout the heliosphere, forcing us to reassess our expectations for a "typical" low-activity time period. For example, galactic cosmic ray (GCR) fluxes near Earth reached the highest levels on record, and a reduction in solar UV heating of the Earth's upper atmosphere led to less drag on satellites than in prior solar minima.

The possibility of an even more extended grand minimum in the future raises questions about implications for both terrestrial and space climate. Recent terrestrial climate model results indicate that a sustained decrease in total solar irradiance (TSI) at levels expected for a grand minimum would have a small -- but temporary -- impact on upward trends in global surface temperature. The impact on space climate would be greater: since variation at short wavelengths is more strongly modulated by solar activity than TSI, the upper atmosphere would change significantly if UV radiation were diminished for an extended period (as the recent solar minimum demonstrated). The effects of couplings between space and terrestrial climate are as yet largely undetermined. Underlying these issues are fundamental uncertainties about how solar magnetic variability translates to changes in spectral solar irradiance – which depends on the distribution of closed magnetic fields, and in solar wind/Heliospheric structure – which depends on the distribution of open magnetic fields.

Critical capabilities. (1) Solar-cycle analyses are needed of both the comprehensive space-age record of remote-sensing and *in-situ* observations that span the heliosphere, and the longer-term historical and geological record of solar-cycle proxies. (2) High-resolution magnetic flux emergence observations and (3) radiative-magnetohydrodynamic (R-MHD) simulations are needed to connect solar magnetic distribution to spectral irradiance. (4) Models that link observations from Sun to Earth -- e.g., as provided by the Community Coordinated Modeling Center (CCMC) -- are important for relating long-lived heliospheric magnetic structures to periodic solar-wind forcing and associated geospace and GCR responses. (5) Data-exploitation efforts are needed to archive and cross-calibrate observational records.

SHP-2. Determine how the Sun's magnetism creates its hot, dynamic atmosphere

How is the solar atmosphere heated and the solar wind accelerated? The fundamental physical problems of how the solar corona is heated to millions of degrees, and how the solar wind is accelerated to supersonic speeds, are still largely unsolved. These problems are related through a dynamic coupling between corona and solar wind, with the lower atmosphere (chromosphere) potentially acting as a source for heat and mass fluxes. A range of coronal heating models based on nanoflares, turbulent current sheets, and/or waves have been proposed and to some extent validated with observations. *In-situ* measurements of the solar-wind plasma velocity distribution functions and electromagnetic fluctuations have been used in studies of the generation and dissipation of Alfvénic fluctuations and other types of solar-wind turbulence, and nonthermal ion and electron distribution functions have yielded clues to how and what kinetic instabilities may develop. Reconnection events in the solar wind have been studied, with connections made to solar phenomena including plumes, spicules, and nanoflares. Finally, charge state and composition measurements coupled with global magnetic models have been used to connect solar wind observations to their origins in the solar atmosphere, with specific signatures found for fast, slow, and transient solar wind.

Magnetism is the common theme in all of these analyses and links them across many scales (temporal and spatial). However, models of coronal/heliospheric magnetic fields generally define a lower magnetic boundary condition using observations of the photosphere where the plasma beta is expected to be high, which limits their reliability. The chromosphere may be a better boundary condition on magnetic models, and it clearly plays an important role in the injection of energy into the corona and solar wind. However, the chromosphere is one of the least well understood regimes in solar-terrestrial physics. In general, a more complete understanding is needed of the physical mechanism or mechanisms responsible for the transfer of energy from the Sun's interior through its atmosphere to the solar wind, and of how solar and heliospheric magnetic fields control and connect these mechanisms.

Critical capabilities. (1) Analyses of high-resolution measurements of plasma and electromagnetic fluctuations in the solar wind, and (2) of high spatial/temporal resolution observations at all heights in the solar atmosphere are needed to test and develop models of the physical mechanisms driving coronal heating and solar wind dynamics. (3) Three-dimensional R-MHD numerical simulations that span the upper-convection zone through the corona as a coherent system are important for progress, as is (4) the development of methodology for driving these simulations with observations from multiple heights of the solar atmosphere. (5) Global magnetic models are important for context and to connect solar wind to its sources.

SHP-3. Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate through the heliosphere.

Again, we have broken this challenge into two components, dealing with the *form of explosive energy release* and the *origins of geoeffectiveness*, in order to focus on the capabilities and requirements distinct to each.

In what form is energy released in flares/CMEs? Flows at the solar surface and magnetic flux emerging from beneath it twist and distort the coronal magnetic field, building up free energy on time scales of days, weeks, or possibly longer. This free energy may be explosively released during a flare and/or coronal mass ejection (CME) in the form of high-speed flows, local plasma heating, and the acceleration of particles to high energies. CME acceleration has been shown to be closely synchronized with high-energy release in flares, implying that fast expansion creates a flare current sheet below a CME. Particle acceleration is seen near the flare site as part of a magnetic reconnection process, as well as at coronal and interplanetary shocks driven by fast CMEs -- the latter being the primary source of large solar energetic particle (SEP) events observed *in situ* in the interplanetary medium and geospace. Measurements have indicated that the accelerated relativistic electrons often contain half of the energy released in a flare while a large fraction of the CME energy (tens of percent) is commonly imparted to the SEPs.

While the combination of multi-point observations, current models and theoretical calculations have led to significant improvements in our understanding of flare and CME generation as well as particle acceleration and transport, many questions remain about the physical processes involved. In particular, how is such a large fraction of the released energy converted into particle energy? Why does SEP acceleration and longitudinal transport efficiency vary so greatly from event to event? What are the roles of preceding CMEs, the conditions of the interplanetary medium, and the characteristics of the suprathermal seed particle population in determining this efficiency?

Critical capabilities. (1) Analysis of the rich remote sensing and *in-situ* datasets obtained throughout the heliosphere are needed to connect source conditions to energetic phenomena. (2) Models incorporating multiwavelength observations of flares and high temporal/spatial resolution magnetometric observations of active regions before, during and after eruptions are needed to understand energy build up and release. (3) Data exploitation of the measurements of the evolution of the halo solar wind and suprathermal tails, CMEs and their associated shocks, radio bursts, energetic neutral atoms (ENAs), and SEPs is needed to advance models of particle acceleration and transport. (4) Making these models available to the community (e.g., via the CCMC) further increases the overall scientific return.

What are the origins of flares and CMEs, and how do these result in geo-effectiveness? Substantial recent progress has been made in creating mature models of CMEs, shocks, and SEPs from solar eruptions (including models served by the CCMC). The success of simulations in reproducing observations of CMEs testifies to a robust scientific understanding of many of the processes of magnetic storage and release, and indeed it is possible to identify which areas on the Sun are most likely to produce flares and CMEs. In addition, observations combined with operational models give advance warning of potential space weather hazards. An initial 1-3 day warning of impending shocks and CME impacts is provided by a CME's launch and subsequent observed propagation: recent work triangulating STEREO observations has significantly reduced uncertainties in arrival time forecasts. More precise information can be obtained from, e.g., measurements of relativistic electrons which arrive approximately one hour before the SEP ions.

However, we have not reached a point where we can predict when an eruption will occur, or the likely severity of the eruption's impact at the Earth, e.g. speed, mass, magnetic flux content and (most significantly) magnetic orientation (see SWP below for further discussion). In addition, recent studies showing "sympathetic eruptions" indicate global connectivity can play a role in triggering CMEs, and the global magnetic environment is known to influence CMEs as they erupt, e.g. through rotation, deflection, and/or reconnection. SEP acceleration and longitudinal transport efficiency similarly depends upon spatial and temporal context. A full understanding of the physical environment within and around CME source regions may be ultimately necessary for prediction.

Critical capabilities. (1) MHD models from active region to global scales are needed to cover the storage, release, and propagation stages of CMEs as are observations of all of these stages from Sun to Earth. (2) Time-evolving measurements of plasma and magnetic fields at multiple heights in the solar atmosphere and covering the global solar atmosphere, along with (3) methods for their incorporation into solar magnetic models, are required to improve the quality of real-time models and to advance the forecasting of space-weather events and heliospheric conditions.

SHP-4. Discover how the Sun interacts with the local interstellar medium

What is the nature of structure of the local interstellar medium magnetic field? Neutrals from the local interstellar medium (LISM) enter the heliosphere, become ionized and are picked up by the solar wind. These singly-ionized 'pickup ions' provide most of the pressure at the boundary of the heliosphere. The structure of the interface between the LISM and the heliosphere regulates the penetration of GCRs. During the recent solar minimum record high intensity levels of GCRs were measured, and additional analysis of past solar cycles indicate that this may be more 'typical' of future solar minima. If this proves true, evaluations of solar cycle dependence of radiation hazards at 1 AU and especially for long-term, manned space-exploration missions may have to be significantly re-evaluated. Additional surprises continue to emerge from the *in-situ* exploration of the solar wind-LISM boundary by the Voyager spacecraft: examples include lower amounts of solar wind heating at the heliopause than expected, the lack of a clear source for anomalous cosmic rays (ACRs), and an unexpected magnetic field orientation in the heliosheath. These observations are currently being combined with neutral atom measurements by IBEX and sensors on Cassini to give a more global picture of the structure of the heliosphere-LISM interaction.

Unfortunately the structure and orientation of the LISM magnetic field is poorly constrained by current measurements. Several new theories have been developed to explain the unexpected observations, but this remains a quickly evolving and active area of science with continuing new measurements, model development and model testing.

Critical capabilities. (1) Model development combined with appropriate data analysis from the Voyager and IBEX missions, are required to correctly interpret the new observations and understand the transport of both cosmic rays and neutral atoms throughout the region. (2) Methods for assimilating/incorporating the data into these models need to be developed, and the models ultimately made available to the community (e.g., via the CCMC) in order to better advance our understanding of ACR acceleration, GCR penetration into and propagation through the heliosphere, the interaction of the solar wind and LISM, and the propagation of solar/interplanetary disturbances out to the boundary and their impact on its structure.

5.4 Space Weather and Prediction

Beginning with its title, "Solar and Space Physics: A Science for a Technological Society," the Decadal Survey (DS) recognizes the importance of the application of space science to address societal needs. Furthermore, Key Science Goal 1 aims to "…predict the variations in the space environment". Prediction of the near-Earth space environment, on which society depends, is tantalizingly within reach. Yet, the DS committee "found that the existing ad hoc approach to providing space weather-related capabilities is inadequate."[13]

Unlike the summaries of the AIMI, SWMI and SHP challenges, which were explicitly called out with DS labels (e.g., AIMI-1, SWMI-3, SHP-4, etc.), goals and challenges for Space Weather and Prediction (SWP) were not organized in this manner. The GS-relevant challenges for space weather prediction may be derived from the following overarching objective.

> **SWP: Develop reliable predictive capabilities for when and in what direction major disturbances will be emitted by the Sun, and how they will affect the geospace environment when coupled with inputs from Earth.**

Major solar disturbances such as flares, CMEs, SEPs, and high-speed solar wind streams are the originators of space weather conditions at Earth and in interplanetary space that can endanger humans in space and damage or interfere with technological systems in space and on the ground. Flares emit intense X-rays and ultraviolet radiation that reaches Earth at the speed of light, affecting conditions in Earth's dayside ionosphere and upper atmosphere. CMEs and the co-rotating interaction regions formed when the high-speed solar wind encounters slower solar wind are sources of: geomagnetic storms and their attendant currents and aurora, atmospheric neutral density variations and geomagnetically induced currents (GICs). When acted upon by solar wind disturbances Earth's magnetic field acts as a natural but erratic particle accelerator; producing enhancements and depletions of the Van Allen radiation belts over short and long time scales. Additionally, the near-Earth space environment is influenced from below by physical and chemical processes associated with atmospheric tides, winds, gravity waves, lightning, the outflow of electrically charged particles from Earth's ionosphere and neutrals from the atmosphere.

Satellite operations, orbit prediction, precision navigation/location/timing services, astronaut activities in space, and HF radio communications with airlines are examples of activities that are affected by space weather disturbances. At Earth's surface, power grids, communication cables and pipelines are examples of infrastructure that can be affected by GICs. The radiation belts are one of the principal threats to human technological systems in space as well as humans flying in low-Earth systems such as the International Space Station. Numerous operational anomalies and outright failures of spacecraft systems and subsystems have been directly linked to radiation belt space weather episodes.

It remains a significant challenge to predict with accuracy where and when a flare will erupt and how intense it will be. There is essentially zero lead time for warning of the arrival of the flare's energy. Because we know SEPs are accelerated in association with flares and at CME shock fronts as they propagate through the background solar wind we can potentially forecast their arrival on time scales of minutes to hours, but it remains a challenge to predict with accuracy whether or not a particular flare or CME will result in SEPs striking Earth, the intensity and energy spectrum of the SEPs and how long the event will last. While recent MHD models of CMEs have improved the accuracy of whether or not a CME will strike Earth and when it will arrive, there are major challenges for better predictions and especially for predicting the vector magnetic field embedded in the CME. While it is perhaps easier to predict the arrival of high-speed streams, there are still significant challenges for predicting their timing and intensity.

[13] DS Chap. 7 page 139

Once a disturbance arrives at Earth the response still depends on many factors unique to the geospace system. Solar cycle and seasonal effects, as well as the preconditioned state of many of the different components of the geospace system, are additional important factors that require consideration and integration into a coupled predictive system.

Critical capabilities. Capabilities needed to address the challenges outlined above can be achieved through a variety of NSF GS programs. These efforts could combine to target space weather predictions and could benefit from feedback between research and operations communities. Many of the critical capabilities needed for this SWP effort are described in the sections 5.1-5.3. We extract the most relevant capabilities and include others that are important to space weather prediction.

Solar-Heliosphere: (1) Models from active-region to global scales of the storage, release, and propagation phases of eruptions Sun-to-Earth, and of periodic solar-wind forcing with associated geospace and GCR responses (2) Detailed knowledge of conditions before, during, and after eruptions from Sun to Earth, and of the global solar and heliospheric magnetic field

Magnetosphere: (1) Global simulations of the coupled SW-M-I-T interaction that include reconnection processes and magnetospheric waves and wave propagation linked to interaction with the I-T system. (2) New predictive models that combine earthward radial particle transport with local acceleration and appropriately incorporate nonlinear processes, as well as energetic particle loss mechanisms. (3) Detailed knowledge of the magnetic field configuration during disturbed conditions, as well as spectral information on the relevant plasma wave modes with respect to local time and latitude.

Space-Atmosphere Interaction Region: (1) Global assimilative and physics models of the electrodynamics of the ionosphere that self-consistently include the major drivers of energy production, transfer and loss throughout the system (2) Multi-scale first-principles models to predict unobservable parameters in the system (e.g., neutral abundances, ion composition); (3) Modeling and measurements of ionospheric irregularities; (4) Modeling of upper atmospheric conductivity; (5) Measurements and modeling of low- and mid-atmospheric phenomena (forcing from tides and orographic/weather system sources).

Geospace-Hazards: (1) Three-dimensional induction models supported by data from global magnetospheric MHD model output; (2) Mapping of the detailed 3-D ground conductivity structures in geomagnetically-induced-current prone regions; and (3) measurements of neutral density, winds and composition scientific studies related to satellite drag and debris mitigation.

Observations and Data Exploitation: (1) Time-evolving measurements of plasma and magnetic fields in the solar atmosphere, Earth's geospace and LEO environments; (2) Cyberinfrastructure capabilities to exploit the growing database of heterogeneous, multi-scale measurements; (3) Data exploitation of the measurements of the evolution of the solar wind, CMEs and their associated shocks, radio bursts, energetic neutral atoms (ENAs), and SEPs for advancing models of particle acceleration and transport; (4) Coordinated measurements of neutral and plasma dynamics, including ground-based measurements of neutral winds and temperatures, and coordinated global-scale observations from space; (5) Measurement of soft and hard precipitating particles; (6) Data-exploitation efforts to archive and cross-calibrate observational records.

The above description of the overarching SWP objective, and associated capabilities, clearly shows that such an endeavor sits at the frontier of current GS-funded efforts and Grand Challenge Science, and also at the boundary of NSF GS- and USGS-funded ground-based observatories and NASA- and NOAA-funded space-based observatories, as well as assets from other nations. In Chapter 6 the PRC describes Grand Challenge Projects that illustrate frameworks for the science that supports space weather prediction.

Similarly, the DS noted inadequacy for predicting "how changes on the Sun may affect Earth's climate, atmosphere, and ionosphere."[14] Predicting such changes is frontier research and thus requires (1) modeling capabilities already under development with NCAR's Whole Atmosphere Community Climate Model (supported by AGS), as well as global climate and chemistry models under development around the world; and (2) observational support for solar spectral irradiance supported by NASA. The Committee believes that GS support for coupling space weather and climate, particularly with respect to particle interactions, is more appropriate for a Grand Challenge Project effort described in Chapter 6 of this report.

[14] DS Chap. 3, page 74

5.5 Summary of Critical Capabilities

Capabilities required to address science goals and challenges of the AIMI, SWMI, SHP and SWP science thrusts of the DS are summarized in Tables 5.2-5.5.

Table 5.2 Summary of required capabilities and recommended investments for AIMI

Decadal Survey Challenge	Required Capabilities			Recommended Investments
	Observational	Theory/Modeling	Data Exploitation	
AIMI-1 *M-I-T System*	Distributed sampling from ground and space. Focus on conductance, electric field, and plasma and neutral composition, temperatures, densities, and velocities.	Development of advanced numerical algorithms and large-scale integration of global assimilative, first-principles, and space weather models	Innovative cloud-based approach to data aggregation and assimilation	**GS:** AER core, CEDAR, DASI, CubeSats, CCMC, ISRs, Data systems, AMPERE, SuperDARN, SuperMAG **External/partner:** EISCAT-3D, EISCAT-Svalbard, NCAR-CISL, DOE/NSF, NASA
AIMI-2 *Plasma-neutral coupling*	Coordinated measurements of plasma and neutral bulk properties	Regional and global models of the coupled plasma-neutral system.	Innovative cloud-based approach to data aggregation and assimilation	**GS:** AER core, CEDAR, DASI, CubeSats, CCMC, ISRs, Data systems, AMPERE, SuperDARN, SuperMAG **External/partner:** EISCAT-3D, EISCAT-Svalbard, NCAR-CISL, DOE/NSF, NASA
AIMI-3 *Lower atmospheric coupling*	Coordinated measurements of lower atmospheric phenomena and geospace effects. Focus on neutral dynamics, with plasma dynamics as proxy.	Innovative methods for advanced whole atmosphere model development.	Innovative cloud-based approach to data aggregation and assimilation	**GS:** AER core, CEDAR, DASI, CubeSats, CCMC, ISRs, Data system **External/partner:** NCAR-CISL, DOE/NSF, NASA
AIMI-4 *Long-term changes*	Multi solar cycle observations of critical geospace parameters (composition, densities, temperatures) at key locations	Coupling to climate models	Persistent long term measurements of critical geospace parameters in cost effective manner, e.g., maintain long term database (Madrigal) and pursue data science initiatives	**GS:** AER core, CEDAR, DASI, CubeSats, CCMC, ISRs, Data systems, AMPERE, SuperDARN, SuperMAG **External/partner:** EISCAT-3D, EISCAT-Svalbard, NCAR-CISL, DOE/NSF, NASA

Table 5.3 Summary of required capabilities and recommended investments for SWMI

Decadal Survey Challenge	Required Capabilities			Recommended Investments (Chapters 6-9)
	Observational	**Theory/Modeling**	**Data Exploitation**	
SWMI-1 *Magnetic reconnection*	Precipitation, ionospheric responses from ISR and imager measurements in dayside and nightside convection throats; global and regional coherent scatter radar (CSR) measurements of high-latitude flows; determination of ionospheric currents	Large-scope 3D kinetic simulations; regional flux tube simulations; Global MHD simulations; high-performance computing	Common database for ground- and space-based measurements; data analysis, visualization tools; innovative cloud-based approach to data aggregation; development of data assimilation methods	**GS:** MAG core, GEM, GCP; PFISR, RISR-N; AMPERE, SuperDARN, SuperMAG, CCMC; Data Systems, DASI **External/partner:** RISR-C, TREx, NCAR-CISL, DOE/NSF Partnership, NASA, DoD
SWMI-2 *Particle energization*	Distributed ground-based and low-altitude measurements of precipitation (imagers, riometers, CubeSats); magnetic perturbations (magnetometers); ionospheric convection (ISR, CSR); TEC;	Bounce-averaged transport models; kinetic and hybrid simulations; global MHD simulations; assimilative and empirical models of waves based on observations.		**GS:** MAG core, GEM, GCP, CubeSats; MH ISR; SuperMAG, SuperDARN, CCMC; Data Systems, DASI **External/partner:** EISCAT-Svalbard, EISCAT-3D, TREx, NCAR-CISL, DOE/NSF Partnership, NASA, DoD
SWMI-3 *SW-M-I-T coupling*	High- and mid-latitude synoptic measurements of electric currents, convective electric fields, energy and flux of charged-particle precipitation, ionospheric conductivities, ionospheric plasma density and number flux of upflowing ions, frequency and wavenumber spectrum of turbulent fluctuations	Global/regional simulations of SW-M-I-T interactions; MHD extensions with generalized Ohm's law, drift kinetics; local/ regional 3D kinetic simulations of charged particle energization; empirical models		**GS:** MAG core, AER core, GEM, CEDAR, GCP, SWR; PFISR, RISR-N, MH ISR; AMPERE, SuperDARN, SuperMAG, CCMC; Data Systems, DASI **External/partner:** EISCAT-Svalbard, EISCAT-3D, RISR-C, TREx, NCAR-CISL, NASA, DoD
SWMI-4 *Comparative M-I-T system science*		Comparative theories and simulations models (MHD, hybrid, kinetic); empirical models		**GS:** MAG core, possibly GCP **External/partner:** NCAR-CISL, DOE/NSF Partnership, NASA

Table 5.4 Summary of required capabilities and recommended investments for SHP

Decadal Survey Challenge	Required Capabilities			Recommended Investments (Chapters 6-9)
	Observational	**Theory/Model**	**Data Exploitation**	
SHP-1 *Solar cycle origins*	Solar synoptic analyses -- helioseismology, surface flows/magnetism; evaluation of constraints from Sun-like stars.	Dynamo theory/model development	Data assimilation methods for driving predictive dynamo and flux-transport models	**GS:** STR core, SHINE, GCP; CCMC; Data Systems **External/partner:** NSO-NIST, NOAO, NASA
SHP-1 *Solar cycle impacts*	Analyses of high temporal and spatial resolution observations of solar plasma and magnetic fields. Analyses of space-age synoptic Sun-to- Earth observations and historical/geological solar-cycle proxies. Global magnetometric observations at multiple heights in atmosphere.	Models connecting observations sun to earth; theory/ models connecting solar magnetic variability to radiative and particulate drivers at Earth.	Data archiving, cross-calibration	**GS:** STR core, SHINE, GCP; CCMC; Data Systems; Midscale (COSMO,FASR) **External/partner:** NSO-DKIST/NIST, NCAR-HAO, NRAO, NASA
SHP-2 *Coronal heating and solar wind acceleration*	Analyses of high temporal and spatial resolution measurements of the solar wind and solar atmosphere, and of synoptic observations connecting solar wind to sources. Global magnetometric observations at multiple heights in atmosphere	Coronal heating and solar wind acceleration models; simulations spanning solar interior - atmosphere; global models for context.	Methods for driving simulations with multi-height measurements	**GS:** STR core, SHINE, SWR, GCP; CCMC; Data Systems; Midscale (COSMO, FASR) **External/partner:** NSO-DKIST/NIST, NCAR-HAO, NRAO, NASA
SHP-3 *Explosive energy release*	Analyses of remote sensing and *in-situ* measurements of flares, CMEs, shocks, suprathermal and energetic particles, neutron monitors. Multi-height solar atmospheric observations. Active region magnetometry; electron beam and shock observations.	Models of particle acceleration and transport, and of storage and release of magnetic energy	Development of data assimilation methods and cross-calibration analysis tools for multipoint analysis	**GS:** STR core, SHINE, SWR, GCP; CCMC; Data Systems; Midscale (FASR) **External/partner:** NSO-DKIST/NIST. NCAR-HAO, NRAO, GEO-PLR-AAGS
SHP-3 *Origins and geoeffectiveness of flares and CMEs*	Analyses of observations before, during, and after eruptions from Sun to Earth; multi-height measurements constraining solar magnetic field from local to global scales. Global magnetometric observations at multiple heights in atmosphere.	Models from active-region to global scales of the storage, release, and propagation phases of eruptions Sun-to-Earth	Analysis tools for multi-height measurements and methods for assimilating into global magnetic models	**GS:** STR core, SHINE, SWR, GCP; CCMC; Data Systems; Midscale (COSMO, FASR) **External/partner:** NSO-NIST/DKIST, NCAR-HAO, NRAO
SHP-4 *Outer heliosphere*	Analyses of outer heliospheric observations	Model development related to transport of ACRs, GCRs and ENA throughout the region	Development of data assimilation methods	**GS:** STR core, SHINE, GCP; CCMC; Data Systems **External/partner:** NASA

Table 5.5 Summary of required capabilities and recommended investments for SWP

SWP Challenge	Required Capabilities			Recommended Investments (Chapters 6-9)
	Observational	**Theory/Modeling**	**Data Exploitation**	
Solar Heliospheric	Multi-height synoptic measurements constraining solar magnetic field from local to global scales. Remote sensing and in-situ measurements of flares, CMEs, shocks, suprathermal and energetic particles.	Models from active-region to global scales of the storage, release, and propagation phases of eruptions Sun-to-Earth, and of particle acceleration and transport.	Common databases, data visualization, data assimilation into global and eruptive models	**GS**: STR Core, SHINE; SWR, GCP; CCMC; Data Systems; Midscale (COSMO, FASR) **External:** NSO-NIST/DKIST, NCAR-CISL/HAO, NRAO, GEO-PLR-AAGS, NASA
Magnetosphere	Measurements of trapped and precipitating rad belt particles (possibly from CubeSats); measurements from neutron monitors, riometers, and ground-based radar for context	Global SW-M-I-T models; comprehensive models of radiation belt acceleration, radial transport and loss (both atmospheric precipitation and magnetopause escape); magnetospheric B-field models	NSF-supported data collections (listed on left) must be fully archived and made broadly available	**GS:** Core, strategic grants; GBOs (Obs. at left); Data Systems; CCMC **External:** NASA, NOAA, DOD data; NCAR-CISL
Space-Atmosphere Interaction Region	GB magnetometers, radars; synoptic measurements of LEO ΔB, E and particles; LIDARs, imagers, DASI; GNSS scintillation; diagnostics for lower atmosphere forcing	Predictive M-I-T models; global conductivity models; models for neutral density and charged particle density to support satellite drag and radio propagation needs	NSF-supported data collections (listed on left) must be fully archived and made broadly available; model visualization, validation; improved data assimilation schemes	**GS:** Core, strategic grants; DASI; CubeSat diagnostics; synoptic observations; CCMC **External:** NASA, NOAA, DOD data; NCEI databases; NCAR-CISL
Geospace Hazards	3-D ground conductivity maps	Linked MHD-GIC models; for satellite drag see above	See above	**GS:** Core, strategic grants; CCMC **External:** NASA, NOAA, USGS data

Chapter 6. GS Core and Strategic Grants Programs

The GS grants programs provide many of the critical capabilities needed to make progress in achieving DS goals. They are the lifeblood of the scientific enterprise, without which little scientific advancement can occur.

The grants programs support analysis of scientific data derived from all types of measurements, not just those from GS-sponsored facilities and instruments. They support development of new theories and computer models that are essential in advancing scientific understanding of geospace and solar processes. The grants programs sponsor early-phase development projects leading to innovative new measurement techniques and simulation capabilities and large collaborative research projects, some wholly funded by NSF, others cosponsored by international partners and other US agencies. GS grants provide the nucleus of funding for GS investigators to participate in a wide variety of workforce, cross-disciplinary, seed and targeted research programs that are initiated and co-funded by other NSF entities and that leverage GS investments. Maintaining vibrant, peer-reviewed grants programs is absolutely critical for the future vitality of geospace and solar science.

The Decadal Survey recommended implementation of a new, integrated, multi-agency initiative (DRIVE—Diversify, Realize, Integrate, Venture, Educate) that will develop more fully and employ more effectively the many experimental and theoretical assets at NASA, NSF, and other agencies. The DRIVE recommendations are an important touchstone for PRC recommendations. For reference later in this and other chapters, the NSF-relevant DRIVE recommendations are listed in TABLE 6.1.

The Survey's recommendations for the DRIVE initiative were derived from disciplinary panel recommendations on scientific priorities and imperatives. The PRC recognizes that panel-specific imperatives are not equivalent to survey recommendations. Nevertheless they do offer useful information in determining how best to align GS investments in support of critical capabilities. The Survey's panel-specific imperatives were also reviewed by the PRC to inform its recommendations.

Two imperatives advocated by the SWMI panel specifically address GS-relevant Space Weather research. In particular, the SWMI panel encouraged all agencies to foster interactions between the research and operational communities and to identify funding for maintaining a healthy research-to-operations/operations-to-research program; and to implement a program to determine, based on past observations, the optimum set of measurements that are required to drive high-fidelity predictive models of the environment. Additionally, in its summary of Application Recommendations,[15] the DS recommended the development and maintenance of distinct funding lines for basic space physics research and for space weather specification and forecasting.

This chapter summarizes the PRC's review of investments in GS core and strategic grants programs and its recommendations to ensure GS investments are positioned to provide the critical capabilities identified in the previous chapter. Capabilities and recommendations for a vital GS workforce were addressed in Chapter 4. Facilities and (non-GS) programs that leverage GS investments are addressed in Chapters 7 and 8, respectively.

[15] DS Executive Summary, p. 4

TABLE 6.1 NSF-Relevant DRIVE Initiatives

Diversify: ***Diversify Observing Platforms with Microsatellites and Midscale Ground-Based Assets.***

D1. The National Science Foundation should create a new, competitively selected midscale project funding line in order to enable midscale projects and instrumentation for large projects.

D2. NSF's CubeSat program should be augmented to enable at least two new starts per year. Detailed metrics should be maintained, documenting the accomplishments of the program in terms of training, research, technology development, and contributions to space weather forecasting.

Realize: ***Realize Scientific* Potential *by Sufficiently Funding Operations and Data Analysis***

R1. NSF should provide funding sufficient for essential synoptic observations and for efficient and scientifically productive operation of the Advanced Technology Solar Telescope (ATST), which provides a revolutionary new window on the solar magnetic atmosphere.

R2. Support a solar and space physics data environment that draws together new and archived satellite and ground-based solar and space physics data sets and computational results from the research and operations communities for (i) coordinated development of a data systems infrastructure that includes data systems software, data analysis tools, and training of personnel; (ii) community oversight of emerging, integrated data systems and interagency coordination of data policies; (iii) exploitation of emerging information technologies without investment in their initial development; (iv) virtual observatories as a specific component of the solar and space physics research-supporting infrastructure, rather than as a direct competitor for research funds; (v) community-based development of software tools, including tools for data mining and assimilation; and (vi) Semantic technologies to enable cross-discipline data access.

Integrate: ***Integrate* Observing *Platforms and Strengthen Ties Between Agency Disciplines***

I1. NASA should join with NSF and DOE in a multiagency program on laboratory plasma physics and spectroscopy, with an expected NASA contribution ramping from $2 million per year (plus increases for inflation), in order to obtain unique insights into fundamental physical processes.

I2. NSF should ensure that funding is available for basic research in subjects that fall between sections, divisions, and directorates, such as planetary magnetospheres and ionospheres, the Sun as a star, and the outer heliosphere. In particular, research on the outer heliosphere should be included explicitly in the scope of research supported by the Atmospheric and Geospace Sciences Division at NSF.

I3. NASA, NSF, and other agencies should coordinate ground- and space-based solar-terrestrial observational and technology programs and expand efforts to take advantage of the synergy gained by multiscale observations.

Venture: ***Venture* Forward *with Science Centers and Instrument and Technology Development***

V1. NASA and NSF together should create Heliophysics [geospace] science centers to tackle the key science problems of solar and space physics that require multidisciplinary teams of theorists, observers, modelers, and computer scientists, with annual funding in the range of $1 million to $3 million for each center for 6 years, requiring NASA funds ramping to $8 million per year (plus increases for inflation).

Educate: ***Educate,* Empower*, and Inspire the Next Generation of Space Researchers*** (*addressed in PR Ch 4*)

E1. The NSF Faculty Development in the Space Sciences (FDSS) program should be continued and be considered open to applications from 4-year as well as Ph.D.-granting institutions as a means to broaden and diversify the field. NSF should also support a curriculum development program to complement the FDSS program and to support its faculty.

E2. A suitable replacement for the NSF Center for Integrated Space Weather Modeling summer school should be competitively selected, and NSF should enable opportunities for focused community workshops that directly address professional development skills for graduate students.

E3. To further enhance the visibility of the field, NSF should recognize solar and space physics as a specifically named subdiscipline of physics and astronomy by adding it to the list of dissertation research areas in NSF's annual Survey of Earned Doctorates.

The next section (6.1) summarizes the PRC's findings and recommendations on general aspects of the GS disciplinary programs, and connections between these and other programs internal and external to GS. Findings and recommendations specific to GS grants programs in Aeronomy (AER), Magnetospheric Physics (MAG) and Solar-Terrestrial Research (STR) follow in Sections 6.2-6.4. Findings and recommendations pertaining to Integrative Geospace Science is addressed in Section 6.5, to the CubeSat program Section 6.6, and to the need for regular Senior Review of the grants programs in Section 6.7.

6.1 General Aspects of GS Grants Programs

Each of the disciplinary programs (AER, MAG, STR) includes core and targeted grant programs. The targeted programs include the Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) Program administered by the AER Program Manager (PM), the Geospace Environment Modeling (GEM) Program administered by the MAG PM and the Solar Heliospheric and Interplanetary Environment (SHINE) Program administered by the STR PM.

Finding. *The current structure of GS Core Research program (AER, MAG and STR) with associated Targeted programs (CEDAR, GEM and SHINE) supports the zeroth order DS recommendation to complete the current program and partially satisfies the DS higher level recommendations to implement DRIVE and extend model development efforts to the point that they support forecasts of the dynamics of this complex, nonlinear system and its impacts on society.*

Finding. *The average proposal success rates (Section 4.1) have been acceptable in the core grants programs (about 1 in 4 on average) and are marginal in the targeted grants programs (closer 1 in 5 on average). However, the rates are uneven across individual programs, e.g., the number of proposals submitted to the SHINE program nearly doubled from 2012 to 2014 when the proposal success rate went from 32% to 17%.*

Success rates below 20% have a lottery quality and encourage PIs to submit highly ranked but unsuccessful proposals to other programs or agencies or to the same program at a later date with updates and/or tweaks. This practice has an adverse impact on the scientific productivity of the community at large as discussed in Section 4.1.

Recommendation 6.1. A collective budget for core programs should be apportioned among AER, MAG and STR according to proposal pressure (number and quality) without fixed budgets for each discipline. Similar principles should be applied to the targeted programs.

Finding. *The critical capabilities described in Chapter 5 place requirements on programs beyond the disciplinary programs, both internal and external to GS. Existing programs include elements of Integrative Geospace Science such as the Space Weather (SW) program (described in Section 6.5), CubeSats (described in Section 6.6), facilities and infrastructures (described in Chapter 7), and NSF-wide programs and partnerships with other entities (Chapter 8).*

Finding. *Some of the critical capabilities described in Chapter 5 require new grants program elements, including the Grand Challenge Projects (GCP) program (Section 6.6), and new facilities and infrastructures programs (Section 7.4).*

Finding. *Because of the enormity and inaccessibility of the geospace system much of its science relies on modeling. The physical system spans a spatial range from Debye lengths (as small as 10^{-6} m) to 1 AU (10^{11} m) and spans a temporal range from chemical reactions (as short as 10^{-14} sec) to the* *electron plasma period (as short as 10^{-7} sec) to the transit time of plasma from the Sun to the Earth (several days) to solar cycle time scales. Additionally, different physical processes dominate on different time and length scales, and require different physical descriptions (e.g., kinetic, hybrid, or fluid). This challenge can only be accomplished with sophisticated, high-level computational models of the system, rather than trying to model it as a collection of loosely connected regions. A considerable amount of research is required to develop models that truly describe the 'system science' of the Sun-Earth system.*

Recommendation 6.2. The PRC recommends that GS continue support of multi-scale physics-based and data-assimilation models with an emphasis on integrated science and the coupling of models. Opportunities for model development and implementation can come from core and targeted research as well as the Space Weather and GCP programs, the CCMC, and the recommended Innovations & Vitality line (Section 7.4).

Recommendation 6.3. AER/MAG/STR grants research also should continue to serve as a technology incubator, funding modest-scale projects in experimental instrument development with a focus on new scientific capabilities. As these development efforts mature, their funding source should transition from the core programs to programs such as the recommended Innovation and Vitality (Section 7.4.1) and DASI (Section 7.4.3) programs and the CubeSat program. The GS should also encourage instrument development projects to seek funding through the NSF-wide MRI and MREFC programs when appropriate (Section 8.1).

6.1.1 Core Grants Programs

***Finding**. The core grants programs are unsolicited grants programs without proposal deadlines. PMs solicit peer reviews of proposals without convening follow-up review panels for further evaluation.*

Recommendation 6.4. The PRC recommends that GS maintain its Core Research Program as a Priority 1 effort, with a collective budget for all three programs not less than the current level. The core programs should conduct innovative data analysis and exploitation, theory, modeling, development and application of new instrumentation, measurement techniques and laboratory experiments aligned with the core goals of each program, as articulated in following subsections.

Recommendation 6.5. The GS should continue to encourage the geospace science community to participate in leveraged, targeted research programs, but caution is advised when the leveraged funding is derived from GS core research programs. In committing core grants funds to these targeted opportunities, GS PMs should guard against scope creep over time that tends to diminish unsolicited core funds available for competition.

6.1.2 Strategic Grants Programs

***Finding.** The current disciplinary targeted grants programs (CEDAR/GEM/SHINE) are also strategic research programs. They advance research strategies by developing community consensus around critical and timely directions for research. Their modus operandi are to use community workshops to target and coordinate specific observing and modeling campaigns, research challenges, event studies, focus group studies and workshop sessions to advance strategic research and to explore scientific issues of immediate concern.*

Finding. *The workshops sponsored by CEDAR, GEM, and SHINE are very popular and well attended. They leverage science enabled by GS investments with programs, data, instruments, facilities and missions sponsored by other agency and international partners. They are effective in facilitating research collaborations. They are also an important professional development opportunity for early career scientists.*

Recommendation 6.6. The GS should continue to support the three targeted research programs and their summer workshops (as also recommended in Section 4.8) and evaluate their continuing alignment with GS goals at semi-decadal intervals using a Senior Review process (Section 6.7).

Finding. *Consistent with the overarching theme of the Decadal Survey, CEDAR, GEM, and SHINE have moved towards systems science in recent years. CEDAR and GEM in particular have a tradition of working together to promote cross-disciplinary interactions between the magnetospheric and aeronomy communities.*

Recommendation 6.7. The GS should encourage multidisciplinary research that bridges the traditional program areas within the Section, in particular, across the three targeted grants programs. Over the next decade and as appropriate projects emerge, a portion of the current budget for targeted grants programs should migrate into the Integrative Geospace Science grants programs (Section 6.5). (See Chapter 9 regarding provisional budget recommendations.)

Finding*. The targeted grants programs solicit proposals for opportunities with proposal deadlines, and they convene review panels to recommend proposal selections. Panel reviews are considered to be useful in identifying proposals that are best aligned with strategic research goals.*

Finding*. Proposal success rates tend to be higher in the core grants programs than in the targeted grants programs.*

Recommendation 6.8. The GS should evaluate the utility of proposal deadlines in its targeted grants programs and determine whether proposal deadlines may be stimulating an artificial inflation in proposal submissions for the limited funding available in the targeted programs, resulting in lower proposal success rates as suggested in an experiment undertaken by the Division of Earth Sciences.[16] If proposal deadlines do result in inflated numbers of proposal submissions, then the GS should charge its Committees of Visitors to evaluate the merit of retaining proposal deadlines in its targeted programs.

An alternative to the current mode of soliciting proposals with a deadline, coupled with proposal reviews and recommendations for proposal selections by ad hoc panels, might involve convening virtual panel reviews at regular intervals throughout the year to recommend selections of unsolicited proposals submitted to targeted programs. This model would retain the desired effect of having panels identify proposals that are best aligned with strategic research goals.

6.2 Aeronomy

Aeronomy is the science of planetary atmospheres in which the physical and chemical processes associated with solar radiation are predominant. At NSF the Aeronomy Program supports "research from the mesosphere to the outer reaches of the thermosphere and all regions of the

[16] Report to the National Science Board on the National Science Foundation's Merit Review Process, Fiscal Year 2014 (NSB-2015-14) p. 48-49, Table 16. (http://www.nsf.gov/nsb/publications/2015/nsb201514.pdf)

Earth's ionosphere." The Aeronomy Program seeks to understand phenomena of ionization, recombination, chemical reaction, photo-emission, and the transport of energy, and momentum within and between these regions. The program also supports research into the coupling of this global system to the stratosphere and troposphere below and magnetosphere above and the plasma physics of phenomena manifested in the coupled ionosphere-magnetosphere system, including the effects of high-power radio wave modification."

Finding. *The research conducted within AER addresses all of the AIMI science challenges and aspects of Key Science Goals 2 and 4 of the Decadal Survey.*

6.2.1 AER Core Program

The Aeronomy program sponsors a diverse range of topics related to phenomena occurring between the atmosphere we breathe and the interplanetary environment. Topics include, but are not limited to, instrument development, laboratory experiments, comparative aeronomy (with other solar system bodies), meteors, lightning, basic research on the ionosphere, thermosphere, and mesosphere, plasma instabilities and their societal effects, neutral gas dynamics (waves, tides), and magnetospheric interactions.

Finding. *Geospace facilities have historically been directed toward aeronomical measurements (e.g., ground-based radars, active and passive optical systems, magnetometers). As such there has been a close connection between the Aeronomy and Facilities Programs within the Geospace Section.*

Finding. *The general trajectory of the Aeronomy program (and CEDAR) over the past 10 years has been toward "system science" supported by the Distributed Arrays of Scientific Instruments (DASI) initiative and parallel efforts in assimilative and first-principles modeling.*

Recommendation 6.9. The GS should encourage and fund AER research projects, in collaboration with the MAG community, for early development of DASI concepts for diagnosing upper atmospheric, ionospheric and magnetospheric processes, as well as the development of self-consistently coupled physics-based models. As the DASI concepts mature, their funding source should migrate to the GS Facilities program (Section 7.4.3).

6.2.2 CEDAR

The primary goal of the CEDAR program residing within AER is to "explain how energy is transferred between atmospheric regions by combining a comprehensive observational program with theoretical and empirical modeling efforts."

The CEDAR program has evolved organically over its three decades of existence. The initial goal of the program was to coalesce a set of individual PIs sponsored by small instrument grants. The meeting soon became a venue for groups of PIs to organize "campaigns" targeting a specific science topic addressed by a specific group of measurements and models.

Finding. *CEDAR is both a community-driven and targeted element of the Geospace Section budget as distinct from the core. The benefits of a funded CEDAR grants program include (1) targeted funding aligned with a community-driven strategic plan, (2) panel reviews, which consider ~30 proposals at one time, that are beneficial for comparisons and community discussions, and (3) occasional cross-disciplinary competitions, such as the CEDAR-GEM M-I coupling competition. The CEDAR grants program has been nimble and responsive to changes in science priorities, technical* *capabilities and funding realities.*

Finding. *CEDAR currently supports an annual meeting and a grants solicitation with nominal deadline of mid-July.*

Finding. *In recent years, the CEDAR "Grand Challenge Workshops" have engaged broad segments of the CEDAR and GEM communities in grass-roots, collaborative, multi-disciplinary research campaigns. These workshops are distinct from the Grand Challenge Project (GCP) program recommended in Section 6.5, although such workshops may help define candidate topics for the GCP program.*

Recommendation 6.10. The CEDAR grants program should continue to support community-defined "Grand Challenge Workshops", preferably jointly with the GEM Grants program.

6.3 Magnetospheric Physics

NSF's Magnetospheric Physics Program "supports research on the magnetized plasma envelope of the outer atmosphere, including energization by the solar wind; the origin of geomagnetic storms and substorms; the plasma population by solar and ionospheric sources; the origin of electric fields; the coupling among the magnetosphere, ionosphere, and atmosphere; and waves and instabilities in the natural plasma."

Finding. *The research conducted within MAG addresses all of the SWMI science challenges and aspects of Key Science Goals 2 and 4 of the Decadal Survey.*

Finding. *The low-altitude regions of geospace encompassing the thermosphere and ionosphere and its outer regions including the solar wind-magnetosphere interaction, the magnetosphere and magnetotail, and the inner magnetosphere and plasmasphere are connected. Consequently, some degree of synergy between the MAG program and the AER and STR programs is expected in cross-over areas of mutual interest.*

6.3.1 MAG Core Program

MAG core grants support data analysis, especially combining ground-based and satellite data sets, theory and simulation of magnetospheric processes, and data acquisition and analysis from GBOs to investigate magnetospheric processes. It supports research into universal processes such as magnetic reconnection, plasma turbulence, transport and energization and waves and instabilities in collisionless plasmas. Research into other planetary magnetospheres has also been supported.

Finding. *Investments in observational capabilities include both ground-based observational programs at high latitudes and laboratory experiments applicable to the geospace environment. Analysis of data from all sources, whether ground-based or from spacecraft, and advancement of numerical simulations using a variety of MHD, hybrid and particle codes are also supported.*

Finding. *Little instrument development is sponsored by the MAG program, most likely because it receives fewer proposals for instrument development than the AER program. However, innovative projects like AMPERE, SuperDARN and SuperMag received MAG core funding for early phase development and operation and have now become Class 2 facilities, as reviewed in Chapter 7.*

Finding. *Historically the MAG program has funded deployment, maintenance and operation of GBOs for magnetometers, optical imagers and radio receivers, and acquisition and analysis of data obtained from these instruments. It also funds synoptic studies relevant to magnetospheric processes* *using data from ISRs, and AMPERE and various DASIs including SuperDARN, magnetometers and imagers, together with satellite data acquired from NASA, DOD and NOAA missions.*

Recommendation 6.11. The GS should encourage and fund MAG research projects, in collaboration with the AER community, for early development of DASI concepts for diagnosing upper atmospheric, ionospheric and magnetospheric processes. As the concepts mature, their funding source should migrate to the GS Facilities program.

6.3.2 GEM

The Geospace Environment Modeling (GEM) Program is a strategic research element of the Magnetospheric Physics Program with the goal "to understand the solar-terrestrial system well enough to be able to formulate a mathematical framework that can predict the deterministic properties of geospace ('weather in space') and the statistical characteristics of its stochastic properties ('climate in space')."

The GEM Program supports global geospace model development and applications, synoptic ground-based observations and the acquisition, coordination and use of data from any sources that advance the program goal. Like the CEDAR Program, GEM has a strong focus on integrative geospace science. Its synergistic outcomes typically culminate in community-initiated campaigns and science challenges.

Finding. *In addition to its overarching goal of developing predictive models for geospace weather and climate, GEM research is organized around evolving community-defined themes that culminate in (typically) five-year duration GEM Focus Groups selected by the GEM steering committee at its Fall AGU meeting. Competitive research proposals for GEM funding must address either some aspect of geospace model development, model validation, or topics relevant to one or more of the currently active GEM Focus Groups.*

Finding. *GEM focus groups coordinate observational and modeling research and issue research challenges to the community at large. The response to past challenges has been successful in advancing GEM goals. These challenges substantially leverage the modest investment in GEM by GS and attract broad interest in integrative science relevant to GEM.*

Finding. *The GEM program funds an annual call for research proposals with a mid-October deadline, a summer workshop, a mini-workshop held in conjunction with the fall AGU meeting and communications for GEM news and workshop summaries.*

Recommendation 6.12. The GEM grants program should continue to support community-defined research challenges and, when appropriate, "Grand Challenge Workshops" jointly with the CEDAR Grants program.

6.4 Solar-Terrestrial Research

The STR program supports research aimed at understanding the flow of energy from the Sun, through the solar wind, to the Earth and beyond. Specifically, STR research focuses on the plasma, fields, and energetic particles that originate at the Sun and propagate towards Earth and the processes that govern their generation and transport. While much of the STR research is related to space weather and has significant potential for improving predictive capability, the focus is on basic research into a wide range of processes of solar-terrestrial physics.

Finding. *The research conducted within STR addresses all of the SHP science challenges and Key Science Goal 1 of the Decadal Survey, as well as aspects of Key Science Goals 3 and 4.*

6.4.1 STR Core Program

STR core grants support data analysis and exploitation, theory and modeling, and instrument development. Major topics include the solar dynamo, the solar cycle, helioseismology, magnetic flux emergence, solar flares, coronal mass ejections, magnetic reconnection, solar wind, interplanetary disturbances, energetic particles, shock acceleration, diffusion, magnetic turbulence, the solar wind/magnetosphere boundary and space weather effects.

Finding. *In addition to funding investigations focused on a single aspect of the Sun or interplanetary space, a large portion of selected proposals study the Sun-Earth as a system, combining ground- and space-based observations with sophisticated models. This movement towards system science has been reflected in the steady increase of collaborative proposals submitted to the program over the last six years.*

Finding. *Most of the observational data relevant to STR research are produced by facilities operated by entities outside the GS section. These include NSF solar facilities managed by the AST Division – the National Solar Observatory (NSO) and National Radio Astronomical Observatory (NRAO) – and by the AGS Division's NCAR/HAO – the Mauna Loa Solar Observatory (MLSO). Observations of solar-analog stars are taken by the National Optical Astronomical Observatory, also managed by the AST Division and measurements relevant to energetic particles are obtained by neutron monitors supported by the Polar Programs (PLR) Division of the Geosciences Directorate. Solar science also often relies on various observatories managed by universities (often with grants from NSF), numerous NASA-run satellites, ground-based telescopes run by the Air Force, as well as various international assets.*

Finding. *The STR research program is important for maximizing the scientific return from these external programs and conversely, these observations are critical to many STR-funded studies. Although review of the management of these facilities is beyond the purview of this Portfolio Review, it is emphasized that non-GS NSF assets are essential in providing critical capabilities identified in Chapter 5.*

Recommendation 6.13. STR grants programs should continue to support analyses of important synoptic and high-resolution observations derived from observatories operated external to GS.

Recommendation 6.14. The STR program manager should continue to meet regularly with managers of the various ground-based telescopes in order to coordinate priorities and improve communication. Such efforts must continue in order to minimize any unintended consequences of altering the priorities of data collection at these facilities.

Finding. *The advent of the DKIST under development by the NSO, and to be operated by the NSO, presents a unique opportunity for exploiting a transformational new observational facility.*

Recommendation 6.15. To reap the full potential of DKIST, the AST and AGS Divisions should explore modes of collaboration that best support science from this new facility.

6.4.2 SHINE

The SHINE program residing within STR brings together researchers from the solar, interplanetary, and heliospheric communities, in order to "study the processes by which energy in the form of magnetic fields and particles are produced by the Sun and/or accelerated in interplanetary space and on the mechanisms by which these fields and particles are transported to the Earth through the inner heliosphere. "

The SHINE program and in particular its grassroots-created workshop originated to bring scientists working on different aspects of the Sun-Earth system together in an environment where active discussion, rather than polished talks, were the main focus. The SHINE workshops are thus an important venue for ST community building and for student training (see Chapter 4).

Finding. *The SHINE program funds an annual call for research proposals with a mid-December deadline, as well as an annual workshop. Proposals focus on the primary topics discussed at the annual SHINE workshop, including the SHP challenges described in Section 5.3 and aspects of solar-terrestrial physics relevant to space weather.*

6.5 Integrative Geospace Science

President John F. Kennedy in his 1963 presentation to the U.S. National Academy of Sciences, on the occasion of the 100th anniversary of that institution, asserted "… that science is already moving to enlarge its influence in three general ways: in the interdisciplinary area, in the international area, and in the intercultural area. For science is the most powerful means we have for the unification of knowledge, and a main obligation of its future must be to deal with problems which cut across boundaries, whether boundaries between the sciences, boundaries between nations, or boundaries between man's scientific and his humane concerns."[17]

Over the past decades GS has supported intense basic science investigations at the "regional" levels associated with the domains of CEDAR-Aeronomy, GEM-Magnetosphere, and SHINE-Solar

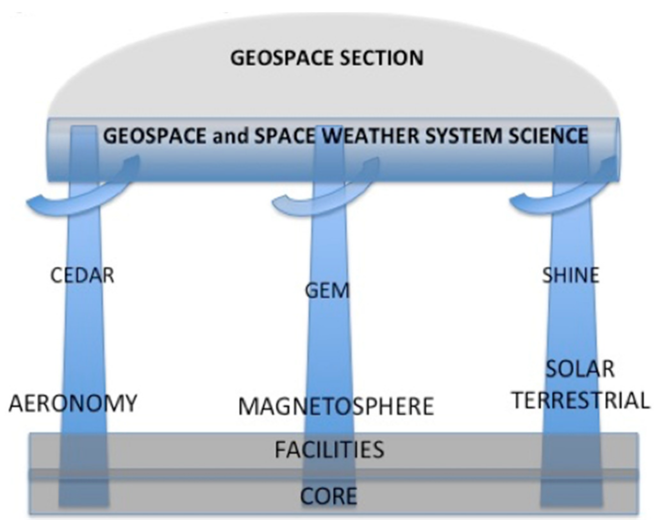


Figure 6.1. A GS framework that illustrates a vision for Integrative Geospace Science

[17] "A Century of Scientific Conquest by John F. Kennedy in The Scientific Endeavor, Centennial Celebration of the U.S. National Academy of Sciences, 1963

Terrestrial. Figure 6.1 depicts an Integrative Systems Science Framework for the Geospace Section. In some ways, this framework represents the work currently supported by the Geospace Science section, but more importantly it presents a view that can serve to enhance and encourage a new and innovative integrative systems science emphasis and approach. It is meant as a vision and framework for future programs rather than a prescribed administrative structure that is best left to those who carry out day-to-day business. The integrative approach rests on a foundation of core research and facilities supported by NSF Geospace Section grants in the areas of Aeronomy, Magnetosphere and Solar-Terrestrial interactions. Each of the core areas has associated targeted science programs represented by CEDAR, GEM and SHINE where both grants and connections to community science programs come together to advance Geospace Section goals. All of these activities are threaded by overarching system science programs that build on the elements below but play an integrative role and cut across discipline boundaries.

Finding. *GS is poised to fuse and integrate the growing knowledge base across these disciplinary areas to create an Integrated Geospace Science (IGS) Program, which encompasses Space Weather as a system science, as well as Grand Challenge Projects which requires cross-disciplinary interactions.*

6.5.1 Space Weather Research

In the 1990's GS (then Upper Atmosphere Section) spearheaded the effort to establish space weather as a viable new science and took an active role in establishing the National Space Weather Program. Space Weather is an example of integrative systems science that threads all the elements of research supported by the Geospace Section. In the GS, "The Space Weather Research program supports the development of integrative space science models, extended network observing capabilities, and targeted education and outreach with the overarching goal to meet societal needs for improved monitoring and advance predictions of space weather phenomena and effects." While fundamental space weather science can be focused on individual elements of the system, it can also focus on an integrative view and interdisciplinary aspects of the heliospheric system.

Finding: *With contributions from AFOSR and ONR, the GS ran an annual solicitation for research in support of the National Space Weather Program from 1996 through 2010. This dedicated funding line was discontinued in 2011, at which time GS posited that research relevant to space weather had started to emerge in the CEDAR, GEM and SHINE programs with some degree of observational support coming from Class 2 facilities (reviewed in Chapter 7). Investments in this seminal space weather research program were subsequently redirected into what has now become the NASA/NSF Collaborative Space Weather Modeling program.*

Finding. *As currently configured the Space Weather Research (SWR) program is an administrative structure for managing a variety of GS grants (NASA/NSF Collaborative Space Weather Modeling and CubeSat), facilities (Class 2 facilities reviewed in Chapter 7) and workforce (FDSS reviewed in Chapter 4) programs. Among these programs as described in Chapter 3, only the NASA/NSF Collaborative Space Weather Modeling program supports clearly differentiated space weather research. An unspecified portion of the budgets for Class 2 facilities and the CubeSat and FDSS programs augments this space weather modeling effort.*

Finding. *Proposals are solicited every three to five years in the NASA/NSF Collaborative Space Weather Modeling Program to address topics ("Strategic Capabilities") established by the Steering Committee for the NASA Living With a Star Program.*

Recommendation 6.16 The PRC recommends the establishment of a distinct funding line for basic space weather research that supports improved capabilities in space weather specification and forecasting, and sustain a robust space weather and climatology program that invests in "predictive space weather science" and activities that "optimize the use of research to address national needs."

Recommendation 6.17. The PRC generally endorses a continuation of the current NASA/NSF Collaborative Modeling under Space Weather. However, well in advance of each new request for proposals to this program, the GS PM for SWR should determine if the NASA call for proposals on Strategic Capabilities continues to be aligned with GS program goals for SWR. If the alignment is consistent with GS program goals, then continuation at appropriate funding levels should be sustained. Additionally, over time, funds in this line should be made available for other strategic space weather focused capabilities.

Finding: *The acquisition and implementation of individual models at NASA's CCMC have produced a vibrant and highly-productive foundation for space weather modeling at all levels. GS supported scientists, as a community, have benefited from CCMC activities such as "runs-on-request." NSF GS has provided significant financial support for CCMC personnel and computer systems, thus strongly contributing to a robust space weather and climatology program as recommended by the DS.*

Recommendation 6.18. The PRC recommends that GS maintain its support to CCMC as a Priority 1 effort in the Facilities Program in order to continue and enhance efforts in Integrative Geospace Science.

Finding: *NSF GS provided strong support for the Global Oscillation Network Group (GONG), which made significant contribution to activities that would now be considered part of IGS. The ongoing support allowed GONG to demonstrate its utility in real-time space weather forecasting. GONG is now supported in part by NOAA for collecting and processing data for space weather operations and will be making H alpha and Carrington maps available to the scientific community.*

Recommendation 6.19. The PRC recommends that GS use the proposed Innovation and Vitality Program (Section 7.4.1) to open funding paths for scientifically viable space weather observations and platforms that could serve demonstrated real-time IGS monitoring needs.

Finding. *In October 2015, the National Science and Technology Council released the National Space Weather Strategic Plan and National Space Weather Action Plan. The Action Plan announces "new commitments from the Federal and non-Federal sectors to enhance national preparedness for space weather events." The plan elaborates 18 actions for NSF, one with NSF having primary responsibility and seventeen others to be implemented in collaboration with other agencies. Many of these actions have milestones within the next few years. One of NSF's primary responsibilities is to "Enhance Fundamental Understanding of Space Weather and Its Drivers to Develop and Continually Improve Predictive Models."*

Finding. *Operations to Research (O2R) informs societally-relevant research; Research to operations (R2O) fulfills societal needs. Through core and targeted research, as well as in some aspects of the current space weather program, NSF GS is devoting resources to curiosity-driven basic research related to understanding and modeling the fundamental physics of the solar-terrestrial system. In some cases, the results of this work relate to problems that ultimately have near-term* *societal relevance and can be judged as contributing to "broader impacts" as defined in NSF proposal criteria. Some of the research and model development supported by NSF is close to being ripe for transition to an operational agency such as NOAA or DOD where additional development will be need to bring new ideas, observations and models into operational use.*

Recommendation 6.20. The PRC endorses NSF's critical role in contributing to national efforts for coordinated space-weather preparedness, and recommends that the GS section pursue opportunities for collaboration between agencies which can be used to further NSF goals to "innovate for society," as well as Decadal goals related to DRIVE.

6.5.2 Grand Challenge Projects

According to the DS, "a mechanism is needed for bringing together critically sized teams of observers, theorists, modelers, and computer scientists to address the most challenging problems in solar and space physics. The scope of theory and modeling investigations supported by the NSF CEDAR, GEM, and SHINE programs … should be expanded so as to enable deep and transformative science. 'Heliophysics science centers' would bring scientists together for significant collaborations to address the most pressing scientific issues of Heliophysics, with success judged according to progress made toward resolving the primary science goals. Centers should consist of multi-disciplinary teams with two to three primary institutions that include theorists, modelers, algorithm developers, and observers. Resources should be focused on the core institutions to avoid spreading the resources too broadly and to achieve a focused investigation of the topic. The centers should be designed to highlight the exciting science problems of the field to bolster the interest of faculty at universities and to attract top students into the field."

Finding. *Grand Challenge Projects could address critical capabilities gaps as described, e.g. in Tables 5.2-5.5.*

Finding. *The Decadal Survey recommended that these centers should be jointly created by NASA and NSF, and term-limited, with a suggested duration of six years.*

Recommendation 6.21. The Integrative Geospace Science program should also be the home of a new Grand Challenge Projects program.

Recommendation 6.22. The PRC recommends that NASA/NSF explore best practices for collaboration on Grand Challenge Projects, perhaps along the lines of the aforementioned NASA/NSF Collaborative Modeling under Space Weather. The broadening of these collaborative efforts embraces the holistic scope of the Decadal Survey.

To add substance to notion of a Grand Challenge Project (GCP), a few illustrative concepts are suggested here. They span projects ranging from universal process, to Sun-to-Earth couplings, to more regionally focused problems that nevertheless require cross-disciplinary interactions. These concepts are meant to illustrate the type of questions that could be addressed in GCPs and should not be interpreted as a special vision for the future content and scope of GCPs. When a Grand Challenge Projects program is launched, community concepts for the most compelling projects together with the peer review process will determine the best candidates.

Understand Particle Acceleration/Transport (maps to DS Key Science Goals 3 & 4)

Particle acceleration and transport represents a universal plasma process with relevance from the Sun, through the solar wind, to the Earth's radiation belts and aurora, to the outer heliosphere. Major developments are needed both in terms of our basic understanding of the connections between source conditions and properties of energetic phenomena, and in terms of our ability to predict the characteristics of the radiation environments through which astronauts and spacecraft fly. Significant progress might be made through coordinated efforts in fundamental research and development of particle acceleration and transport models, observational analyses of remote-sensing and *in-situ* data, and advances in cross-calibration of multipoint analysis and data-assimilative methodologies.

Connect Sun-Geospace-Climate (maps to DS Key Science Goals 1 & 2)

Although the effect of long-term solar irradiance variability on tropospheric climate is not expected to be large, uncertainties remain in particular regarding sensitivities to short wavelength radiation from the sun. In addition, enhanced ionization from energetic particle precipitation (EPP) produces HO_x and NO variations, which have been traced to changes in middle atmosphere ozone balance, thus providing a potential link to dynamics and regional climate. Analyses studying the origins of solar magnetic fields and how their variability translates to radiative, particulate and possibly electrical forcings at the Earth are needed, connecting fundamental theory to observational studies from Sun to Earth. Coordinated efforts could involve developments in community models, data-assimilation, and high-performance computing, and potentially draw on historical, geological, and solar-stellar analog data.

Predict the geoeffectiveness of solar drivers of space weather (maps to DS Key Science Goals 1 & 2)

This challenge is at the heart of space weather prediction. To fully address it, the upper solar-convection zone through the corona to the solar wind, geospace, and the Earth's upper atmosphere needs to be considered as a coherent system, across multiple scales (temporal and spatial). Answers must be sought to questions about reconnection and explosive releases of energy at the Sun and at Earth and the state of the medium through which such disturbances propagate. Closer to Earth it requires investigations into societally-relevant areas of geomagnetically induced currents, spacecraft environment and health and communications vulnerability. Significant efforts in data assimilation and high-performance computing are needed, as are development of data-analysis and inversion tools, fundamental research into the physical mechanisms driving coronal heating and solar wind dynamics, and observational studies at both high temporal/spatial resolution and involving ongoing synoptic data.

Develop capabilities for satellite drag and debris prediction and mitigation *(maps to DS Key Science Goal 2)*

Satellite drag and debris mitigation are growing commercial, governmental and defense concerns. Atmospheric drag is the largest contributor among the many error sources in low-Earth orbit (LEO) orbital estimation and is at the root of many issues associated with re-entry prediction, tracking/identifying active payloads, and collision avoidance. Presently orbit projections are not sufficiently accurate, nor timely enough, to determine whether an avoidance maneuver, if one can be made, is actually warranted. Investigations related to long and short-term solar emissions, M-I-T coupling, meso- and small-scale thermospheric structuring, lower atmosphere forcing and, infrared radiative cooling could all contribute to a holistic address of the problem. Connections between models and observations, data assimilation methodologies, and high-performance computing are also key elements.

6.6 CubeSat Program

The NSF CubeSat program grew out of the June 2006 "Report of the Assessment Committee for the National Space Weather Program" (FCM-R24-2006). The assessment committee recommended exploring the use of microsatellites to make key measurements from—and about—space in order to advance understanding of basic physics, as well as for addressing key aspects of space weather observations. The Geospace Section (Upper Atmosphere Section at that time) took that recommendation to heart and exhibited visionary leadership in bringing CubeSats to the national stage in support of Geospace science. The GS's efforts in providing access to space are widely recognized in government and academia as an enterprising program for the geospace sciences. As an exploratory program the NSF GS CubeSat program has been productive in education, in training, in engineering development, and in some aspects of basic research.

Subsequent to the May 2007 community workshop about CubeSat mission possibilities and the first NSF solicitation for CubeSat mission ideas in February 2008, dozens of CubeSat proposals have been submitted to NSF. The result has been an active space flight program built around smaller spacecraft that fit into cubes or stacked cubes.

Recognizing the early success of the NSF GS CubeSat exploratory program, the DS made two primary and one secondary CubeSat recommendations to NSF. These recommendations were made during a period when at least modest budget growth was expected.

1. "NSF's CubeSat program should be augmented to enable at least two new starts per year."
2. "Detailed metrics should be maintained, documenting the accomplishments of the program in terms of training, research, technology development, and contributions to space weather forecasting."
3. "As this program grows, it is critical to develop best-in-class educational programs and track the impacts of investments in these potentially game-changing assets."

With resources carved out of the previous core science program and supplemental funding from the NSF EBSCoR program, the GS has supported 12 CubeSat missions plus three new starts (Appendix E). Several additional awards are pending as of mid-2015. CubeSat support has primarily been to universities and small businesses. Total expenditures by NSF from 2008 through 2015 for CubeSat missions and related expenses were about $15.6 M, with annual expenses varying from year to year, but on the order of $1 M to $2 M/year. Additional funding and/or in-kind support from NASA and DoD are not reflected in the numbers above.

Seven NSF-sponsored CubeSat missions (ten spacecraft) have launched; three are awaiting launch, two missions are in advanced design, and three missions are in early stage design. Of the seven missions in space, five successfully acquired part or all of their intended data. Two missions experienced early communications failures resulting in only "first light" data. Three missions returned science data for 18 months or more. The Radar Auroral eXplorer (RAX) and Colorado Student Space Weather Explorer (CSSWE) generated more than two-dozen refereed science and engineering journal publications. In particular, CSSWE has contributed significantly to integrative system science carried out by the Van Allen Probe mission with papers appearing in journals such as *JGR-Space* and *Nature,* and has submitted its science data to NASA's National Space Science Data Center. The first eight missions collectively have contributed to ~15 Ph.D. theses and the education of more than 250 BS and MS students and at least six high school students (Figure 6.2).

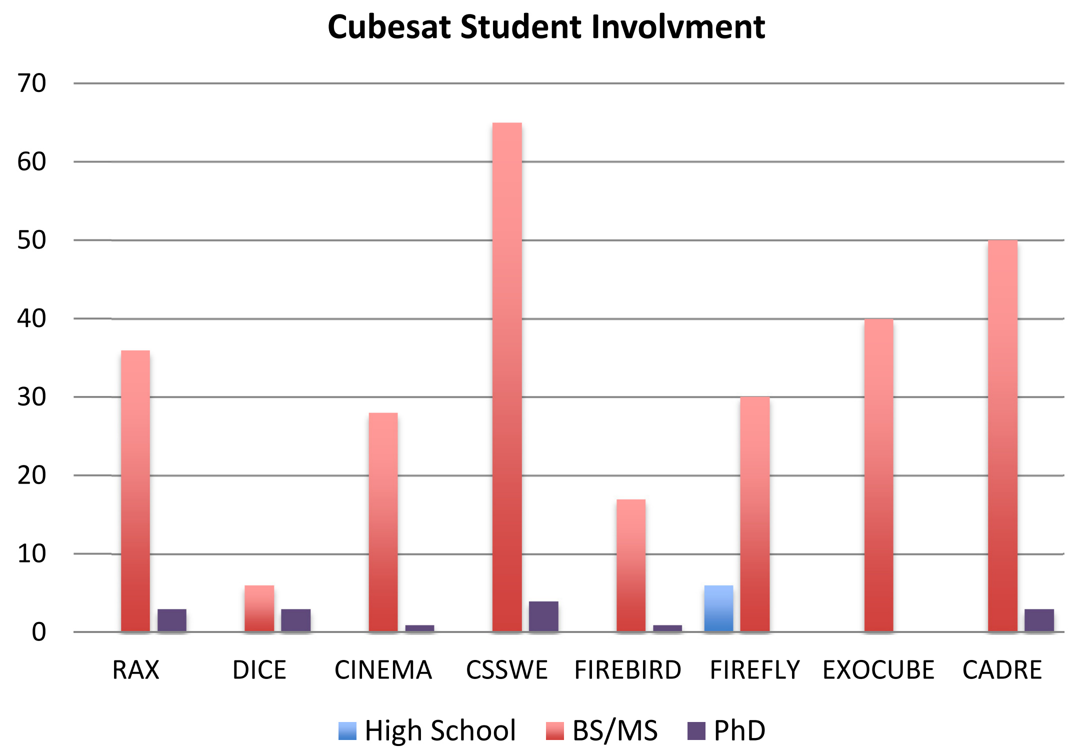


Figure 6.2. Number of students involved in each of the first eight CubeSat missions (from NSF GS).

Finding. *The NSF GS investment in CubeSats is a paradigm-shifting effort to show that GS science can be enabled and extended by reaching into space with inexpensive CubeSats. The program paves a path for expanding space-based activities more broadly in NSF grants, particularly in Earth and Ocean Sciences, Biological Sciences and Engineering; and for expanding opportunities for industrial collaboration and commercial innovation and cross-disciplinary technology development.*

Finding. *The GS section has developed a CubeSat program that leverages support from NASA, DoD and international partners. NASA and DoD have provided and continue to provide CubeSat "rides to space." Current and future CubeSat missions have NASA partnership and/or funding. About 10% of the NSF CubeSat budget goes to the NASA Wallops Flight Facility for mission support.*[18] *GS is funding four CubeSats for the European QB50 mission.*

Finding. *The NSF CubeSat program has been an educational success and has supported many engineering advances. Seven spacecraft have launched and nearly 300 students have engaged in some aspect of CubeSat design and or operation. The program has developed an extraordinary model for training the next generation of scientists and engineers in space and for enhancing university and student participation in space activities. Student and university enthusiasm for the CubeSat program is very high. For a few students the program offers a rare, end-to-end mission experience. For many other students the program provides an introduction to space mission development, which has spurred new excitement for science and engineering.*

[18] NSF GS presentation to NRC dated June 22, 2015

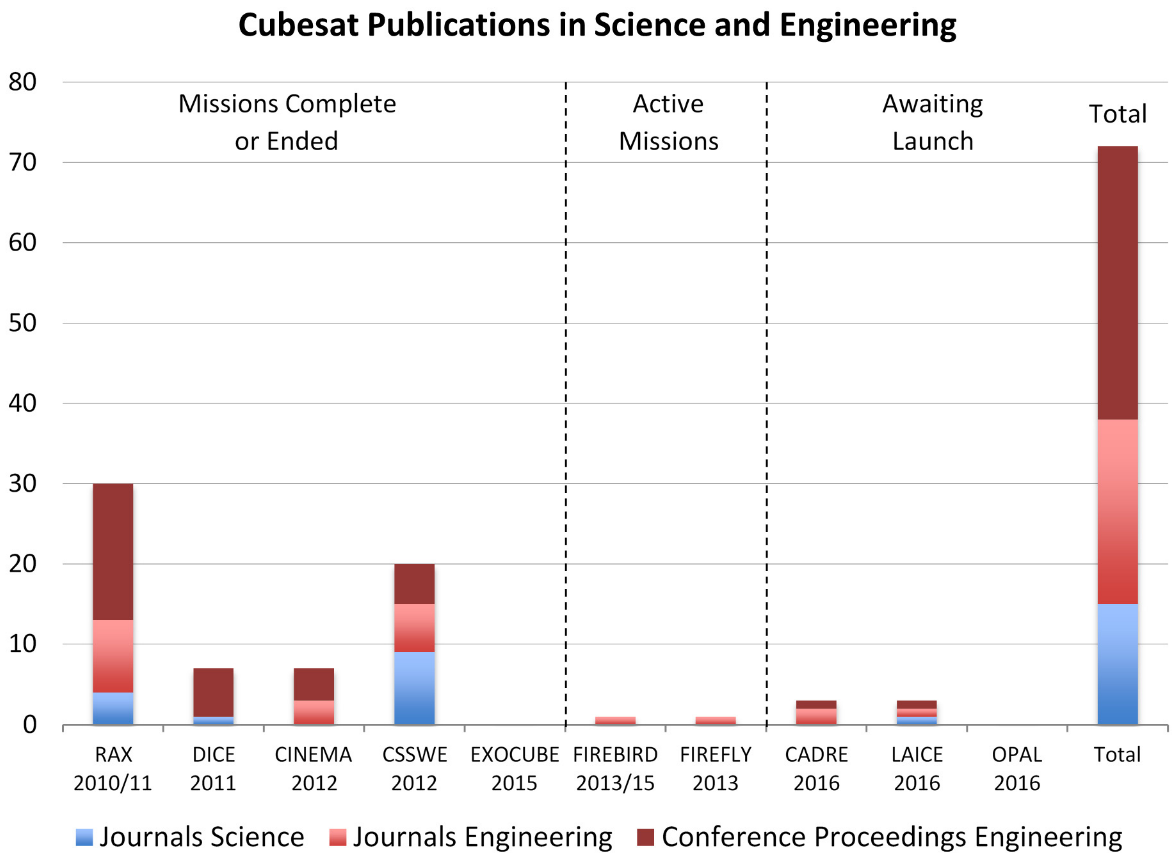


Figure 6.3. Publications in science and engineering journals and conference proceedings for the first ten CubeSat missions. Many proceedings were associated with SmallSat Conferences. Data provided by NSF and supplemented with searches at the SAO/NASA Astrophysics Data System and on the Web.

Finding. *The CubeSat program has produced more than 70 refereed and proceedings publications along with numerous press releases and web pages. In total publications, including conference proceedings and journal publications, about 80% of the CubeSat publications are in engineering proceedings and journals vs about 20% in science journals (Figure 6.3).*

Finding. *Of the five missions completed or no longer collecting data, two have contributed the bulk of archival engineering and science publications and provided data to a website or science data center. The CSSWE and RAX missions contributed to collaborative analyses to understand complex interconnected systems and have published archival results. In the case of CSSWE, combining low-altitude energetic particle observations with elliptical-orbiting Van Allen Probes data have contributed to radiation belt science. In the case of RAX, coordination with ground-based radars has contributed to ionospheric E-region science. Two missions experienced early communications failure, as such their potential for science contributions was not realized.*

Finding. *In harmony with the Decadal Survey recommendation, some community white papers submitted to the PRC suggest that GS should establish a more rigorous design review process to insure CubeSat mission success.*

Recommendation 6.23. The CubeSat program should include additional design reviews and oversight aimed at achieving mission success and be evaluated for impact and effectiveness in order to justify the investment. This oversight should be implemented in a way that does not undermine the high-risk high-payoff benefits of CubeSat projects.

Recommendation 6.24. CubeSat missions should contribute their data to a science data center or other curated archive.

Finding. *A unified, tabulated database of CubeSat status, successes, challenges, funding profiles and productivity would allow better tracking and comparisons of investments, consistent with the DS recommendations.*

Recommendation 6.25. NSF GS should provide an annual, tabulated set of detailed metrics, documenting the accomplishments and challenges of the program in terms of training, research, technology development, and contributions to geospace science and/or space weather forecasting.

Finding. *An examination of publications resulting from the NSF CubeSat program suggests that the results are predominantly engineering-oriented and that, on average, basic science productivity is low in comparison to the number of publications one might expect from the same financial investment in GS programs for core and targeted research grants and facilities. While most missions generate many conference presentations and proceedings, comparatively fewer results show up as refereed publications contributing to archival knowledge in basic science. In some cases, missions returned little or no science or only limited science was published. This finding is consistent with the typical university model for CubeSat development in which most of the available resources are devoted to developing science instruments and spacecraft busses with an ever-changing student work force. Grant money may last long enough to see these small missions to space, but perhaps not long enough to support a robust data analysis program at a level similar to core and targeted grant programs.*

Recommendation 6.26. In this budget-constrained environment GS should continue to invest in the CubeSat program with an enhanced focus on science/strategic instrument development and less focus on the satellite bus and system development and strive for greater scientific value from this investment. GS should also continue its collaborative and partnering efforts with NASA, DoD, and international partners and investigate partnering opportunities with industry.

Recommendation 6.27. It is the PRC's view that additional collaboration with other Directorates and NSF Offices, whose activities align with education, engineering and multidisciplinary efforts (e.g., NSF Office of Emerging Frontiers and Multidisciplinary Activities) are needed for the GS initiative in CubeSats to continue as a vibrant cross-Foundation effort and to allow the GS section to augment NSF's CubeSat program to support "two new starts per year," as recommended by the Decadal Survey. Short of such whole-of-Foundation support for this frontier effort, the PRC must recommend a rebalancing of the GS CubeSat effort to focus on science and with perhaps fewer missions than envisioned by the Decadal Survey.

6.7 Senior Review of GS Grants Programs

Recommended investments in GS Core and Strategic Grants Programs, as summarized in Chapter 9 to follow, will require approximately 63% of the GS budget over the next decade, assuming the inflation-adjusted, flat budget scenario for this review. This recommended portfolio fulfills the PRC charge to “recommend the balance of investments in the new and in existing facilities, grants programs, and other activities that would optimally implement the Survey recommendations and achieve the goals of the Geospace Section.” However, the budget landscape over the decade of the recommended portfolio may deviate from the assumptions of the review and past trends suggest that new opportunities for scientific advancement will emerge during the next decade. An interim (semi-decadal) senior review of the GS portfolio would ensure that the portfolio remains aligned with research priorities and would provide community input to GS PMs in navigating an evolving budget and research landscape.

The PRC considered the merits of a single senior review of the entire portfolio versus separate reviews of the GS Grants Programs (core plus strategic as reviewed in Chapter 6) and the GS Facilities Program (reviewed in Chapter 7). A single full review has the advantage of examining the balance of investments across all programs and its alignment with science goals and new opportunities. Its disadvantage is the large and complicated scope of a full portfolio review, to which this PRC can attest. Separate reviews of grants and facilities programs have two advantages: 1) The separate reviews are quite different in scope and have different metrics, so the senior review committees could be optimized for the nature of the reviews, and 2) the review process for two separate senior review committees would be less onerous than a full portfolio review and could be completed more efficiently and quickly. The obvious disadvantage of separate reviews is the possibility of producing myopic reviews of the two separate elements rather than a holistic portfolio review.

As recommended below, the PRC opts for two separate reviews, with the proviso that special attention be given to crossover issues in both reviews. One important issue concerns the transition from a core or strategic research activity to a facilities activity.

Finding. *The geospace research community is expected in the next decade to continue aggressive development and deployment of new Distributed Arrays of Scientific Instruments (DASI) and other Class 2 facilities in order to provide emerging critical capabilities for geospace science and to address the big challenges of geospace system science.*

Finding. *M&O for Class 2 facilities and nascent Class 2 facilities (Section 7.2), especially but not limited to DASI (Section 7.4.3), are currently funded by both the GS Grants Programs and the GS Facilities Program. These grants include widely varying levels of support for research within the facilities or research award for the Class 2 facility.*

Finding. *The GS does not have clear guidelines for delineating i) when facility-class research, development and operation crosses the transom from a PI-led research project to a Class 2 community facility as discussed in Chapter 7; ii) when the funding source for an emergent Class 2 facility, or the portion of its funding specifically for M&O, should migrate from the GS Grants Programs to the GS Facilities Program and be reviewed separately from research proposed for the Class 2 facility; and iii) an appropriate level of research funding for inclusion in a Class 2 facility award. The budgets for GS grants and facilities programs lose transparency without such guidelines.*

These issues are mainly addressed in the context of the GS Facilities Program in Chapter 7, and guidelines will be presented there for appropriate M&O support for facility-class activities. These issues clearly cross over into the GS Grants Program, however. Ideally the GS Grants Programs support development and application of innovative measurement techniques; novel observations typically of more limited scope and duration than a facility-class activity; data analysis and data exploitation; and modeling and theory that advance and transform our understanding of geospace.

Retaining M&O support for facility-class activities in the GS grants programs diminishes investment in critical core and strategic geospace science.

Recommendation 6.28. Beyond a level of M&O support by the GS Facilities Program to be described in Chapter 7, proposals for research activities associated with facilities should be peer-reviewed separately from facilities proposals and evaluated against the same scientific standards as any competitive research proposal conducting the same research with data from the facility.

Recommendation 6.29. The GS should charge a senior review committee to conduct an interim, semi-decadal review of the GS Core and Strategic Grants Programs. A separate senior review of the GS Facilities Program is also recommended, as described in Chapter 7.

The objectives of the interim Senior Review of GS Grants programs are to:

1. Review the balance of investments in core and strategic grants programs in light of the budget and research environment at the time of the review, evaluate the programs' effectiveness in achieving Section and Decadal Survey science goals and, in consultation with GS staff, recommend adjustments in the direction and balance of the grants programs if such adjustments would enhance the overall effectiveness of the GS Grants Programs in achieving Section and DS science goals.

2. Facilitate transparency in GS investments in its grants programs by evaluating progress of the Section in implementing recommendations of the decadal portfolio review and by reviewing funding allocations in various grant categories, including but not limited to grants that fund both M&O and research for emerging facility-class projects.

Finding. *The purpose of this review (and the recommended facilities' senior review) is distinct from the mandated periodic reviews conducted by Committees of Visitors, which are charged with providing assessments of the quality and integrity of program operations and program-level technical and managerial matters pertaining to proposal decisions.*

Recommendation 6.30. Administration and decisions on the structure of the Senior Review process should reside with the GS Head and Program PMs.

Given its experience in conducting this portfolio review, the PRC can offer some suggestions for ensuring that the review is most efficiently and effectively conducted. Soon after a Senior Review panel for GS Grants Programs is charged, and well before its scheduled meeting at NSF, the GS could provide the panel with the following data on its grants programs:

1. Budgets by year since the portfolio review for each GS grant program (AER core, MAG core, STR core, CEDAR, GEM, SHINE, GCP, SWR, CubeSat, Grand Challenges and FDSS);

2. Separate listings of grants from the NSF Awards database currently funded by each of the aforementioned grant programs;

3. Status of all CubeSat missions funded or co-funded by the GS;

4. Proposal success rates by year since the portfolio review for each program with a reasonably detailed description of the basis for the success rate and with a methodology consistent with that employed across NSF ; and

5. Identification of projects that may be on a path to becoming a Class 2 facility.

Annual publication of the data in 1-4 above would keep the community informed. With this information in hand, the Senior Review panel would be in a good position to request additional information as needed in order to conduct a comprehensive and efficient review.

The PRC recognizes the many challenges of managing GS research and facilities programs. Effective Section administration may require GS Program Managers to administer both research and facilities proposals and grants, with some of them in GS programs outside the PM's primary area of responsibility. Resource sharing across GS programs may also be the best way to fund deserving projects, especially cross-disciplinary projects, when the overall budget is constrained. Such management decisions are best left to the very capable GS staff. One the other hand, transparency in program administration is greatly facilitated when a program and its accounting includes, to the fullest extent possible, grants directly relevant only to that program element. Administrative constructs like the existing Space Weather Program, while administratively expedient, tend to confuse the research community at large in understanding how GS resources are being allocated; the PIs of grants administered by the program who may be pursuing projects not necessarily focused on space weather research; and a review committee like the PRC which has difficulty disentangling resource administration from resource allocation in its review. The same confusion arises for grants managed by a PM for a program outside that of the PM's primary area of responsibility e.g., a facility grant managed by the AER PM. From the community perspective, the most transparent accounting of program investments is to list funded activities with the program most relevant to the project rather than with the program of the PM managing the grant. This practice appears to have been followed in most but not all cases in the program grant listings provided to the PRC. For cross-disciplinary projects funded by two or more programs, it would also desirable to account for the portion of funding allocated from each program, although the PRC recognizes that this level of detail may be difficult to achieve in practice.

Chapter 7. GS Facilities and Infrastructure

The maintenance of the leading position of the U.S. in geospace scientific research requires a broad-based program of activities that supports, sustains and stimulates a vibrant, novel scientific enterprise. This enterprise includes three key research elements that the future GS research program must encourage:

- Curiosity-driven research driven by proposals from principal investigators (PIs);
- A collection of larger-scale research initiatives that address particularly compelling scientific questions poised for significant advance but are in size, cost, and complexity beyond the scope of a PI-driven project; and
- Strategic research, i.e., science that should deliver new understanding that will, over time, contribute to addressing some of the major research challenges of the geospace environment, its impacts on other parts of our planet, and resilience to space weather hazards.

One of the fundamental requirements for international-class science is for scientists to have ready access to international-class facilities and capabilities in modeling, theory, observation and data management.

As described in Chapters 5 and 6, increasing emphasis on "system science" is expected over the next decade. This approach will require both sophisticated sites with colocation of many instruments for comprehensive measurements of the local geospace environment, and distributed networks of instruments to provide a regional and global context and perspective of geospace. Complementary modeling and data management initiatives will be key elements too. National and international partnerships will be essential in providing a comprehensive range of capabilities and global coverage (see Chapter 8).

7.1 Recent History of GS Facilities

In the early 1990s, the Geospace Facilities (GF) program (then known as Upper Atmospheric Facilities, UAF), funded principally incoherent scatter radars (ISRs), e.g., Sondrestrom Fjord (Sondrestrom), Millstone Hill, Arecibo and Jicamarca, and some instrumentation clustered around those facilities. The annual funding was about $9M.

With time, more ISRs and other instruments and infrastructure were added to UAF, in particular, US SuperDARN (polar and mid latitudes), Advanced Modular ISRs (AMISRs), namely Poker Flat Incoherent Scatter Radar (PFISR) and Resolute Bay North Face ISR (RISR-N), and the Consortium of Resonance and Rayleigh LIDARs (CRRL). By 2008 the UAF annual budget was about $14M. The principal increase was from the addition of the AMISRs, which had been in planning since the 1990s. The construction and development of these new instruments were funded by the former AGS Mid-Size Infrastructure Program and/or ARRA (American Recovery and Reinvestment Act of 2009), or with funding from other agencies and NSF programs, and not with the UAF/GS funds.

By 2013, further facilities, infrastructure and capabilities were added to the portfolio. These additions included: AMPERE (I and later II), SuperMag, Community Coordinated Modeling Center (CCMC), and CubeSats, with the annual budget rising to about $18M.

The annual GS budget for Arecibo Observatory jumped from $1.8M ($2M in 2015 dollars) in

2008 to $4.1 M in 2016 as support from the NSF Astronomy Division was substantially decreased. At the same time, other ISRs experienced about a 10% reduction relative to their support prior to 2008.

It is clear that the GF program has been experiencing an evolution towards including what we define here as "Class 2" facilities, in addition to the implementation of new Class 1 facilities. The characteristics of these classes are given in section 7.2.3.

7.2 Characteristics of GS Facilities

NSF has long supported several large incoherent scatter radar facilities. Several of the large ISR facilities have been inherited by the NSF from former Department of Defense (DoD) programs. In general two ownership models of facilities are funded:

- Facilities owned by NSF and operated and maintained by external organisations.
- Facilities funded by NSF, and now owned by external organisations.

Some of the facilities are provided to give support and service to a wide community, while others are highly focused to meet the needs of a specific Principal Investigator or a small group of researchers.

7.2.1 Definition of a Community Facility

The Committee found that NSF/GS does not have a clear definition of a Community Facility – what it should provide and how it should interact with its users. The contribution of each facility to GS program goals and objectives does not appear to be consistently evaluated, nor its performance in serving its user community. The contractual arrangements between facility PIs and NSF vary significantly from facility to facility, and funding for science under the primary grant or cooperative agreement of each facility also varies significantly among the facilities. This practice has meant that the expectations of the facilities and their management is not clear or transparent.

As a result of its examination of NSF/GS practises regarding facilities, the Committee has identified the essential characteristics of a NSF GS facility.

Recommendation 7.1. A facility should exhibit the following functions:

1. Serve a community of users well beyond a single PI or small group of investigators, i.e., at least national but may be international;
2. Be operated in such a way as to ensure responsiveness to the needs of the research community to sustain international-class scientific productivity; thus each facility is expected to have both an advisory group and a user forum, with membership not selected by facility management;
3. Operate for more than one award cycle and typically substantially longer if warranted by the Senior Review process (see Section 7.8);
4. Make all data openly available and accessible in a timely fashion according to a published data distribution and dissemination plan;
5. Develop and deliver an effective long-term plan to maintain the facility at an international

cutting-edge level;

6. Carry out a limited amount of science funded from the Maintenance and Operations (M&O) contract (see Section 7.5.2);
7. Support the deployment and operations of co-located instruments with the full costs covered by each co-located instrument Principal Investigator;
8. Deliver substantial education, outreach, and diversity programs; and
9. Provide cost-effective operations.

7.2.2 Community Facility: Funding and relationship with NSF

1. Facilities may be owned by NSF, universities or research institutions.
2. Facilities are expected to have multiple funding sources involving interagency and international partners.
3. Facilities may be funded through either continuing grants or cooperative service agreements (CSAs). A CSA ensures appropriate NSF involvement in facility operation and use.
4. Recompetition of the CSA typically occurs every five years for NSF-owned facilities. A peer-reviewed proposal is required for renewal of a continuing grant.
5. The entire portfolio of NSF GS (facilities and programs) would be reviewed every five years (see Section 7.8, Senior Review).

7.2.3 Class 1 and Class 2 Community Facilities

The PRC found it helpful to consider the Community Facilities in two classes. A Class 1 facility is a major, complex facility at a single site. Its investment over time typically reaches many $10sM, requires significant M&O funds and accommodates a variety of complementary instruments at or very near the site. Class 1 facilities might be expected to have a lifetime of 20+ years from first deployment. In the current portfolio, all the incoherent scatter radars (ISRs) are considered to be Class 1.

Class 2 facilities are more modest and diverse investments. They include distributed networks of instruments that are simpler to operate than ISRs (e.g. SuperDARN), facilities producing value-added products from data from other sources (e.g. SuperMAG and AMPERE), model support for the community (e.g. CCMC) and data management (Madrigal Database, currently funded through the Millstone Hill ISR contract).

It is recognised that most US facilities operate in an international context. This important characteristic is addressed further in Chapter 8.

7.3 Current Investments and Capabilities

7.3.1 Evidence Used by the PRC

Prior to the PRC's first in-person meeting at NSF on April 6-7, 2015, the GS Acting Head made available to the Committee a written introduction to each facility prepared by its PI. The PRC subsequently requested more detailed written information from each PI regarding the current status of each facility and future plans. After receiving the written responses to these requests, the PRC then interviewed each facility PI via web conference (about 1 hour duration each) to delve deeper into issues addressed in the written responses; a few of these interviews were then supplemented by additional written information from the PIs. Supplementary information, such as funding levels, was provided by NSF. The PRC also held a web conference interview with the Director of the European Incoherent Scatter Facility (EISCAT). On the basis of all this information the PRC produced the following findings and recommendations.

7.3.2 Class 1 Facilities: Summary

The NSF GS currently funds the operations for six Incoherent Scatter Radar (ISR) facilities (Table 7.1). The ISR operating frequency, power, sensitivity and the data acquisition and handling infrastructure at each of these six sites vary widely. Their locations range from the geomagnetic polar cap region (Resolute Bay, Canada) to the geomagnetic equator (Jicamarca, Peru). The original ISRs – stretching from Sondrestrom, Greenland (geomagnetic cusp region), to Millstone Hill, Massachusetts (geomagnetic midlatitude), to Arecibo, Puerto Rico (geomagnetic low latitude), and to Jicamarca – have been called a latitudinal array of ISRs at various times. The newest ISRs are Advanced Modular Incoherent Scatter Radars (AMISRs). They are located at Resolute Bay (RISR-N) and at the Poker Flat rocket range in Chatanika, Alaska (PFISR). A recently built 14-panel AMISR is currently located at Jicamarca. The Poker Flat rocket range, located some 30 miles north of Fairbanks, is operated by the University of Alaska. The locations of the GS-funded ISRs along with their fields of view are illustrated in Figure 7.1.

The operational costs of the ISR facilities is about $13M/year, which represents about 30% of the GS budget.

7.3.3 Class 1 Facilities: Findings and recommendations

Finding. *Little significant science has been produced utilising collective data from the "latitudinal array" of ISRs. The importance of atmospheric/ionospheric coupling during Sudden Stratospheric Warming events is one of the few examples.*

Finding. *The ISR facility at Sondrestrom, Greenland, has been in operation for geomagnetic cusp studies for nearly 35 years (having been moved from Chatanika, Alaska, in 1982). Its maintenance and operations (M&O) costs are $2.55M/year. Among other features, the radar operates with klystron technology. Spare klystrons are not available and require special builds. A comprehensive suite of ancillary instrumentation is located at Sondrestrom.*

Finding. *A number of European countries and countries from the Far East have developed a coordinated set of ISR radars (EISCAT), deployed in northern Scandinavia. EISCAT provides an excellent research capability extending from sub-auroral latitudes to the polar cap. A wealth of ancillary research instrumentation, including a high power HF heater, are located within the fields of view of the EISCAT radars. USA PIs provide some of these instruments.*

Finding. A *consortium of EISCAT countries has recently initiated development of the EISCAT-3D radar. EISCAT-3D will give unparalleled 3-D spatial and temporal measurements of the geospace environment especially in the auroral oval. EISCAT-3D will consist of five phased-array antenna fields located in the northernmost areas of Finland, Norway and Sweden, each with around 10,000 crossed dipole antenna elements. The core site at Tromsø, Norway, will transmit at 233 MHz. All five sites*

Table 7.1 Main characteristics of GS-funded ISRs

MHO	MIT	440	One steerable and one fixed parabolic dish	46 m steerable 68 m fixed	2.5	6	1960	52.1°N	1000	Madrigal, Cluster	± 70°
JRO	IGP	50	Square Phased array	290 m x 290 m	3	6	1961	0.3°N	1000	JULIA[1], Cluster	± 3° on-axis
AO	NSF	440	Spherical dish	305 m	2.5	6	1962	27.6°N	1000	Heater, Cluster	± 15°
Sonde	NSF	1290	Steerable parabolic dish	32 m	3.5	3	1983[2]	72.6°N	2000	Cluster	± 45°
PFISR	NSF	449	Phased array	32 m x 28 m	2	10	2007	65.4°N	>6000	Rocket Range, Cluster	± 23° on-axis
RISR-N	NSF	449	Phased array	32 m x 28 m	2	10	2010	>80°N	1000	Cluster	± 23° on-axis

Abbreviations: Millstone Hill Observatory (MHO), Jicamarca Radio Observatory (JRO), Arecibo Observatory (AO), Sondrestrom Geospace Facility (Sonde), AMISR at Poker Flat (PFISR), NSF AMISR at Resolute Bay (RISR-N), Frequency (Freq), Operation (Oper), Geomagnetic Latitude (Geom Lat) and Infrastructure (Infrastr)

[1] *JULIA is Jicamarca Unattended Long-term Investigations of the Ionosphere and Atmosphere* – a continuously operating meso-sphere, stratosphere, troposphere radar

[2] Before 1983, it was at Chatanika, Alaska, and before that at Stanford University.

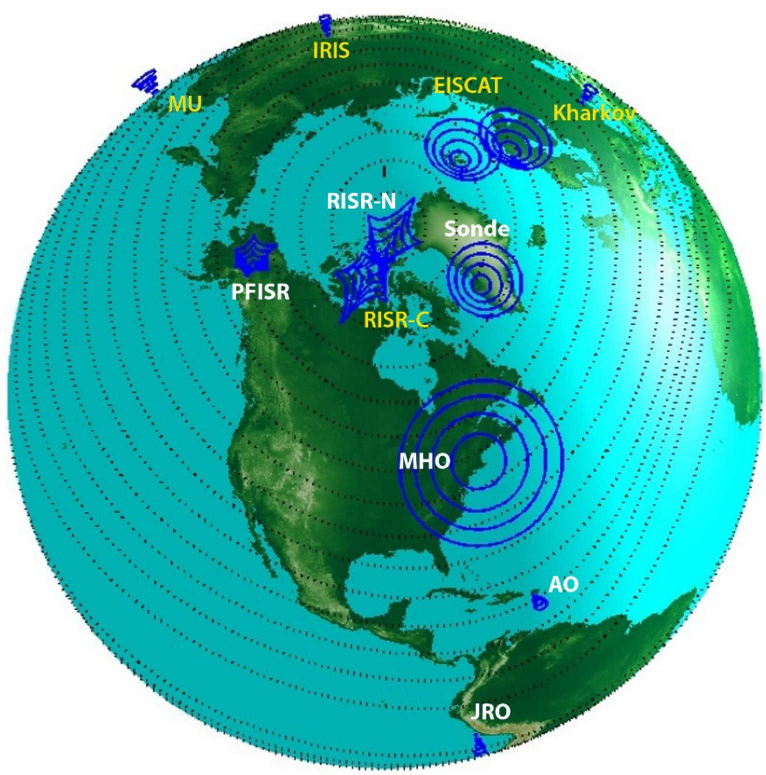


Figure 7.1. Locations of the Incoherent Scatter Radars and their fields of view. US funded radars in white (PFISR, RISR-N, Sonde, MHO, AO and JR0), others in yellow (MU, IRIS, Kharkov, RISR-C and EISCAT with two fields of view). Figure courtesy of C. Heinselmann

will receive the returned radio signals. Instantaneous electronic steering of the transmitted beam and measurements will be used. Smaller outlying arrays will facilitate aperture synthesis imaging to acquire sub-beam spatial resolution.

Finding. *The EISCAT consortium will continue to operate and enhance its facilities at Svalbard in the cusp region.*

Finding. *No plans are in place for enabling U.S. investigators to use the EISCAT or the EISCAT-3D facilities for auroral or cusp studies.*

Recommendation 7.2. The ISR facility at Sondrestrom should be terminated, and science performed at Sondrestrom should be covered by participation, after peer review, in EISCAT and EISCAT-Svalbard for cusp studies.

Recommendation 7.3. Ancillary instrumentation for geoscience studies and their operational costs at Sondrestrom should be budgeted and decided by a peer review process from the Core or Targeted GS programs.

Recommendation 7.4. The GS should investigate costs and contractual arrangements for U.S. investigators' access to the existing EISCAT facilities and, more importantly, to the planned EISCAT 3-D facility (See section 7.4.2 for further details).

Finding. *The Arecibo ISR is the most sensitive of any ISR in the world, allowing the highest altitude and temporal resolution.*

Finding. *The Arecibo 430MHz transmitter is 50-year-old, vacuum tube klystron technology. The SRI Report of June 2012 indicates that five spare klystrons existed at that time (klystrons donated by the U.S. Air Force from their Thule, Greenland location). The SRI Report of October 2013 stated that the "useful power is about 1.25MW". The SRI Report of October 2014 states that the "system has continued to achieve 1.5MW of power". The transmitter can only operate at these low power levels (less than half the original rated power level of 4MW) due to the aging electronics.*

Finding. *The research program in optics (including LIDAR) at Arecibo has greatly expanded in recent years, with optics scientific personnel exceeding ISR scientific personnel.*

Finding. *An ionosphere heating facility has been under construction at Arecibo for a number of years. The heating facility was recently completed and preliminary experiments have been carried out. M&O funds have not been designated by NSF for its use.*

Finding. *The FY 2016 M&O cost of Arecibo from the GS budget is $4.1M, which is currently matched by the Astronomy Section (AST) of the NSF. NASA provides minimal M&O support for its use of Arecibo. GS increased its M&O contribution to the $4.1M level from an original $1.8M in 2008. The 2012 AST Portfolio Review recommended that AST should re-evaluate its participation in Arecibo later in the decade in light of the science opportunities and budget forecasts at that time.*

Finding. *About 11% of the total proposals received from 2012 to 2014 for use of the Arecibo facility were for GS-related research.*

Finding. *SRI Reports show that the GS-related program usage of total (including maintenance) telescope time ranged from about 8% to about 13% over 2012-2015. In the SRI Report dated January 2016, about 40% of this GS-related telescope time was devoted to World Day campaigns of data acquisition, not to individual PI peer-reviewed research programs.*

Recommendation 7.5. The GS should reduce its M&O support for the Arecibo ISR to $1.1M/year; i.e., to a proportional *pro rata* level approximately commensurate with the fractional NSF GS proposal pressure and usage for frontier research.

This reduction in Arecibo funding by GS is imperative for meeting the PRC charge to recommend the balance of investments in new and in existing facilities, grants programs, and other activities that would optimally implement Decadal Survey recommendations in the presumed flat budget environment of the next decade. Independent of metrics on proposal pressure and observing time, rebalancing the GS investment in Arecibo corrects an increasing distortion in its relative value to future geospace science. Taking this hard step now will enable new and innovative distributed measurements, data systems and research required to accomplish the integrative geospace science described in Chapters 5 and 6 of this review and emphasized in the Decadal Survey.

Recommendation 7.6. Ancillary instrumentation (including the extensive optics instrumentation) for geoscience studies and their operational costs at Arecibo should all be budgeted and decided in the peer review process.

Recommendation 7.7. Costs of running the HF heater at Arecibo should be budgeted as a pay-as-you-go system, and decided in the peer review process.

Finding. *The PFISR is located at the site from which the current Sondrestrom radar was removed in 1982. Proximity to the Poker Flat rocket range is reported to provide convenience and efficiencies in the operation of PFISR, as well as research synergies resulting from ancillary instrumentation for support of rocket launches. Possible relocation of PFISR to one of several alternative sites has been considered.*

Finding*. The M&O costs for PFISR are currently combined with those for the AMISR at Resolute Bay (RISR-N) and are thus not readily determined.*

Recommendation 7.8. Funding for RISR-N should be decoupled from the funding for any other facility in order to have accurate cost analysis available.

Recommendation 7.9. The future location and use of the PFISR radar for research should be determined by peer review by the time the EISCAT-3D begins operations. Peer review should determine the value proposition for continuing to use the radar's capabilities at its current site or if they might be better used for new, frontier research if the radar were to be installed at another location.

Finding. *Millstone Hill ISR has a very large field of view that has been utilized for innovative new science. This extensive coverage could contribute significantly to system science.*

Finding. *The Millstone Hill group has developed and extended the original CEDAR database (now called Madrigal) to provide an excellent multi-instrument database that is used extensively by the community.*

Finding. *The Millstone Hill group has secured significant external funding for science and engineering technical developments. The Group's research to develop a low cost ISR may be of considerable value to NSF, leading to replacement of older ISR technology, including the Millstone Hill installation.*

Finding. *The Millstone Hill dish has significant structural problems.*

Recommendation 7.10. Investment is required to extend the lifetime of Millstone Hill until such time as it may be replaced by a lower cost option, and/or at another location.

Finding. *The Jicamarca ISR (JRO) is the only ISR located at the magnetic equator and under the equatorial electrojet. JRO is owned by Peru.*

Finding. *Jicamarca is the most powerful ISR in terms of (power) × (aperture). Spatial coverage is limited to ±3° to the vertical. Expansion of the near-by city is a threat to operation owing to increased radio interference.*

Finding. *Lack of funding for decades has prevented the modernization of the antenna beam switching.*

Finding. *JRO hosts a large cluster of ancillary instrumentation for upper atmosphere and ionosphere studies, many supported by separate funding. It is the current location of an orphaned 14-panel AMISR system built with MRI funds.*

Recommendation 7.11. The JRO PI should apply to the recommended, competitive Innovation and Vitality Program (Section 7.4.1) for support to install needed upgrades to bring the ISR system up to modern radio science standards.

Finding. *Ancillary instrumentation for studies of various upper atmosphere and space phenomena are often co-located at each ISR site. The instrumentation varies considerably with site but usually increases significantly the potential for novel research.*

Finding. *Some ancillary instruments are supported by the ISR M&O contract whereas others are funded through the instrument PI grant.*

Recommendation 7.12. NSF should develop a consistent policy and procedure for supporting the M&O of the ancillary experiments at ISR facility sites. Normally the M&O costs should be the responsibility of each ancillary instrument PI.

7.3.4 Class 2 Facilities: Findings and recommendations

Finding. *AMPERE I/II provides magnetic perturbation data and data products derived from the Iridium satellite constellation. The unprecedented spatial and temporal coverage of the measurements is facilitating basic research in magnetosphere-ionosphere physics and space weather. These products are of increasing importance, particularly with the growing emphasis on system science.*

Finding. *It could be possible to produce near-real time AMPERE data products of value for space weather operations. To date, a compelling case for the use of real time data for basic science research has not been made, and hence this capability is outside the NSF remit at this time.*

Recommendation 7.13. AMPERE I/II should continue to be funded at the current levels.

Finding: *CCMC provides easy access to many models used for geospace research. Currently NSF funding supports ionosphere-thermosphere-magnetosphere (ITM) expertise, and outreach and educational activities.*

Recommendation 7.14. NSF involvement in CCMC should continue at the present level and its funding focus should be on the provision of scientific expertise and model capabilities not supported by NASA, e.g. ITM and atmosphere-ionosphere-thermosphere coupling.

Finding. *SuperMAG is a data service, initially developed to satisfy the interests of the original PI,* *but it has now evolved a strong community service component.*

Recommendation 7.15. SuperMAG should continue to be funded at the current level.

Finding. *Several magnetometers and magnetometer arrays are funded through research projects.*

Recommendation 7.16. The GS should assess if the era may now exist wherein greater scientific synergies and optimization of operations could be obtained if all GS-sponsored magnetometers were managed as a single array. Such an array could thus evolve into a Class 2 facility (see Section 7.4.3 for more details on DASI).

Finding. *The current SuperDARN U.S. network, in conjunction with the International SuperDARN program, provides good spatial and temporal coverage at polar latitudes in both hemispheres. Such capabilities have been expanded more recently to mid-latitudes.*

Finding. *The recent extension of university involvement in SuperDARN responds directly to the recommendations of the 2004 Avery review of the (then) Upper Atmospheric Research Facilities. This change has made community service (data products, data access and community support) more difficult to deliver.*

Finding. *The U.S. SuperDARN network has expanded markedly in recent years using a variety of funding sources, but the deployment and additional M&O costs have not been fully assessed.*

Recommendation 7.17. The U.S. SuperDARN groups should determine an optimal equilibrium between local research and community service, and optimize the efficiency of their M&O.

Finding. *The Consortium of Resonance and Rayleigh Lidars (CRRL) comprises four different LIDAR sites and a CRRL Technology Center (CTC). The Center is developing the next generation of LIDARs for geospace research.*

Finding. *While each of CRRL sites provide measurements of key stratospheric, mesospheric, and lower thermosphere neutral parameters, the flow down from coherent CRRL science objectives to requirements for the particular choice of locations of the sites is unclear.*

Finding. *CRRL as currently organized and directed is not a community facility as defined in Section 7.2. Its scientific objectives and its decisions on how different technological capabilities and scientific priorities are pursued are consistent with research activities funded by the GS Core and Targeted Grants Programs rather than the GS Facilities Program.*

Recommendation 7.18. The participating members of the CRRL group should seek peer-reviewed funding individually or collectively from the Core or Targeted GS programs.

Recommendation 7.19. If the CTC aspires to develop innovative instrument capabilities and concepts for a new GS facility, e.g., an Observatory for Atmosphere Space Interaction Studies (OASIS), it should apply for separate funding from the proposed Innovation and Vitality Program (see Section 7.4.1).

Finding. *A Low-latitude Ionosphere Sensor (LISN) network has recently been established across South America under an MRI grant. LISN currently consists of about 50 GPS receivers, 5 magnetometers and 5 ionosondes. Specific resources for science and for M&O of this distributed array are currently covered by non-facility sources. LISN has many of the required characteristics of a class 2 facility.*

Recommendation 7.20. The M&O and science resources for LISN should be funded via peer review under the recommended "DASI" line as outlined in section 7.4.3.

7.4 New Investments and Capabilities

7.4.1 Innovation and Vitality Program

Ongoing investment in existing facilities beyond annual M&O budgets is essential in maintaining cutting-edge GS facilities. Development of innovative capabilities that may one day provide the impetus for future investment in a new facility is also essential for the vitality of the field. Community inputs to the Decadal Survey indicated that there were many excellent ideas for substantial new initiatives hence a pressing needs for support.

Finding. *At present, facility upgrades are done on a facility-by-facility basis in a rather piecemeal fashion. No mechanism exists to develop new facilities within the GS portfolio, except in a rather ad hoc manner.*

Finding*. There is limited funding available for the development of computational models and numerical algorithms to improve the efficiency and fidelity of physics-based models of the space environment. Such models are critical to the value of the CCMC and to considering geospace as a system science.*

These findings imply that GS funding is likely not optimally deployed to promote GS science and thus meet the strategic needs for innovative research.

Recommendation 7.21. A central fund to support innovation and vitality for GS facilities should be established. It is envisaged that this fund would support several different activities. These should include, but not be limited to:

- Major repairs and renovation of an existing facility
- Funding for developing software and/or hardware that will significantly improve the performance of currently-funded class 1 and 2 facilities
- The development of new instrumentation, probably already designed and developed from research funds, into a capability where it could operate as a facility; this could include operation of a prototype.
- The development of numerical algorithms and methodologies (independent of science objectives) to improve the efficacy and accuracy of computational models for community use.
- The development of facilities - including models, data provision and measurement capabilities – to make them operational in real time, if a compelling scientific need for real time capabilities becomes evident.

Recommendation 7.22. Funds from the proposed Innovation and Vitality Program should be competed every 1-2 years depending on the level of funding available. It is expected that some awards might extend over 1-3 years. Given the diversity of the possible applications, a panel review is recommended so that the broader requirements of the GS community can be represented.

7.4.2 EISCAT and EISCAT-3D

Section 7.3.3 includes a recommendation that NSF should investigate the possibilities for U.S. investigators to gain access to European-based ISR systems (EISCAT and the EISCAT Svalbard Radar) that extend from the polar cap during disturbed times into the auroral oval to mid-latitudes during geomagnetically quiet times (see Figure 7.1). In developing this recommendation, the PRC reviewed basic information about EISCAT,[19] the EISCAT Blue Book (regulations),[20] EISCAT Annual Accounts,[21] a brief overview of the EISCAT standard experiments and other supported experiments[22], an overview of EISCAT-3D[23] and discussions with the Director of EISCAT.

The current EISCAT ISR system based on the Scandinavian mainland is the only radar that can make true 3D electric field measurements, but only a single point. EISCAT-3D will enable 3D measurements at multiple points simultaneously. In addition, a very extensive network of ancillary instruments, including an HF heater, is deployed within and surrounding the EISCAT field-of-view. The EISCAT ISR system and ancillary instrumentation provide a holistic view of the coupled mesosphere-thermosphere-ionosphere system that is intimately linked to the magnetosphere-solar wind system through the magnetic field.

EISCAT-3D is the new world-leading ISR under development. It will give many significant advantages over the current radars, including:

- Phased-array technologies for rapid beam steering (volumetric imaging)
- Multiple sites for 3D vector measurements of the ionosphere plasma
- Sufficient sensitivity for sub-second measurements of auroral phenomena
- Interferometric capabilities for 100m spatial-scale measurements

Thus EISCAT-3D would provide an unparalleled range of new science opportunities for the US geospace science community, particularly for measurements requiring small spatial and fast temporal scales. Observations of cross-scale coupling processes from the micro- to the macro-scales and *vice versa* are essential for obtaining deeper understanding of how the geospace system operates.

Recommendation 7.23. The GS should solicit proposals from the US GS community to form a US EISCAT consortium that would be funded by a block grant from NSF, initially to join EISCAT as Affiliate and eventually as an Associate.[24] The initial Affiliate status would allow the consortium to gain experience with EISCAT before making a five-year commitment as an Associate and to develop a deeper understanding of EISCAT system capabilities when EISCAT-3D becomes operational. Upon attaining Associate status, the consortium should be tasked with (1) transfer of the EISCAT annual membership fee to EISCAT-3D and (2) development and administration of a proposal and panel review process for the selection of US EISCAT users. The consortium should develop procedures for

[19] https://www.eiscat.se/groups/Documentation/BasicInfo
[20] https://www.eiscat.se/eiscat2014/eiscat-bluebook-draft-2015-version-2014-04-02/view
[21] https://www.eiscat.se/groups/Documentation/Council/annual-report-of-the-accounts-2014/view
[22] https://www.eiscat.se/groups/Documentation/UserGuides/eiscat-experiments/view
[23] https://eiscat3d.se/
[24] See Appendix F for an overview of the EISCAT membership type and conditions.

cost-effective grant administration that minimizes the encumbered overhead expenses of multiple member institutions.

7.4.3 Distributed Arrays of Small Instruments (DASI)

The DASI concept was recommended in the first decadal survey of solar and space physics research *The Sun to the Earth and Beyond: A Decadal Research Strategy in Solar and Space Physics* (2003). DASI would provide the temporal and spatial coverage of many atmospheric and ionospheric parameters that complement measurements from other ground- and space-based facilities. The DASI concept was subsequently examined by a National Academies workshop.[25]

In the last decade, the DASI concept has not evolved as rapidly as originally envisaged. This shortcoming has been due to a variety of factors, including a lack of funding opportunities, inadequate community experience in cultivating the required international collaborations, and inadequate experience in developing robust capabilities for unmanned and energy-efficient operation of distributed instruments and for automated data processing, analysis and transfer. Nevertheless, some members of the US scientific community have forged ahead with the development and improvement of new ground-based instrumentation and the deployment of small networks. These activities have been sponsored by diverse funding streams including NSF MRI, GS Core, the Office of Naval Research, and the Department of Defense University Research Instrumentation Program (DURIP).

DASI-type networks that have either emerged or augmented operations over the last decade include SuperDARN, CRRL and LISN. Some have been developed specifically to achieve the science objectives defined by the PIs and not necessarily to the significant benefit of the wider geospace community.

The types of instruments deployed in DASI-type networks include but are not limited to Global Positioning System receivers giving total electron content and scintillation activity, Fabry-Perot interferometers measuring winds and temperatures at mesospheric and/or thermospheric altitudes, magnetometers, meteor wind radars, digital ionosondes, LIDARs, optical imagers, photometers, riometers and VLF radio receivers.

Finding. *With growing recognition for the importance of geospace system science, the geospace community can expect, in the next decade, an increasing demand for higher spatial and temporal resolution in measurements, not only to determine the local, regional and global scale of processes but also for data assimilation into geospace models.*

Recommendation 7.24. The GS should create a "DASI" fund with two purposes: (i) to develop and build new "small" instrumentation suitable for deployment in a DASI network and (ii) to provide M&O funds to maintain the network once created.

Recommendation 7.25. The initial opportunity for awards, to be evaluated by an ad hoc review panel, should provide funding of sufficient duration that the DASI projects can be evaluated in conjunction with the other Class1 and Class 2 facilities by the proposed Senior Review Panel (Section 7.5) at its first meeting.

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[25] http://www.nap.edu/catalog/11594/distributed-arrays-of-small-instruments-for-solar-terrestrial-research-report

Mature and scientifically-compelling DASI networks that are operating as a Class 2 facility (as defined in Section 7.2) are envisaged to be candidates for incorporation into the GS facilities budget, if the capabilities and scientific objectives of the facility would enable substantial progress on the science program articulated in the 2013 Decadal Survey for Solar and Space Physics.

Advancement of a GS DASI Program faces two fundamental challenges: What types of DASI will be deployed where and for what purposes? How will the US developments be integrated most effectively with those from the international community, which is progressing along a similar trajectory?

In order to ensure cutting-edge science, funds allocated to the proposed GS DASI Program would be competed with regular announcements of opportunity and with selections recommended by a peer-review panel. Primary criteria for selection would include assessments of:

- Capabilities that would enable progress on the science program articulated in Chapter 1 of the 2013 Decadal Survey for Solar and Space Physics;
- Quality of the new science to be derived from the development and/or deployment of the network of instruments;
- Size of the potential user community;
- Quality and range of services to be provided to the United States GS community; and
- Leverage of the proposed investment from international partners.

7.4.4 Data Systems, Products and Management

Observations are critical to the success of GS research. They are essential for describing processes in geospace, for robustly testing models and for assimilation into models. With the ever-increasing capabilities and number of distributed instruments, the growth in data quantity is very significant.

The ISR data and many of those from the co-located instruments are managed and archived through the Madrigal database currently supported through the Millstone Hill ISR M&O budget.

Finding. *Data from US facilities are validated, processed to at least level 1, and archived by the PIs using M&O funding. Limited statistics are available on data downloads and on the number of data users.*

As system science develops further, an ever-pressing need is expected for non-data experts to be able to access, visualise and utilise data easily from a proliferation of sources. As a result, coherent, integrated data systems need to be developed that allow easy access to all data collected by US-funded science, and sometimes including data from international partners.

There is a real opportunity to produce more “value-added” geospace products by combining data from several sources. For example, ionospheric conductance is essential for many science objectives; regional and global conductance maps could now be produced using AMPERE, SuperDARN, SuperMAG and other available data sets (e.g., GPS, optical, ISR and space-based data). It is not essential to have all GS data on a single server but inter-operability is essential.

Recommendations. NSF should create a separate competitive fund for the further development of data management and data visualisation from many sources, including new value-added data products. This funding should include the further development and operation of the Madrigal database, thus separating it from the Millstone Hill ISR M&O funding for greater transparency.

7.5 Facility Extensions

7.5.1 Advisory/User Groups

The delivery of facilities to users always presents major challenges in balancing inevitable competition for limited facility resources. These challenges include maintenance, operations, additional support for the user community, development of new hardware and software and operating costs (e.g., the cost of fuel and repairs to the infrastructure). Prioritising such activities is particularly difficult at times of limited resources. Priority decisions on the challenges have been normally made by the PI, sometimes in consultation with NSF staff.

Finding. *Facilities PIs often convene only informal users meetings, e.g. embedded within the CEDAR meeting. A users' consensus (if one emerges in such meetings) typically has limited influence in deciding priorities.*

Recommendation 7.26. All facilities should have a formal and active users/advisory group, appointed by NSF and chaired by an independent person to support NSF and the PI in deciding priorities.

Recommendation 7.27. Each facility PI should provide an annual report to NSF that should include a 3-year development plan, prioritised and budgeted for the facility.

Recommendation 7.28. All annual reports should be open to the GS community, except for sections that are commercially sensitive or involve individual personnel issues.

7.5.2 Scientific Research Within Facilities Awards

Some facility awards budget a portion of the facilities grant or cooperative service agreement for scientific exploitation of facility data. The rationale for this practice is not always clear.

A modest budget for staff research (not more than 10% of staff costs) in the M&O budget of Class 1 and Class 2 facilities can provide the following advantages:

- Recruitment and retention of highly-rated staff to operate the facility and interact with its community of users;
- Support for M.S. and Ph.D. students engaged in the delivery of the facility services as part of their training and professional development; and
- Development of a thorough understanding of facility data sets with provision of expert support to the facility's user community (e.g. advising on the modes of operation of the facility and data processing methodologies).

The quality of the science undertaken must be internationally competitive. Therefore a Senior Review (Section 7.8) should evaluate the quality of science supported by the facility grant or contract when reviewing the facility.

Scientists and engineers associated with facilities are strongly encouraged to apply for additional funds through the many science, engineering and technical opportunities available to them to enhance the research of the facility.

Recommendation 7.29. NSF should develop clear procedures for deciding whether to award science research funding within a facility contract, and the level of that funding, which normally should not exceed 10% of the personnel costs.

Recommendation 7.30. The semi-decadal Senior Review of facilities should evaluate the quality of the science undertaken with the M&O funding.

7.6 Non-GS Funded Instrumentation

Finding*: Ongoing M&O costs for geospace instruments and arrays of instruments initially developed with funds obtained from NSF (e.g., the MRI program) and other agency announcements of opportunity are not typically included in the initial award. After the instruments have been deployed or used for an initially-proposed period, the GS will often receive a proposal to cover ongoing M&O costs of the instruments. Examples include LISN, GIMNAST, the heater facility at Arecibo, a mini-AMISR at Jicamarca and multiple Fabry-Perot instruments.*

Recommendation 7.31. NSF should identify both the ongoing M&O costs and their funding source(s) before awarding the grant.

Recommendation 7.32. For instruments funded from external sources, the Senior Review panel (Section 7.8) should be tasked to determine whether facility funding is appropriate.

7.7 Midscale Projects Program

The Decadal Survey recommended that NSF should create a new, competitively selected midscale project funding line in order to enable midscale projects and instrumentation for large projects. The envisioned approaches were considered necessary by the DS steering committee to fill gaps in observational capabilities and to move the survey's integrated science plan forward. The PRC concurs with the Survey committee's recommendation and rationale for it.

To quote the DS:

> "Important research is often accomplished through midscale research projects that are larger in scope than typical single principal investigator (PI)-led projects (MRIs) and smaller than facilities (MREFCs). The Advanced Modular Incoherent Scatter Radar (AMISR) is an example of a midscale project widely seen as having transformed research in the ground-based AIM community. Although different NSF directorates have programs to support unsolicited midscale projects at different levels, these programs may be overly prescriptive and uneven in their availability, and practical gaps in proposal opportunities and funding levels may be limiting the effectiveness of midscale research across NSF. It is unclear, for instance, how projects like the highly successful AMISR would be initiated and accomplished in the future. Mechanisms for the continued funding of management and operations at existing midscale facilities are also not entirely clear.
>
> The NSF Committee on Programs and Plans formed a task force to study how effectively it supports midscale projects, how flexible the funding is, how uniformly it is administered across NSF, and how well such projects serve the interests of education and public outreach. The resulting report affirmed the importance of strongly supporting midscale instrumentation but did not recommend any new or expanded NSF-wide programs.

Nevertheless, as described in Chapter 4 in the "Diversify" recommendations of DRIVE, the committee strongly endorses the creation of such a competitively selected midscale project line for solar and space physics. This approach is also consistent with the 2010 astronomy and astrophysics decadal survey, which recommended a midscale line as its second priority in large ground-based projects."

This survey committee's white-paper process and the subsequent disciplinary panel studies brought forward a number of important 'Heliophysics' projects that would require a new midscale funding line. The unranked examples listed below illustrate the kind of science that the line could enable. These projects are seen as being central to the integrated science program outlined in the survey: (1) *The Frequency-Agile Solar Radiotelescope*; (2) *The Coronal Solar Magnetism Observatory*; (3) *An All-Atmosphere Lidar Observatory*; (4) *A Heterogeneous Ionospheric Facility Network*; (5) *A Southern-Hemisphere Incoherent Scatter Radar*; and (6) *Next-Generation Ground-Based Instrumentation*.

To the midscale candidates identified by the DS, the PRC can add *The Coronal Mass Ejection Radar*, which was proposed in one of the white-paper comments submitted to the PRC.

The Midscale Innovations Program recommended in the AST Portfolio Review, and now implemented, is an AST division-wide program for projects ranging from $4M to $30 M. If a midscale projects program were to be implemented at the GS level, funding for it at an annual level $1M to $6M would sustain a new project with a total cost of $5M to $30M every 5 years.

The PRC agrees with the DS that numerous compelling Midscale projects could address gaps in critical capabilities for geospace and solar science (e.g., Tables 5.2-5.5). Investing in a midscale line would enable innovative measurement capabilities, but accommodating all new GS program elements recommended by the Survey is not possible for the flat budget assumed for GS out to 2025. A Midscale Projects line, in particular, has a lower priority at this time than other items in the budget scenario presented in Chapter 9. However, the PRC would recommend a Midscale Projects Program if one or both of the following conditions are met.

Recommendation 7.33. If use of the Arecibo Observatory is no longer available to GS researchers, e.g., due to divestment or insufficient funding for its continuing operation, and the GS budget remains at or above the flat funding level assumed for the Portfolio Review, then the recommended annual funding of $1.1M for Arecibo should be redirected to the Innovations and Vitality Program described in Section 7.4. Depending on community consensus and the recommendations from the facilities Senior Review recommended in Section 7.8, a significant portion of this augmented I&V annual budget might be directed to funding for a new Midscale project.

Recommendation 7.34. If future GS budgets exceed the flat-budget assumption of this review by $1M per year or greater, then the additional annual funding should be directed to a Midscale Projects Program.

7.8 Facilities Senior Review

Maintaining state of the art facilities for geospace research is crucial in enabling discoveries that transform understanding of geospace. As discussed in Chapters 3, 4 and 6 and Section 7.3, the addition of new programs, new GS facilities and a doubling in the GS financial support of Arecibo during the past decade came at a time when the inflation-adjusted GS budget remained flat. While some of the new programs and facilities have enabled new capabilities, their costs produced a funding squeeze on all GS programs including support for science, for existing GS facilities and facilities upgrades. Consequently, funds for timely facility upgrades and improved capabilities have been deferred. The recommendations of this portfolio review are intended to correct this situation in the coming years.

If the GS budget remains flat for the next decade, as presumed in the PRC charge, past practice suggests that GS funds for facility upgrades will again become stressed as new facilities come online from successful MRI or MREFC initiatives and other peer-reviewed proposals. Successful MRI (and potentially MREFC) initiatives are awarded with GS consent, but without adequate planning for subsequent M&O support, let alone science support. The result is that ongoing M&O costs for these new facilities must be covered by the GS budget. If space is not made in the presumed flat budget, these costs will further substantially reduce funds for existing facilities M&O and their upgrades to be supported by the new Innovation and Vitality Program described in Section 7.4.

Recommendation 7.35. To prevent scope creep in future facilities without adequate budget to support the additional M&O costs, a periodic "Senior Review" of all GS facilities should be conducted, at least every 5 years. This review should include established facilities i.e. all Class 1 and Class 2 facilities. Nascent "facilities" that may be on a trajectory for facility status but either are not yet operating as a facility, as defined in Section 7.2, or have not yet been fully developed, e.g., as part of an MRI, MREFC, a possible new Mid-Scale Projects line, or other initiative, should also be included in the Senior Review if their transition to facility class is expected to occur before the next Senior Review. Ideally, all facility proposals (including those for new facilities) should eventually be synchronized on a 5-year renewal for the envisioned Senior Review process.

The purpose of the Facilities Senior Review is two-fold:

1. To reconcile the GS facilities budget with the costs required to provide adequate M&O for all GS facilities and to maintain the state-of-the-art in facilities instrumentation and capabilities. As described in this portfolio review, reconciliation may require closure or divestment of some facilities to accommodate the innovative capabilities provided by new facilities or augmented facilities.
2. To review and rank each facility's capabilities (i) to enable, as a standalone instrument or system, transformative scientific discoveries, and (ii) to contribute to integrative scientific understanding as a complementary element in NSF's distributed capabilities for observing geospace as a system. Capability (ii) cuts across all GS programs, so the panel charged with conducting the Senior Review would draw on expertise in each of the GS core research programs.

Although the administration and decisions on the structure of the Senior Review process reside with the GS Head and Facilities Project Managers, the PRC offers some suggestions for how to ensure that the review is most effective given its experience in reviewing GS facilities for the portfolio review. The PRC envisions the Senior Review to be an open process in which written proposals for facility continuation are first reviewed by the Senior Review panel. The PIs and key staff of each of the facilities are then subsequently invited to present in a face-to-face meeting with the Senior Review panel and GS staff, the facility's past successes and future plans for meeting criteria (i) and (ii) above. The recommendations of the Senior Review and their justifications would be made publically available in a Senior Review report following the review.

The Senior Review panel would be charged well before the presentations and interviews are scheduled. To better inform the review, prior to the face-to-face meeting the panel would reach a consensus (e.g., via web conference) on the major issues of concern and clarification for each facility so that facility PIs may prepare appropriate responses.

It would be advantageous and administratively efficient if the written proposals submitted to the Senior Review served as the NSF proposal for the five-year grant or cooperative agreement for the facility. Some facilities may require upgrades or augmented capabilities to fulfil the PI's or the community's vision for its future success. Proposals to complete upgrades or augmentations might be included in the proposals submitted to the Senior Review.

NSF has developed a set of criteria for reviewing major scientific initiatives. These criteria could be adapted for the senior Review assessment. They are:

–*Primary filter:*

Compelling science: research that has the potential for important, transformative steps forward in understanding and discovery.

Secondary filters (important criteria, but each one may not be met in every case):

Potential for societal impact: research that yields information of near-term and/or long term benefits for society.

Time-sensitive in nature: research that involves systems/processes undergoing rapid change that need to be observed sooner rather than later; research that could help inform current public policy concerns.

Readiness/feasibility: research that is poised to move forward quickly within the coming decade, in terms of needed technologies and community readiness.

Key area for U.S. and NSF leadership: research for which the United States, and NSF in particular, is advantageously positioned to lead.

Tertiary filters (additional factors to consider):

Partnership potential: research for which NSF investments could leverage investment by other federal agencies, other parts of NSF, or international partners.

Impacts on program balance: research that would not cause significant adverse impacts on other projects by requiring disproportionate funding support, or logistical support.

Potential to help bridge existing disciplinary divides: research that could provide opportunities to bring together disciplinary communities that seldom work together.

Recommendation 7.36. NSF GS should develop a common set of annual metrics from each facility which can be collected year-on-year to provide an underpinning of the next Senior Review. These metrics could include science outputs both from facility staff and external users, annual expenditure (capital and resource), data downloads and usage, and key technical developments (hardware and software).

Chapter 8. Partnerships and Opportunities

This portfolio review formalizes the geospace science community's recommendations to the AGS Division for how best to optimize investments in critical capabilities needed over the period from 2016 to 2025 that would enable progress on the science program articulated in the 2013 Decadal Survey for Solar and Space Physics. The recommended GS portfolio presented in the next chapter does so within the flat-budget constraint assumed for the review. However, some critical capabilities are provided by NSF programs external to the Geospace Section and do not explicitly enter the budget scenario of the recommended portfolio. Other capabilities may be augmented or leveraged through partnerships both internal and external to NSF. These extra-GS programs and resources are summarized here. Leveraging investments in critical capabilities for geospace science necessarily requires collaboration between GS program staff and the geospace research community. It also requires initiative on the part of geospace PIs in applying for resources external to the GS. This chapter of the review is directed to both GS program managers and the geospace research community.

8.1 NSF Intra-Agency Partnerships and Opportunities

8.1.1 Programs Within AGS

NCAR and HAO

The National Center for Atmospheric Research (NCAR) is a national institution and resource dedicated to the study of the atmosphere, the Earth system, and the Sun.

The High Altitude Observatory (HAO) is the geospace laboratory of NCAR. HAO provides capabilities that directly support NSF-GS science objectives and community research efforts. In particular, HAO manages the Mauna Loa Solar Observatory (MLSO) which makes daily observations that are distributed via the internet in near-real time. These form a unique solar coronal synoptic dataset which is required for several of the Solar-Terrestrial science challenges (see Section 5.3). HAO also works with the community to develop large-scale, computational models that support community research in upper atmospheric, ionospheric, and magnetospheric physics. These include the Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM), and the Whole Atmosphere Community Climate Model (WACCM), with extension upward into the ionosphere, thermosphere, and mesosphere (WACCM-X; currently under development). HAO has a substantial visitor's program that supports interactions with the broader community, and that annually funds both postdoctoral associates and graduate students. HAO represents a significant investment by the AGS Division in support of geospace science. The FY 2015 HAO budget was projected to be $6.1M including NSF base funding and Directorate transfers.

NCAR's Computational and Information Systems Laboratory (CISL) deploys and operates the physical and virtual computational facilities needed to support its science community. CISL's supercomputing resources serve approximately 1,800 users in a wide variety of disciplines including geospace science. CISL develops and curates research data sets and maintains online user access to the archive. CISL also provides virtualization and grid technologies, promoting collaboration and sharing of valuable scientific resources. University use of CISL resources is intended to support research in the atmospheric and related sciences by scientists holding NSF grants and graduate students at U.S. universities. Allocations for CISL resources are made at no cost to eligible users and emphasize extensive projects that are beyond the scope of university computing centers. This resource enables critical capabilities for large-scale simulation modeling studies and big data analysis projects of NSF geospace scientists.

NCAR's Advanced Study Program (ASP) helps NCAR and the scientific communities it serves prepare for the future by: encouraging the development of early career scientists in fields related to atmospheric science; directing attention to timely scientific areas needing special emphasis; organizing new science initiatives; supporting interactions with universities; and promoting continuing education at NCAR. ASP supports three programs for scientists and graduate researchers to work in residence at NCAR: Postdoctoral Fellowship Program, Faculty Fellowship Program, and Graduate Student Visitor Program. These programs contribute to the vitality of the geospace science profession.

Recommendation 8.1. The AGS Director and GS Head should continue to coordinate with the Director of HAO to facilitate alignment of HAO science goals with GS science goals.

The AGS Postdoctoral Research Fellowships Program, as discussed in Chapter 4, also contributes to the vitality of the profession by sponsoring postdoctoral fellows pursuing research in geospace science.

8.1.2 Programs Within the Geoscience Directorate

Office of Polar Programs

The Antarctic Astrophysics and Geosciences (AAGS) Program of the Division of Polar Programs (DPP) supports substantial solar-terrestrial research at a budgetary level of the order of slightly more than $2M/year. As the name implies, the Program also supports, at a budgetary level of about $9M/year, a significant research program in astronomy and astrophysics, largely at the Amundsen-Scott South Pole Station. Because its land mass spans a very large geomagnetic area under the polar cap and auroral regions, the Antarctic continent is an ideal location for deploying, at the manned stations and in the deep field, state-of-the-art instrumentation for solar-terrestrial research. The programs in solar-terrestrial research currently include a wide range of instrumentation for polar cap, polar cusp, and auroral studies.

Instruments in the deep field consist of several latitudinal magnetometer chains, one of which, the Automatic Geophysical Observatories, also includes instrumentation such as imaging riometers, photometers, VLF receivers, and other studies. These chains of remote sites use innovative solar, wind, and battery power for yearlong operations. The manned U.S. stations at McMurdo/Arrival Heights (in the polar cusp region) and at South Pole (the auroral zone) are home to instrumentation including magnetometers, imaging riometers, Fabry-Perot Interferometers (FPI), all-sky imagers and photometers, Lidars, VLF and ELF receivers. The U.S. Palmer Station, on the Antarctic Peninsula, has an FPI and also studies at VLF frequencies natural (from lightning) and man-made signals. Two SuperDARN radars based in the Antarctic (South Pole and McMurdo) are supported by the AAGS.

DPP also supports the operation of two neutron monitors (at McMurdo and South Pole) which provide unique measurements for several areas of solar-terrestrial research. Of the 13 neutron monitors previously supported by NSF, only these two are currently NSF-funded and are critical to continuing the >50 year-long record of high energy particles impacting the Earth's atmosphere. Particle measurements from neutron monitors provide information regarding long-term solar cycle variations as well as short-term space weather conditions and are an essential link between the lower energy particle measurements made by sensors on spacecraft and the higher energy regime monitored by ground-based detectors such as muon detectors and air shower arrays.

The challenging environment of the Antarctic demands vastly different logistics requirements for instrumentation and M&O than in other international locations. Thus, logistics are handled by the GEO-PLR and not by individual PIs.

International instrumentation is hosted at both of the manned stations, and international investigators collaborate with data analysis and modeling of phenomena from the remote field sites. International collaboration also occurs in other ways, including the conjugacy of portions of the Antarctic magnetometer arrays with northern hemisphere locations, and with instrumentation arrays in other Antarctic locations of other nations, notably the UK.

On occasion and as science priorities arise, the Division also supports the science and logistics of long-duration balloon flights for solar-terrestrial research. In the past, rockets for auroral studies have also been launched from the Antarctic. Both rockets and balloons have been supported by the Division and by NASA. Also, as science priorities and objectives require, there is close collaboration between the Antarctic Astrophysics and Geosciences Program and the Geoscience Section of AST.

Recommendation 8.2. The GS Head should continue to coordinate with the GEO=PLR AAGS Program Director to facilitate alignment of AAGS science goals with GS science goals.

Research in Hazards and Disasters (Hazards SEES) and Prediction of Resilience against Extreme EVENTS (PREEVENTS) Programs

NSF supports basic research in scientific and engineering disciplines necessary to understand extreme natural events and hazards. Programs with this goal include the Interdisciplinary Research in Hazards and Disasters (Hazards SEES) program, which completed its second and final competition in 2015, and its recently announced successor program, Prediction of and Resilience against Extreme EVENTS (PREEVENTS). Hazards SEES is currently funding or co-funding two significant projects relevant to geospace science: AMPERE II as reviewed in Chapter 7 and a project to improve prediction of geomagnetic disturbances, geomagnetically-induced currents, and their impacts on power distribution systems.

Finding. *Participation in these programs may require co-funding from GS when a selected project is relevant to geospace science or space weather.*

Recommendation 8.3. GS PMs should continue to encourage GS investigators to pursue co-funding from the PREEVENTS and similar future programs of the Geoscience Directorate. Whenever possible co-funding these types of targeted programs from the GS budget should be derived from GS Strategic Grants or Facilities programs rather than the GS Core Grants program.

8.1.3 Cross-Directorate Programs

AST-GS Partnership in Solar Physics: NSO, NRAO, NOAO

Solar physics is also a part of the mission of the NSF-MPS-AST division. Synoptic observations of solar surface magnetism and flows that can be used in GS analyses are taken by the National Solar Observatory (NSO) Integrated Synoptic Program (NIST). High temporal and spatial resolution observations of solar plasma and magnetic fields will be taken by the Daniel K. Inouye Solar Telescope (DKIST) currently under construction. The NSO also (with NASA) coordinates the Virtual Solar Observatory (VSO). Relevant stellar observations are obtained by the National Optical Astronomical Observatory (NOAO), and flare/CME-related radio observations are taken by the National Radio Astronomical Observatory (NRAO). All of these are required capabilities for Solar-Terrestrial science challenges, as described in Section 6.4.

As discussed in that section, coordination across directorates is important. The AST investment in NSO was $8M in FY 2015 for base NSF funding plus $5M for ramping-up DKIST operations.

Recommendation 8.4. This recommendation reaffirms the finding and recommendation in Section 6.4 that GS should continue to coordinate with PMs and Directors of these external entities to ensure continuing acquisition of these critical data streams and access to them for geospace and solar science investigations.

EarthCube

EarthCube is a community-driven activity sponsored through a partnership between the NSF Directorate for Geosciences (GEO) and the Directorate for Computer & Information Science & Engineering (CISE) Division of Advanced Cyberinfrastructure (ACI) to transform research in the academic geosciences community. EarthCube aims to create a well-connected and facile environment to share data and knowledge in an open, transparent, and inclusive manner, thus accelerating our ability to understand and predict the Earth system.

Achieving EarthCube will require a long-term dialog between NSF and the interested scientific communities to develop cyberinfrastructure that is thoughtfully and systematically built to meet the current and future requirements of geoscientists. New avenues will be supported to gather community requirements and priorities for the elements of EarthCube, and to capture the best technologies to meet these current and future needs. The EarthCube portfolio will consist of interconnected projects and activities that engage the geosciences, cyberinfrastructure, computer science, and associated communities. The portfolio of activities and funding opportunities will evolve over time depending on the status of the EarthCube effort and the scientific and cultural needs of the geosciences community.

This EarthCube program currently sponsors a geospace science project "EarthCube IA: Magnetosphere-Ionosphere-Atmosphere Coupling" with the intent to develop a series of interlocking web services that provide access to the underlying MIAC datasets (AMPERE, SuperDARN and SuperMAG), that apply the science algorithms to derive the desired electrodynamic products, and provide data translation and visualization services.

Finding. *The EarthCube program is an effective vehicle for augmenting GS investments in the recommended GS Facilities program for Data Systems, Products and Management (Sect. 7.4.4).*

Recommendation 8.3. GS PMs should continue to encourage GS investigators to pursue co-funding from the EarthCube program for Data Systems, Products and Management. If co-funding from the GS is desirable or required to secure external EarthCube funding, whenever possible the co-funding should be derived from the newly recommended GS Facilities Program for Data Systems, Products and Management (Sec. 7.4.4).

8.1.4 Foundation-Wide

Major Research Instrumentation Program (MRI)

As described on the NSF program web page, the Major Research Instrumentation Program (MRI) serves to increase access to shared scientific and engineering instruments for research and research training in our Nation's institutions of higher education, not-for-profit museums, science centers and scientific/engineering research organizations. The program provides organizations with opportunities to acquire major instrumentation that supports the research and research training goals of the organization and that may be used by other researchers regionally or nationally.

Each MRI proposal may request support for the acquisition (Track 1) or development (Track 2) of a single research instrument for shared inter- and/or intra-organizational use. Development efforts that leverage the strengths of private sector partners to build instrument development capacity at MRI submission-eligible organizations are encouraged.

The MRI program assists with the acquisition or development of a shared research instrument that is, in general, too costly and/or not appropriate for support through other NSF programs. The program does not fund research projects or provide ongoing support for operating or maintaining facilities or centers.

The instrument acquired or developed is expected to be operational for regular research use by the end of the award period. For the purposes of the MRI program, a proposal must be for *either* acquisition (Track 1) *or* development (Track 2) of a single, well-integrated instrument. The MRI program does not support the acquisition or development of a suite of instruments to outfit research laboratories or facilities, or that can be used to conduct independent research activities simultaneously.

Instrument acquisition or development proposals that request funds from NSF in the range $100,000-$4 million may be accepted from any MRI-eligible organization.

Cost-sharing of precisely 30% of the total project cost is required for Ph.D.-granting institutions of higher education and for non-degree-granting organizations. Non-Ph.D.-granting institutions of higher education are exempt from cost-sharing and cannot include it.

Finding. *The MRI program has been used effectively by GS investigators to acquire and develop instrumentation to augment research conducted at Class 1 facilities and to develop DASI projects that have the capacity to become Class 2 facilities.*

Recommendation 8.5. The GS should continue to encourage and work with PIs applying for and receiving MRI funds to develop innovative new instrumentation for use in geospace science research. Consistent with the finding and recommendation of Section 7.6, when additional funds will be requested from the GS for future M&O costs for the MRI, the funding source(s) and space in the GS Facilities budget should be planned well in advance of taking-on the new facilities' costs.

Alternatively, PIs should be encouraged to explore non-NSF sources of funding for future M&O costs.

Major Research Equipment and Facilities Construction (MREFC)

The National Science Foundation (NSF) defines a facility under MREFC as an essential part of the science and engineering enterprise that will advance science in ways that would not be possible otherwise. The facility can either be centralized or consist of distributed installations. The project "should offer the possibility of transformative knowledge and the potential to shift existing paradigms in scientific understanding and engineering processes and/or infrastructure technology and should serve an urgent contemporary research and education need that will persist for years" (NSF, 2007).

MREFC projects are so large that the total construction costs would be >10 percent of the budget for the sponsoring directorate or office. Thus, funding of the facility would distort the base program of funding in that discipline(s) without MREFC funding. Investments in computing resources and for supporting cyberinfrastructure can be included in the design plan and the construction costs. Development of the DKIST by the NSF-MPS-AST division has been enabled by an MREFC grant.

Finding. *To date, no GS facilities have been developed with MREFC funds. The MREFC program could provide the means for development of next-generation GS facilities that have the capacity to transform our understanding of geospace.*

Recommendation 8.6. Concepts appropriate for MREFC investment in geospace science have recently emerged in GS community forums (e.g., at the conference on Measurement Techniques in Solar and Space Physics held in Boulder in April, 2015 and at recent CEDAR and GEM workshops). The GS should encourage development of transformative facility concepts appropriate for MREFC investment by co-sponsoring community workshops to advance innovative new concepts.

Recommendation 8.7. Planning for a possible future MREFC investment should include budget scenarios for how M&O would be accommodated for a new facility of this scale, including possible sun setting of one or more existing GS facilities.

Software Infrastructure for Sustained Innovation (SI2)

NSF's program for Software Infrastructure for Sustained Innovation (SI2) is a long-term investment focused on realizing a portion of the Cyberinfrastructure Framework for 21st Century Science and Engineering vision and for catalyzing new thinking, paradigms and practices in science and engineering. It envisions a linked cyberinfrastructure architecture that integrates large-scale computing, high-speed networks, massive data archives, instruments and major facilities, observatories, experiments, and embedded sensors and actuators, across the nation and the world, and that enables research at unprecedented scales, complexity, resolution, and accuracy by integrating computation, data, and experiments in novel ways.

The objectives of the new GS Data Systems program recommended in Section 7.4 are well-aligned with the goals the SI2 program. SI2 could enable investments in new GS data systems at three different levels: 1) Scientific Software Elements awards targeting small groups to create and deploy robust software elements for which there is a demonstrated need that will advance one or more significant areas of science and engineering; 2) Scientific Software Integration awards that target larger, interdisciplinary teams organized around the development and application of common software infrastructure aimed at solving common research problems faced by NSF researchers in one or more areas of science and engineering; and 3) Scientific Software Innovation Institutes that focus on the establishment of long-term hubs of excellence in software infrastructure and technologies, which will serve a research community of substantial size and disciplinary breadth.

SI2 is an excellent vehicle for augmenting GS investments in geospace data systems. The PRC offers no particular recommendation regarding SI2 other than to suggest that the GS to continue to encourage the geospace research community to develop competitive concepts for future SI2 investment.

Integrated NSF Support Promoting Interdisciplinary Research and Education (INSPIRE)

The INSPIRE program seeks to support bold interdisciplinary projects in all NSF-supported areas of science, engineering, and education research. INSPIRE has no targeted themes and serves as a funding mechanism for proposals that are required both to be interdisciplinary and to exhibit potentially transformative research. Complementing existing NSF efforts, INSPIRE was created to handle proposals whose:

- Scientific advances lie outside the scope of a single program or discipline, such that substantial funding support from more than one program or discipline is necessary.
- Lines of research promise transformational advances.
- Prospective discoveries reside at the interfaces of disciplinary boundaries that may not be recognized through traditional review or co-review.

Finding. *Successful INSPIRE proposals have augmented geospace science accomplished in GS grants programs. GS CubeSat projects (Section 6.6) also appear to be a good fit for INSPIRE funding, which could leverage GS investment CubeSats.*

Finding. *The INSPIRE program is designed to utilize mixed funding, with up to half of each award being provided by central funds and the rest shared between several divisions (programs). The INSPIRE funding model is set to change so that over the next 2 years, the central funding contribution will be phased out.*

Recommendation. If and when NSF central funding for INSPIRE projects phases-out, the GS should continue to use its own internal and well-established processes to fund high-quality projects that cross the disciplinary boundaries of its core grants programs and seek appropriate partners external to GS for projects that cross section, division or directorate boundaries.

EPSCoR Research Infrastructure Improvement Program

The mission of EPSCoR is to advance excellence in science and engineering research and education in order to achieve sustainable increases in research, education, and training capacity and competitiveness that will enable EPSCoR jurisdictions to have increased engagement in areas supported by the NSF. EPSCoR goals are:

- to provide strategic programs and opportunities for EPSCoR participants that stimulate sustainable improvements in their R&D capacity and competitiveness;
- to advance science and engineering capabilities in EPSCoR jurisdictions for discovery, innovation and overall knowledge-based prosperity.

EPSCoR objectives underlying the program goals are:

- to catalyze the development of research capabilities and the creation of new knowledge that expands jurisdictions' contributions to scientific discovery, innovation, learning, and knowledge-based prosperity;
- to establish sustainable STEM education, training, and professional development pathways that advance jurisdiction-identified research areas and workforce development;
- to broaden direct participation of diverse individuals, institutions, and organizations in the project's science and engineering research and education initiatives;
- to effect sustainable engagement of project participants and partners, the jurisdiction, the national research community, and the general public through data-sharing, communication, outreach, and dissemination;
- to impact research, education, and economic development beyond the project at academic, government, and private sector levels.

Finding. *CubeSat projects satisfy many criteria for EPSCoR funding, which has been used to co-fund some CubeSat projects. Eligibility to compete in NSF EPSCoR program opportunities is currently limited to twenty-five states, the Commonwealth of Puerto Rico, Guam, and the U.S. Virgin Islands.*

Recommendation 8.8. GS PMs should encourage eligible PIs to pursue EPSCoR opportunities to leverage funding for appropriate geospace research and educational projects.

CubeSats

The GS CubeSat program to date has been a standalone program funded primarily by the GS with modest augmentations from other NSF programs (e.g., EPSCoR).

Recommendation 8.9. In line with the findings and recommendations of Section 6.6 regarding the future of the GS CubeSat program, the GS should explore possible partnerships across NSF (and with DoD, NASA, industry, international partners) for augmenting the scientific impact of investments in the GS CubeSat program.

8.2 Interagency Partnerships

8.2.1 Department of Defense (DoD)

A number of existing and future DoD programs are focused on university research of direct relevance to the research areas of the Geospace Section. AFOSR has announced a Multidisciplinary University Research Initiative (MURI) for 2016 on 'Active Ionosphere-Thermosphere Coupling: Mechanisms and Effects.' The objective of this program 'is to characterize the thermospheric response to space storms from the polar cap to equatorial latitudes, to uncover the basic physical processes that determine where and how the I-T system responds to energy input, and to determine the mechanisms of energy dissipation in the ionosphere.' This objective capsulizes much of the CEDAR program as well as magnetosphere-ionosphere coupling within the scope of the GEM program. Additionally, DoD sponsors a Defense University Research Instrumentation Program (DURIP) with the goal to provide major equipment to 'augment current or develop new research capabilities in support of DoD-relevant research.' Although no financial relationship between NSF and DoD exists for these types of programs, instrumentation and models developed and implemented under such

DoD programs may contribute to critical capabilities for GS investigations during and after the period of performance of the DoD contract.

Finding. *Innovative instrumentation and models have been developed and implemented for geospace research by the university research community using funds from DoD programs. The useful lifetime of these DoD investments often exceeds the period of performance of the original DoD funding. In some cases, continuing use of legacy DoD instrumentation and models for geospace research has been supported by GS grants.*

Recommendation 8.10. The GS should carefully review the impact on its facilities and grants programs of assuming M&O costs for legacy DoD instrumentation. When doing so is well-aligned with DS and Section science goals, continuing use of such equipment may bring significant added value to GS programs with no up-front costs for investment in the instrument development. The GS should use the recommended Senior Review processes (Section 6.7 and 7.7) to determine the overall value of assuming M&O costs for legacy DoD equipment.

8.2.2 Department of Energy (DoE)

NSF/DOE Partnership in Basic Plasma Science and Engineering

The National Science Foundation (NSF), with participation of the Directorates for Engineering, Geosciences, and Mathematical and Physical Sciences, and the Department of Energy, Office of Science, Fusion Energy Sciences has co-funded the joint Partnership in Basic Plasma Science and Engineering since 1997. The goal of this program is to enhance basic plasma research and education in the broadly applicable, multidisciplinary field of plasma science by coordinating efforts and combining resources of the two agencies. The partnership encourages basic research into fundamental plasma science and basic plasma experiments at NSF and DOE supported user facilities, such as the Basic Plasma Science Facility at the University of California, Los Angeles, designed to serve the needs of the broader plasma community.

Finding. *Co-sponsorship of basic plasma science through the NSF/DOE Partnership significantly leverages GS investments in critical capabilities to make progress on DS Key Science Goal 4: Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.*

Recommendation 8.11. The GS should continue to participate in the NSF/DOE Partnership and co-fund research projects that address DS Key Science Goal 4.

8.2.3 National Aeronautics and Space Administration (NASA)

Community Coordinated Modeling Center (CCMC)

The CCMC is a multi-agency partnership to enable, support and perform the research and development for next-generation space science and space weather models. As described in Chapter 7, the GS co-sponsors CCMC although the bulk of its funding comes from NASA.

Finding. *CCMC models and simulation data from CCMC runs-on-request are used extensively by the geospace science and space weather research communities.*

Recommendation 8.12. The GS should continue to co-fund CCMC at the current level as recommended in Section 6.5.1).

NASA/NSF Partnership for Collaborative Space Weather Modeling

The GS in collaboration with the NSF-GEO Polar Programs Division, the Air Force Office of Scientific Research and the Office of Naval Research funds basic research in support of national space weather objectives. This support includes the development of space weather models for specification and forecast of conditions throughout the space environment.

Similarly, a primary goal of NASA's Living With a Star (LWS) Program is the development of first-principles-based models for the coupled Sun-Earth and Sun-Solar System, similar in spirit to the first-principles models for the lower terrestrial atmosphere. Such models can act as tools for science investigations, as prototypes and test beds for prediction and specification capabilities, as frameworks for linking disparate data sets at vantage points throughout the Sun-Solar System, and as strategic planning aids for enabling exploration of outer space and testing new mission concepts.

Because of the common goals among the agency programs described above, NASA and NSF have periodically agreed to renew their partnership to support new rounds of Strategic Capabilities, large-scale research projects that are more ambitious than those typically supported by a single grant by either organization. The partnership funds projects totaling approximately $4M/year with the GS contribution running $1.5M/year.

Finding. *The NASA/NSF Partnership for Collaborative Space Weather Modeling has been effective in advancing GS and DS science goals for space weather research. To assess its continuing alignment with both GS and LWS science goals, continuation of the partnership is reviewed by both NASA and NSF at 3-5 years intervals when a new Announcement of Opportunity is due to be released,*

Recommendation 8.13. The GS should continue the NASA/NSF Partnership for Collaborative Space Weather Modeling in the current modus operandi and as long as it continues to advance space weather research goals for the GS (as recommended in Section 6.5.2).

Grand Challenge Projects (GCP) Program

A GS GCP program is recommended in this portfolio review (Section 6.5), and NASA is currently evaluating a new Heliophysics Division funding line to create Heliophysics Science Centers to pursue GCR. Since neither the NSF nor the NASA program exists today, the extent to which the science goals of the two programs will overlap is not known. The Drive Initiative of the Decadal Survey recommended “NASA and NSF together should create Heliophysics science centers to tackle the key science problems of solar and space physics that require multidisciplinary teams of theorists, observers, modelers, and computer scientists, with annual funding in the range of $1 million to $3 million for each center for 6 years, requiring NASA funds ramping to $8 million per year (plus increases for inflation).

This nascent program element is a candidate for a NASA/NSF partnership. If their respective science goals and eligibility criteria and metrics for proposal selections are well-aligned, then such a partnership could be forged and managed similarly to the NASA/NSF Partnership for Collaborative Space Weather Modeling.

Recommendation 8.14. The GS should explore a new partnership with NASA to create a co-funded Grand Challenge Research program (as recommended in Section 6.5.2).

8.2.4 National Oceanic and Atmospheric Administration (NOAA)

The NSF Geospace Section supports long-established, and mutually beneficial, partnerships with NOAA. Collaborations are primarily with the Space Weather Prediction Center (SWPC), one of NOAA's National Weather Service (NWS), National Centers for Environmental Prediction (NCEP), but also with NOAA's National Center for Environmental Information (NCEI, formerly NGDC) where data are made available to NSF supported scientists.

An example of a recent partnership is the NSF Science Technology Center (STC), Center for Integrated Space Weather Modeling (CISM). STC goals include establishing meaningful links and benefits to society and promoting links to federal agencies. In the case of CISM, this was accomplished through a "Knowledge Transfer" component with SWPC scientists playing key roles throughout the 10-year program. In addition, one of the models supported by NSF's CISM, the Wang-Sheeley-Arge Enlil model that predicts solar wind conditions at Earth, was later transitioned to operations at SWPC.

The Geospace Section has also been a partner with SWPC's annual Space Weather Workshop that brings together space weather research, applications, operations, and users. In another partnership, NOAA is contributing substantial resources for the long-term operations and maintenance of the Global Oscillation Network Group (GONG) that is part of the National Solar Observatory supported by NSF's Division of Astronomical Sciences (AST). In this partnership, NOAA will be collecting and processing data from 6 sites for use in space weather operations and making these data, related to Hα images and Carrington magnetogram maps, available to the entire science community.

In addition to these partnerships, there are many collaborations between NSF supported organizations such as the National Center for Atmosphere Research (NCAR) High Altitude Observatory (HAO) and NOAA SWPC, and between NSF supported researchers who utilize NOAA data in their research. With regard to programs, NSF's GEM, CEDAR, and SHINE have always involved participation from SWPC, including NOAA members on the steering committees of these NSF led community programs that, in many cases, improve our understanding and modeling of processes related to space weather, as well as space science.

Finally, new and ongoing opportunities for collaborative work between NSF and NOAA are identified in the White House Office of Science and Technology Policy (OSTP) National Space Weather Action Plan.[26]

Finding. *The GS SWR program, currently in collaboration with NASA, undertakes basic and applied research for improved understanding of space weather phenomena and for development of "strategic capabilities" to improve space weather forecasting -- the province of NOAA's SWPC. This symbiotic relationship between SWPC and the GS SWR is mutually beneficial. It provides important societal context and relevance for GS research, and it enables improved capabilities for SWPC's directive to provide space weather forecasts.*

Finding. *Cooperation between NOAA's SWPC and the GS SWR program has been multifaceted, ranging from capability-enabling through NOAA-NSF (AST) co-sponsorship, e.g., the Global Oscillation Network Group, to substantial research collaboration, e.g., via NSF's former CISM STC, to data provision for GS research derived from NOAA satellite and ground-based measurements, to information*

[26] https://www.whitehouse.gov/administration/eop/ostp/nstc/docsreports

sharing at CEDAR, GEM, SHINE and the co-sponsored annual Space Weather Week workshops. This cooperation has required very modest resources from the GS.

Recommendation 8.15. The GS should continue its collaboration with NOAA's SWPC through resource and information sharing in ways that are consistent with each agency's respective goals in advancing basic and applied knowledge of space weather and capabilities for predicting its effects.

8.3 International Partnerships

To address the outstanding research problems identified in the Decadal Survey, ground- and space-based measurements of the geospace environment from many different parts of the coupled system are required at increasing temporal and spatial resolution. Providing this capability is far beyond the capacity of any one nation and hence international collaboration and cooperation are essential. This need for distributed geophysical measurements has been recognized for well over a century through initiatives such as the International Polar Year (IPY) (1882-83), the second IPY (1932-33) and the International Geophysical Year 1957-58. Excellent international coordination is also arranged through the family of scientific unions and science organizations that are members of the International Council for Science (ICSU), together with cooperation between the national space agencies.

The US has been and continues to be a major contributor to international projects and programs. NSF-GS supports a wide range of international activities on many continents. In the future, international cooperation is likely to increase given the emphasis on system science, the ever-growing importance of space weather, and the need to maximize the cost-benefit of investments. Some of the most important international partnerships for ground-based observation of geospace are summarized below. The list is by no means exhaustive.

Examples of international cooperation for Class 1 facilities include the Arecibo and Jicamarca ISRs in Puerto Rico and Peru, respectively. The US has been the majority financial sponsor but the host nations make critically important contributions to the successful operation of the facility. These ISRs also have strong local public outreach and technical training programs.

Another excellent example of joint international development is RISR-N and RISR-C. The former has been developed with funds from NSF and the latter is funded by Canada. These radars utilize similar technology, and with the radars co-located but looking in different directions, significant scientific and technical benefits accrue, as well as financial savings on M&O costs.

GS-sponsored investigators have also forged a number of important international partnerships to broaden the scope and geographic reach of various Class 2 facilities, especially DASI-like networks.

SuperDARN (Super Dual Auroral Radar Network.) is an international partnership to jointly design, develop and operate coherent-scatter HF radars for the purpose of conducting research on Earth's geospace environment. The very large fields of view of the radars (each $\sim$ 1Mkm^2) allow a wide range of scientific topics to be studied including the structure of global convection and its response to changes in interplanetary conditions, substorms, ULF waves, gravity waves, mesosphere winds and plasma irregularities. All data are freely shared amongst the partners, and the vast majority of data are open to all scientists soon after collection.

SuperDARN began in the early 1990s and progressively expanded. It involves 35 radars today, supported by the funding agencies of nine countries. The US continues to be a major player in SuperDARN, supporting nearly half the radars, and operating in both hemispheres.

The leverage of SuperDARN has been significant. Keys to this success include the excellent spirit of international collaboration, and the organization has been bureaucratically light. SuperDARN is a critical system for current and future geospace system science as it provides a global perspective on many key processes of the coupled solar wind-magnetosphere-ionosphere-thermosphere system.

Other examples where NSF grant funding has made a significant contribution to international networks include LISN, a network of instruments involving eight countries in South America; GIMNAST – a US extension of the Canadian ground-based network of All Sky Imagers (ASIs) initially developed to support the NASA Themis mission; Magnetometer Array for Cusp and Cleft Studies (MACCS) - a high latitude array of eight high-time resolution magnetometers and four standard observatories in northeastern Canada; and the recently initiated Transition Region Explorer (TREx) – a Canadian network under development to replace and enhance the THEMIS-ASIs with 21 all sky imagers in 3 different wavelength bands and 10 imaging riometers (these to be developed with funds from the NSF MRI program).

Ampere, SuperDARN, SuperMAG and the Madrigal database all harvest data from different sources both in the US and overseas. These Class 2 facility activities provide access to the calibrated data. They also produce value-added data products. These services require significant cooperation and goodwill of the international partners but the benefits to all geospace scientists are very significant. Some of these data could be made available in near real-time for application in space weather forecasting or nowcasting, but at present the need for real-time data for scientific purposes is not urgent.

Most of these developments have been initiated by US investigators, but opportunities also exist for the US to engage in new international facilities developed by other national entities. A prime example is the recommendation in Section 7.4 for the US to become a partner in EISCAT and particularly EISCAT-3D to provide access to new capabilities.

Finding. *US funding for engagement in international partnerships provides excellent leverage for additional data, access to an expanded base of scientific and technical skills and knowledge, and to new and innovative software and hardware. Significant benefits accrue to all partners.*

Recommendation 8.16. The GS should continue to sponsor highly-rated proposals to develop, deploy and operate new instruments, instrument networks and data acquisition, especially when GS resources for the project are leveraged through international partnerships.

The GS provides modest support for workshops for the development of new ideas, technology and/or facilities. Often these involve international experts. Also GS supports US representatives, often NSF officers, to attend overseas meetings with similar objectives.

Finding. *GS-funded international workshops and attendance at international planning workshops can catalyze exciting and important new opportunities.*

Recommendation 8.17. The GS should continue to provide funding for international workshops.

Chapter 9. Recommended GS Portfolio

9.1. Balance of Investments

The current balance of investments in the GS portfolio among core grants programs, strategic grants programs and facilities (Figure 3.1) is partitioned in the FY 2015 budget at 33%, 28% and 38%, respectively, with the remaining 1% in the GS reserve account. The balance of investments in the recommended portfolio out to 2025 maintains this approximate balance but shifts 2% of facilities funding into strategic grants programs to address DRIVE initiatives recommended by the Decadal Survey. By tilting the balance toward strategic grants programs, the GS can encourage and enable the integrative science elements advocated by the DS, in particular, regarding predictive science underlying space weather applications and large-scope cross-disciplinary science.

Provisional budgets for the recommended portfolio in 2020 and 2025 are given in Table 9.1, with relative distributions shown graphically in Figure 9.1. For comparison, the FY 2015 budget for each continuing and discontinued line item is also included. In keeping with its charge, the PRC has assumed that the projected future budgets are flat in inflation-adjusted FY 2015 dollars.

Recommendations for the various line items in the portfolio are included in the next sections. Additional details, findings and recommendations related to the recommendations of Chapter 9 are discussed in Chapters 4-8.

9.2. Core Grants Program

The vitality of the geospace science enterprise depends critically on a vibrant core grants program. The PRC and many members of the geospace science community (as expressed in responses to the solicitation for community input) recommend maintaining the current level of funding for the core (unsolicited) grants program. Although a higher level of funding for core grants was recommended in some community comments and would moderate the proposal pressure reviewed in Chanter 4, the balance in the GS portfolio would have to change to accommodate such an increase. If future GS budgets were to be more optimistic than assumed, augmenting the budget for the core grants program would be beneficial.

The PRC is concerned that the core grants program, at times, may be providing a significant portion of its budget for "targeted" objectives such as the CAREER and the Post-Doctoral Fellowship programs. While these programs are of merit in their own right, and are secured by peer review, they are not core in the sense that core is envisioned: support of innovative frontier research without regard to any specifics concerning the proposer.

Recommendation 9.1. The GS should maintain the existing budget share for the ***Core Grants Program*** in Aeronomy, Magnetospheric Physics and Solar-Terrestrial Research within the assumed inflation-adjusted 2015 level (or greater) for the next decade. It should use proposal pressure in concert with portfolio balance to determine an optimum distribution of investments across the three programs. The PRC recognizes that the budget allocation between core and targeted grants programs (CEDAR, GEM, SHINE) may vary from year to year depending on the number and quality of proposals submitted to the various grants programs. GS program managers should continue to have the flexibility to adjust these budget lines in response to proposal pressure, but they should strive to maintain a minimum budget for the core program. A good balance for the portfolio would be at least ⅓ of the GS budget for the core grants programs and not less than $14-15M per year should the overall budget decline.

Table 9.1 Recommended Portfolio in 2015 Dollars (x $1M)

Core Grants Program (Priority 1)		2015	2020	2025	%
AER (1)	Core†	6.14	14.4	14.4	Core
MAG (1)		3.88			
STR (1)		4.36			
Core Grant Total		**14.38**	**14.4**	**14.4**	**33%**
Strategic Grants Program (Priorities 1, 2, 3)			Change from 2015 to 2020		
CEDAR (1)	Targeted†	3.09	8.7	6.7	Strategic
GEM (1)		2.63			
SHINE (1)		2.98			
Space Weather (1)	IGS	1.50	1.5	5.0	
Grand Challenge (2)			1.5		
CubeSat (3)		1.50	1.0	1.0	
FDSS (3)		0.60	0.6	0.6	
Strategic Grants Total		**12.30**	**13.3**	**13.3**	**30%**
Class 1/2 Facilities (All priority 1)		2015[a]	2020	2025[b,c]	**Facilities**
Arecibo [d]	Class 1‡	4.10	1.1	8.4	
PFISR [e]		1.50	1.5		
RISR-N [e]		1.50	1.5		
Sondrestrom		2.50	0.0		
Millstone Hill [f]		2.10	1.9		
Jicamarca		1.35	1.4		
SuperDARN	Class 2‡	0.96	1.0	4.8	
AMPERE		1.02	1.0		
SuperMag		0.15	0.2		
CCMC		0.50	0.5		
CRRL[g]	not a facility	1.20	0.0		
Class 1/2 Facilities Subtotal		***16.88***	***10.1***	***13.2***	
New Facilities Programs (Priorities 1, 2)					
EISCAT (1)	Class 1‡		1.0	b	
Data Systems (1)	Class 2‡		0.5	c	
DASI (1)			1.6		
Innovation & Vitality (2) — Upgrades	Instruments, Facilities		2.4	**2.7**	
	Community Models		0.3		
New Facilities Programs Subtotal			**5.8**	**2.7**	
Facilities Total		***16.88***	***15.9***	***15.9***	**36%**
Midscale Projects Line [h]	out of budget		$1-6M/year		
GS Reserve		**0.43**	**0.4**	**0.4**	**1%**
Grand Total *		**43.99**	**44.0**	**44.0**	**100%**

NOTES

Priorities: (1) Science Grants Programs; Space Weather; Facilities; EISCAT; Data Systems; DASI. (2) I&V; GC Projects. (3) CubeSats; FDSS

† 2020/25 budget split between core & targeted and between individual programs in core & targeted TBD by proposal pressure

‡ New Class 1/2 facilities may be developed via MRI, Midscale (if created) or MREFC awards; addition may require discontinuation of other facilities

[a] Budget value is 3- or 5-year average based on most recent award, except AO which is in the last year of a 5-year cooperative agreement

[b] EISCAT/EISCAT-3D membership becomes Class 1 facility by 2025

[c] New DASI/Data Systems projects become Class 2 facilities by 2025

[d] If AO use for GS research cannot be secured for $1.1M, redirect its $1.1M budget to the I&V Program

[e] PFISR+RISR-N budget is $3M; delineated 50/50 here

[f] New data systems line to absorb MH Madrigal budget by 2020

[g] CRRL is not currently operating as a facility (Sec. 7.2); it should seek future funding from core or targeted grants programs.

[h] To be funded only with additional future GS funding; if NSF divests from AO, its $1.1M budget should be added to the I&V Line, a portion of which could go to Midscale Projects

* Grand Total exceeds the actual FY 2015 budget of $43.56M because Class 1/2 facilities budgets are 3- and 5-year averages (see note a)

Fixed fractional budget allocations (or approximately fixed) for each of the three GS disciplinary grants programs (AER, MAG, STR) and their associated targeted programs (CEDAR, GEM, SHINE) is not, in the PRC's view, the most prudent way to allocate resources. Relaxing this restriction and allowing proposal pressure to play a role in determining relative budget allocations among disciplines, can achieve geospace science of higher value. With the expectation that geospace science will increasingly encompass more integrative science, disciplinary boundaries can be expected to blur in the future.

Recommendation 9.2. GS program managers should allow proposal pressure to play a role in determining the relative budget allocations among the core grants programs in ***AER***, ***MAG*** and ***STR*** and among the targeted grants programs ***CEDAR***, ***GEM*** and ***SHINE***.

This recommendation is reflected in the 2020 and 2025 budget scenarios of the Portfolio Review wherein separate line items for ***AER***, ***MAG*** and ***STR*** and for ***CEDAR***, ***GEM*** and ***SHINE*** are eliminated.

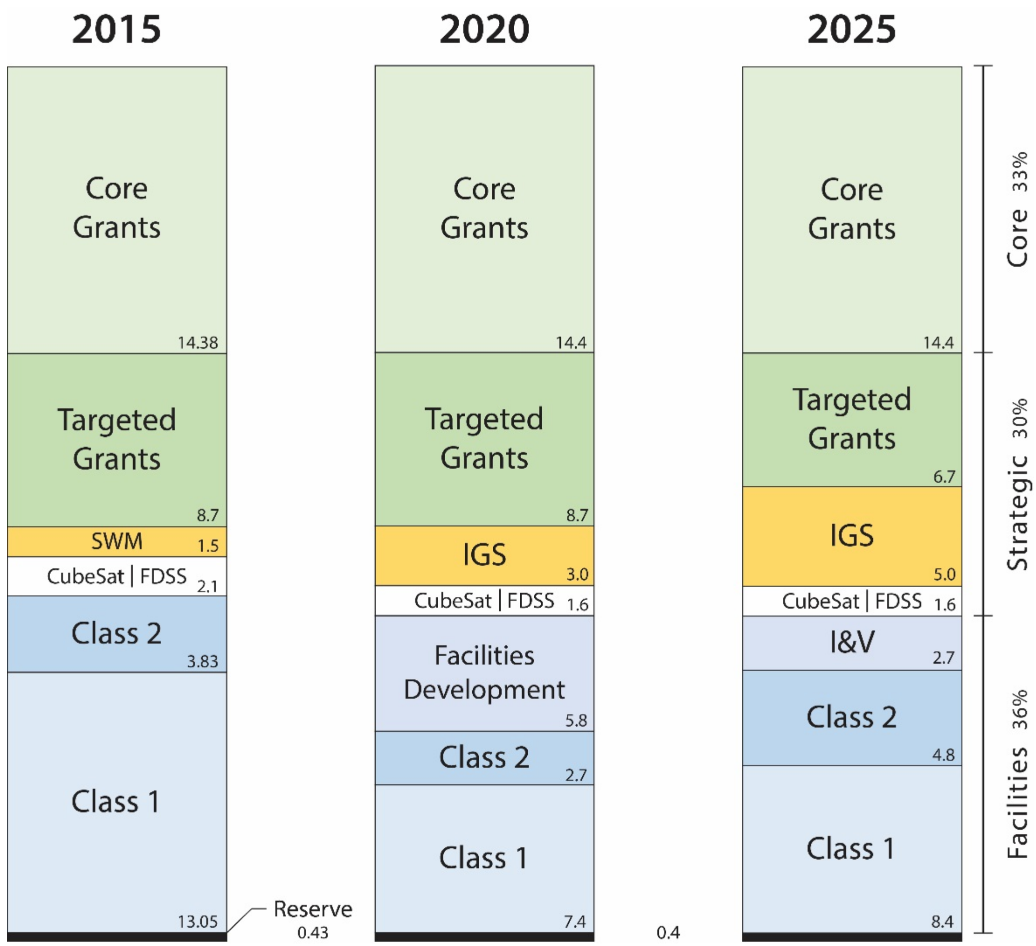

Figure 9.1. Relative budgets for GS program elements and Class 1/2 facilities itemized in Table 9.1 for FY 2015 and recommended distributions for 2020 and 2025. IGS in 2020 and 2025 includes the Space Weather Modeling (SWM) and Grand Challenge Projects (GCP) programs. "Facilities Development" in 2020 includes support for initiation of a US EISCAT consortium, DASI facilities, Data Systems and an Innovation and Vitality (I&V) program. EISCAT becomes a Class 1 facility by 2025 and the DASI and Data Systems lines become Class 2 facilities.

9.3. Strategic Grants Programs

As discussed in Chapter 6, ***CEDAR***, ***GEM*** and ***SHINE*** are both targeted grants programs and strategic grants programs because they target and coordinate campaigns, research challenges, event studies, focus group studies and workshop sessions while serving to inform and develop community vision for strategic research directions. An important element of each of the three targeted grants program is the funding allocated for their very popular and highly regarded community workshops. Strategic research direction crystallizes in these workshops and in the review panel selections of proposals submitted to the targeted grants programs.

The DRIVE initiative of the DS recommends that NSF partner with NASA to "create Heliophysics science centers to tackle the key science problems of solar and space physics that require multidisciplinary teams of theorists, observers, modelers, and computer scientists". This proposed strategic grant program effectively anticipates the recent trend in the GS grants programs to fund large collaborative projects. However, the envisioned initiative to create science centers calls for an even higher degree of multidisciplinarity than is presently occurring in the GS grants programs. The GS targeted grants programs have been undertaking community-driven research challenges and organizing grand challenge workshops since their inception. The PRC sees aspects of the proposed science centers as a natural progression in the evolving direction of community-driven grand challenge projects with one significant exception. The center concept conveys enduring institutional firmament with vision and mission. In contrast, a grand challenge project brings resources to bear on a strategic research problem and has research goals and objectives. It solves or makes significant progress in solving the problem and then diminishes in intensity of effort to make way for other pressing strategic research problems.

Recommendation 9.3. The GS should initiate a new strategic grants program, ***Grand Challenge Projects,*** initially with a budget of $1.5M per year by 2020.

The Grand Challenge Projects model is more consistent with community-driven, collaborative research initiatives emerging from GS targeted grants programs than would be a Heliophysics Science Center model. It will also encourage greater cross-disciplinarity and greater emphasis on integrative and system science than presently occurs in the more disciplinary-oriented, targeted grants programs.

The Decadal Survey recommends maintaining and growing basic research programs at NSF (and at NASA, AFOSR and ONR) for more effective transition from basic research to space weather forecasting applications. The successful NASA-NSF Partnership for Collaborative Space Weather Modeling has maintained a basic research program with this objective for the past 10+ years. As discussed in Sections 6.5 and 8.2, the PRC generally endorses continuation of the collaboration as long as the science goals for the NASA and NSF programs are aligned. The modest increase in space weather funding in the recommended portfolio beyond 2020 could be used to augment a continuing NASA-NSF Partnership, or it might fund a modest GS-only space weather program similar to the one that existed prior to 2011.

Recommendation 9.4. The budget for ***Integrative Geospace Science***, including ***Space Weather Modeling*** and ***Grand Challenge Projects,*** should grow from $3M per year in 2020 to $5M per year by 2025 by acquiring IGS projects funded by the ***Targeted Grants Programs***.

The designation of $2M from the Targeted Grants Programs to IGS by 2025 is not considered so much a redirection of resources to a different type of research but a recognition and more accurate accounting of the actual nature of research that has been continuing unabated in these programs and is expected to continue well into the future.

Recommendation 9.5. With the assumption that future research in core and targeted grants programs will entail an increasing number of collaborative projects devoted to integrative and cross-disciplinary geospace science, the GS should migrate future funding for such projects into strategic grants programs for ***Space Weather*** research and ***Grand Challenge Projects***. As these projects migrate from either core or targeted grants programs into Space Weather Research or Grand Challenge Projects grants, the core grants program budget should remain approximately constant (or grow if future budgets are more optimistic than flat) while the budget for targeted grants program decreases.

As discussed in Section 6.6, the GS CubeSat Program has been a pioneering effort and has demonstrated that (1) inexpensive small satellite missions are viable, (2) they are an effective vehicle for stimulating interest in STEM education among university students, especially undergraduates, and (3) useful science can be accomplished by such missions. Interest in CubeSats has broadened well beyond the GS, and it has become a truly emergent capability. While the GS should continue to play a key role in the scientific utilization of CubeSats, it is important that the focus and level of support for this program be commensurate with its value proposition for advancing geospace science. The PRC recommends that the GS continue its CubeSat Program, at a somewhat reduced level, but the Section should consider possible partnerships with other agencies or industry to accomplish more science for the investment in the program. A CubeSat program might also be of interest and utility in other divisions of the NSF. Indeed, the DS recommendation to increase the number of new CubeSats starts per year with a suitably augmented budget was directed to NSF as a whole and not to the GS alone. More general recommendations to NSF are beyond the PRC's charter.

Recommendation 9.6. GS should continue its ***CubeSat Program*** with a focus on mission concept, instrument development and science exploitation of the data while partnering with other entities with engineering experience in the development of CubeSat buses. The PRC recommends an annual budget of $1M for the reduced scope of GS CubeSat mission development.

The GS Program for Faculty Development in Space Sciences (FDSS), in addition to funding career development and research of early-career faculty in the space sciences, has the broader impact of establishing bulwarks for space science in university departments. This impact includes the transmission of taxpayer-funded knowledge of the space environment of the Earth and solar system to students in astronomy and general science courses that often do not incorporate such knowledge. The primary metric for success of the FDSS program is the number for FDSS faculty who have achieved tenure. With an 88% success rate (7/8) to date, the program may be doing better than the average tenure rate for junior faculty at large.

Recommendation 9.7. GS should continue to support the ***FDSS*** program with an annual budget of $0.6M (cf. Section 4.2).

Priorities in GS grants programs enabling core frontier science, strategic science initiatives and special programs for workforce development will naturally evolve in response to new science imperatives, new funding opportunities arising within NSF and beyond, and prospective new partnerships that have the capacity to leverage GS resources. Changes in funding priorities in GS grants programs have typically been made by the GS Head and Program Managers in consultation with various standing steering committees and ad hoc review committees charged with oversight or review of some specific program element. A formal, semi-decadal review of all grants programs would provide a more holistic review of the effectiveness of the grants programs in meeting Decadal Survey and Geospace Section science goals.

Recommendation 9.8. The GS should implement a semi-decadal Senior Review of its Core and Strategic Grants Programs, as described in Section 6.7.

9.4. GS Facilities Program

Although the facilities budget is reduced by only 2% in the recommended portfolio, the actual changes in the recommended GS Facilities Program are substantial. Recommended changes include termination of the Sondrestrom ISR and a 73% reduction in the GS contribution to Arecibo Observatory (AO) funding, from $4.1M in FY 2016 to $1.1M by 2020. These two changes make $5.5M available for alternative investments in the portfolio.

The relatively high latitude of the Sondrestrom ISR has made it a stalwart for cusp research for more than two decades. Sondrestrom's relatively high budget is driven in part by the logistics of operating in Greenland and by higher M&O costs for its older dish and klystron-tube technology. In place of the Sondrestrom ISR, the PRC recommends forging a new partnership with the EISCAT consortium. The $1M annual cost of associate membership in EISCAT is substantially less than $2.5M budget for Sondrestrom. The EISCAT Svalbard facility also samples cusp latitudes, and the geomagnetic latitude-local time positioning of the PFISR (auroral), RISR-N / RISR-C (both polar cap) and the EISCAT Svalbard (cusp) ISR may offer advantages over Sondrestrom for some coordinated polar region studies. EISCAT-3D, a new multistatic radar composed of five phased-array antenna fields, is expected to replace the EISCAT system at Kiruna by 2020.

Membership in ESICAT currently takes one of several forms. (1) A rolling long-term commitment of 5 years as an *associate member* with a funding commitment of about $1M per year. Termination of the membership would require a phase-out period of 5 years. Such a membership would allow the US to have a seat on the EISCAT Council which would consist of two persons, one to represent the funding agency and one to represent the chief scientist. This membership would provide access to all archival EISCAT data immediately as well as the opportunity to participate in specific observing programs geared to achieve science objectives. The member would have access to Common Programs that would include immediate data analysis of the observations to yield data products that could be applied immediately for science analysis. Normally, a one-year embargo is imposed upon any observations obtained by a Member nation. (2) *Affiliate membership* incurs a user fee of about $25,000 for about 8 hours EISCAT observing time. Multiple affiliates from a single country are possible. (3) *Peer-reviewed science projects* are awarded 200-300 hours a year. The awards are made based on the proposed research and its evaluation by EISCAT scientists.

Recommendation 9.9. The GS should terminate funding for the ***Sondrestrom ISR*** facility after the current continuing grant for its management and operation ends (December 2017). Ancillary instrumentation for geospace studies and their operational costs at Sondrestrom should be budgeted and decided by a peer review process from the Core or Targeted GS programs.

Recommendation 9.10. The GS should investigate costs and contractual arrangements for U.S. investigators' access to the existing ***EISCAT*** facilities and to the planned ***EISCAT-3D*** facility. If no barriers to system use and data access arise, NSF investigators could begin using the EISCAT system soon after the current continuing grant for Sondrestrom M&O expires.

The GS contribution to the Arecibo cooperative service agreement is $4.1M in FY 2016. This cost is incommensurate with Arecibo's value for geospace science, and it has a significant adverse impact on the balance of investments in the GS portfolio. NSF divestment from AO is currently under study by the National Science Board, with unknown implications for future operation of the facility by NSF.

Recommendation 9.11. The GS should reduce its M&O support for the ***Arecibo Observatory (AO)*** to $1.1M by 2020, i.e., to a proportional *pro rata* level approximately commensurate with its fractional NSF GS proposal pressure and usage for frontier research.

Termination of ***Sondrestrom ISR*** funding (Recommendation 9.9) and the reduction in ***AO*** funding (Recommendation 9.11) could occur in one step when their current agreements with NSF expire (September 2016 for AO, December 2017 for Sondrestrom) or via a progressive ramp-down toward 2020 (to $1.1M for AO and $0 for Sondrestrom) upon expiration of their current agreements. Without a step change or ramp-down in funding for these facilities, the new initiatives recommended by the PRC would not have sufficient funds to be in place by 2020.

If NSF divests from ***AO*** in the near future or if the recommended level of support for AO prevents GS researchers' future access to the facility, Recommendation 9.16 below recommends an alternative disposition of the $1.1M GS contribution to AO.

The recommended changes in GS investments in AO and Sondrestrom, discounted by the expected cost of joining EISCAT, open 10% in the GS budget for implementation of DS recommendations for NSF. This wedge falls short of the estimated 25% increase in the GS budget required for full implementation of DS recommendations (Section 3.2), but it does allow initiation of important new program elements that will provide critical capabilities: A Distributed Array of Scientific Instruments (DASI) Program leading to new Class 2 facilities (see Section 7.2); a Data Systems Program to enable deployment of new systems for data management, products and distribution, also expected to evolve into new Class 2 facilities; and an enduring Innovation and Vitality Program for upgrades to facilities and models. All are expected to be in place by 2020.

The DRIVE initiative of the DS directs NSF to provide funding sufficient for essential synoptic and multiscale observations. Distributed measurements are required to provide synoptic ground-based observations of geospace phenomena. DASI networks can fulfill this requirement. The recommended portfolio includes an explicit line item for DASI development, deployment and operation.

Recommendation 9.12. The GS should create a new ***DASI Facilities Program*** with a $1.6M annual budget. This fund should be used initially to develop and implement one or more DASI Class 2 facilities with concept selection determined by peer review. For a fully operational DASI to transition to a Class 2 facility, it must satisfy the criteria for a community facility as defined in Section 7.2.

In most cases, operational costs for a DASI are expected to be less than development and implementation costs. As more DASI facilities become operational, at some point the annual budget for DASI will be fully subscribed by DASI operations. When this occurs a new DASI cannot be developed without an increase in the GS budget for DASI or without defunding one or more existing DASI facilities to make funds available for new developments. A rigorous senior review for DASI programs will be required to determine the future of the DASI program, and future new initiatives in the DASI program.

The Decadal Survey calls for NASA to augment its data systems support for the Heliophysics System Observatory (Decadal Survey Table 4.1). Data from NSF-sponsored GBOs are increasingly being combined with HSO data for synoptic studies of geospace phenomena. GS ground-based assets in effect constitute elements of an emerging NSF-sponsored Geospace System Observatory (GSO). NSF should augment its support for GSO data systems. The Madrigal system developed by the Millstone Hill Observatory manages data mainly for the Aeronomy community. The SuperMAG project manages data from US and international ground-based magnetometers. SuperDARN data are managed by the SuperDARN consortium, and data management for AMPERE is handled by the AMPERE PI institution. Other datasets of utility for geospace science are being managed in a more ad hoc manner. The PRC does not necessarily advocate a single data system for data derived from all GS assets, but more effective coordination of these data sets and development of value-added data products would improve their accessibility and utility for geospace science. Key elements of the recommended data environment are listed in Table 4.1 of the Decadal Survey.

Recommendation 9.13. The GS should fund a new ***Data Systems Program*** for data exploitation with an annual budget of $0.5M, of which $0.15M should be redirected from the current Millstone Hill Observatory budget for the Madrigal system. Selection of a proposal(s) for development and management of the new system should be determined by peer review. Once the system becomes fully operational, it should become a Class 2 facility, with competitive renewals determined by peer review.

All GS facilities, computer models and data systems require periodic upgrades to maintain state-of-art capabilities. A dedicated GS fund for such upgrades does not currently exist. Past upgrades have been ad hoc, sometimes dealing with urgent unscheduled maintenance or failed components, and they are often funded through negotiation with GS Program Managers. Some facilities have required upgrades for many years, yet funds have not been available for them. The PRC recommends a new enduring program dedicated to maintaining state-of-art capabilities of GS facilities.

Recommendation 9.14. The GS should fund a ***Facilities Innovation and Vitality (I&V) Program*** with an annual budget reaching a steady-state value of $2.7M by 2020. Allocation of I&V Program funds should be decided using a peer-review proposal process to determine improvements of greatest value in any given year for instrument, facility and/or community model upgrades. The budget scenario in Table 9.1 provides notional budgetary guidance on an approximate, average partition of the fund between instrument and facility upgrades and model upgrades.

In reviewing the ***Consortium of Resonance and Rayleigh Lidars (CRRL)***, which is funded as a GS facility, the PRC reached the opinion that CRRL as currently organized and directed is not operating as a community facility (see Sections 7.2 and 7.3). While the measurement techniques being advanced by CRRL and the measurements themselves are innovative, the PRC does not recommend funding a PI-led research activity from the facilities budget. Such research is appropriate for funding from the core or targeted grants programs. The CRRL might achieve facilities class by adopting the characteristics of community engagement described in Section 7.2. For this reason, the budget for CRRL becomes zero by 2020 in the recommended GS facilities budget.

The budget scenario that enables the new grants and facilities programs described above and listed in Table 9.1 is illustrated in Figure 9.2. The scenario uses reprogrammed funds from the Sondrestrom ($2.5M) and CRRL ($1.2M) facility line items, $3M of the Arecibo budget, a portion of the CubeSat program budget ($0.5M) and the Millstone Hill budget for community data systems ($0.2) to implement the first phase by 2020. With subsequent development of new DASI facilities, community Data Systems and a US consortium for EISCAT participation, these facility elements become Class 1/2 facilities by 2025. The current Space Weather Modeling program combined with

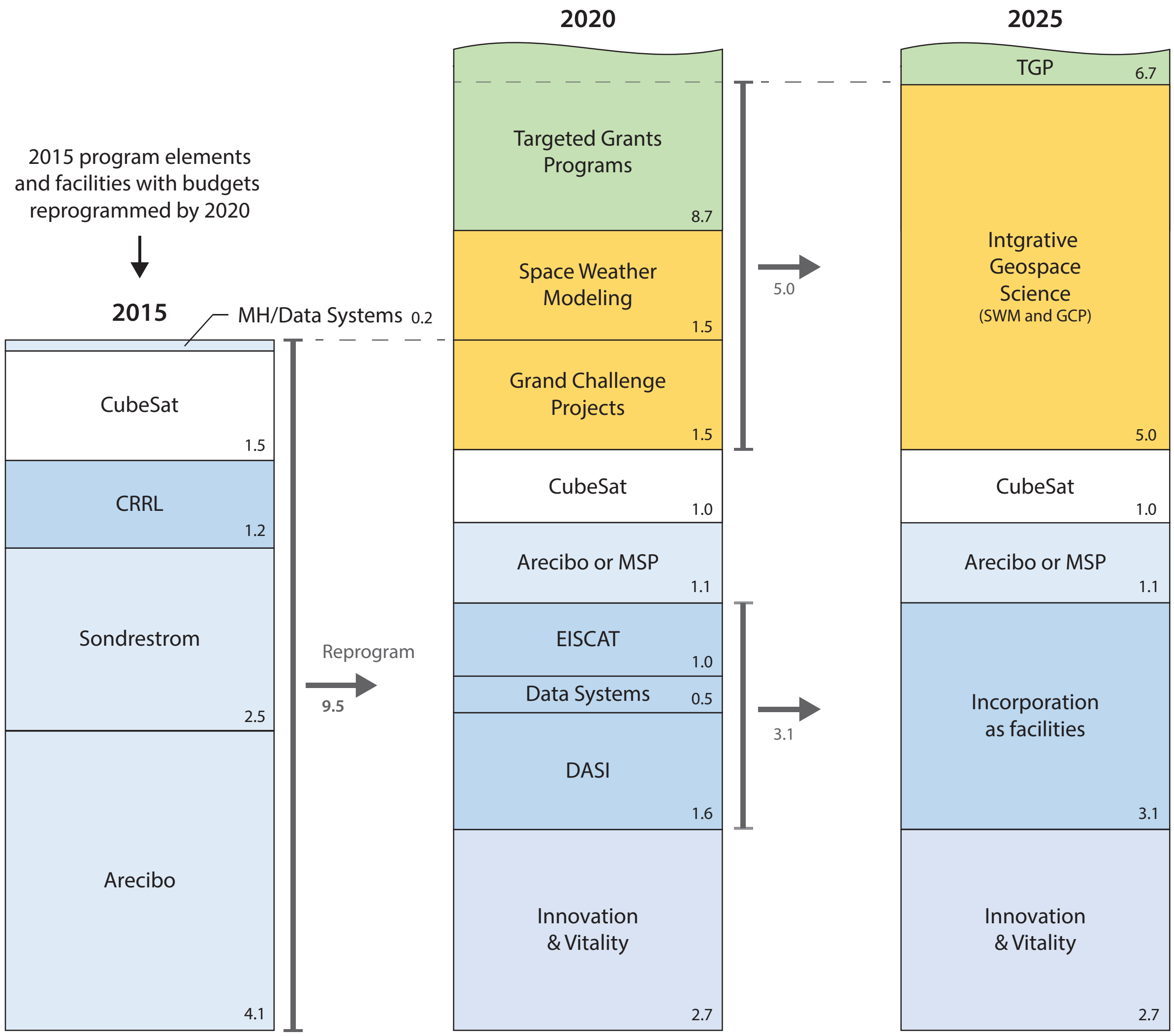

Figure 9.2. Program elements in Table 9.1 with budget changes going from 2015 to 2020 and 2025. Sondrestrom, CRRL and the community data systems line item in Millstone Hill are eliminated as facilities by 2020. The Arecibo budget is reduced from $4.1M to $1.1M. If NSF divests from Arecibo in the future, the $1.1M for AO science is redirected to a GS Mid-Scale Projects (MSP) line. The CubeSat program is reduced from $1.5M to $1.0M. New facilities development programs initiated by 2020 (EISCAT, Data Systems and DASI) become incorporated as Class 1/2 facilities by 2025. Space Weather Modeling (SWM) is carried from 2015 to 2020 with a flat $1.5 M budget and is combined with the Grand Challenge Projects (GCP) program (launched by 2020) to form an Integrative Geospace Science program by 2025. Their combined budgets of $3M in 2020 grow to $5M by 2025 by acquiring $2M in projects from the Targeted Grants Programs.

the recommended Grand Challenges Projects program initiate an Integrative Geospace Science (IGS) program by 2020. This program is envisioned to acquire $2M of additional investment from projects aligned with IGS goals and originally funded by the Targeted Grants programs.

The individual facilities budgets for 2015 in Table 9.1 are average values determined from the current 3- or 5-year award to the facility. The exception is Arecibo, which is in its final year of a cooperative service agreement. The line item for Arecibo is its FY 2016 budget requested from the GS.

The recommended budgets for Class 1 and Class 2 facilities in Table 9.1 purposely do not specify line items for individual facilities in 2025 to emphasize that (1) no facility nor its current budget should be considered enduring and (2) some turnover in facilities is considered healthy as new technologies and new scientific knowledge and measurement techniques emerge. Thus in response to evolving science, modeling, instrumentation and facilities imperatives of the future some of the GS facilities in 2025 are likely to be quite different than those supported today.

Recommendation 9.15. Going forward the GS should strive to maintain a balanced portfolio of cutting-edge facilities and should periodically evaluate the performance and budget of each facility against Decadal Survey and Geospace Section science goals using the Facilities Senior Review process described in Section 7.8.

A Midscale Projects Program represents a significant opportunity for augmentation of GS science, which, considering the compelling and mature nature of potential next-generation ground-based observatories discussed in the DS, is likely to offer high return on investment to the NSF. The Midscale Projects Program recommended by the DS is intended to fund projects with development costs in the range of $4-30M. Unfortunately, this cost does not fit into current GS budget envelope and is not explicitly included in the recommendation portfolio in Table 9.1. However, as discussed in Section 7.7, the PRC would recommend a Midscale Projects Program if one or both of the following conditions are met.

Recommendation 9.16. If use of the Arecibo Observatory is no longer available to GS researchers, e.g., due to divestment or insufficient funding for its continuing operation, and the GS budget remains at or above the flat funding level assumed for the Portfolio Review, then the recommended annual funding of $1.1M for Arecibo should be redirected to the Innovations and Vitality Program described in Section 7.4. Depending on community consensus and the recommendations from the Facilities Senior Review recommended above, a significant portion of this augmented I&V annual budget might be applied to investment in a new ***Midscale Project Program***.

Recommendation 9.17. If future GS budgets exceed the flat-budget assumption of this review by $1M per year or greater, then the additional annual funding should be directed to a ***Midscale Projects Program***.

9.5. Prioritizations

The PRC was charged with prioritizing elements of the recommended portfolio in sufficient detail to enable GS to make subsequent appropriate adjustments in response to variations in Federal and non-Federal funding. Should future GS funding be less optimistic than flat, the recommended portfolio in Table 9.1 gives highest priority in rank order to the core and targeted grants programs, facilities, the space weather grants program, EISCAT membership and the new Data Systems and DASI programs. The facilities Innovation and Vitality program and the Grand Challenge Projects program are ranked equally as second priority programs. The FDSS and CubeSat programs are the lowest priority programs in the portfolio.

If future GS budgets are more optimistic than assumed for this review, a new Midscale Projects Program should be initiated with highest priority if the additional funds including some portion of the I&V line are sufficient to fund a $4-30M midscale project over a five-year period. If a lesser budget increase occurs, Priority 1 programs should be augmented with relative program increases left to the Section's discretion, followed by augmentation in the Grand Challenge Projects program then the CubeSat program.

9.6. GS Management Processes

The PRC would like to acknowledge cordial interactions with AGS Director Paul Shepson, recently appointed Section Head Therese Moretto and all GS PMs and acting Heads over the course of this review. Their candid opinions and responses to requests for information throughout the portfolio review helped the PRC understand many aspects of GS programs. These requests at times must have brought to mind the Spanish Inquisition.

The past year has been a difficult time of transition for the GS, and this transition added complications to the review process that were not anticipated when the committee accepted its charge. During the roughly nine months of the review, the PRC interacted with three different Section Heads, two different facility PMs, two different AER PMs, and the three standing PMs for the MAG, STR and SWR programs. Some of the GS staff were on temporary assignment to the Section and, while knowledgeable and capable, were not necessarily prepared to deal with the demands of a first-ever GS portfolio review. They responded admirably.

Changes in staff and management occur in all organizations, and the best strategy for managing a smooth transition requires maintaining a high degree of transparency in program operations and accounting. The PRC can recommend several improvements in GS organizational processes, which would make future reviews of this type more straightforward and efficient, facilitate smoother transitions for the inevitable changes that will occur in GS program management and build stronger relationships with the GS community.

- Develop accurate, complete and transparently understandable data metrics, including success rates (NSF-standard) for all grants in the various programs of the Section. Both historical data and data for the current fiscal year are useful for understanding trends and in assessing the vitality of the grants programs;[27]
- Consider a set of the above defined metrics to make publically available on the Section's web portal;
- Separate fully funded GS research proposals from special categories of awards, such as conference awards, MRI awards and co-funded projects such as CAREER, AGS Postdoc, NSF/DOE partnership
- Track, maintain and publish data on workforce issues, e.g., diversity and gender, for awards and for postdocs in each program. For grants, it would also be desirable to track years since the PI received the PhD;

[27] *Historical budget data (2014 and earlier) provided to the PRC for the GS programs changed with section heads during the portfolio review, indicating that the Section may not have a common and readily accessible extraction procedure or format for such data. The PRC received data on proposal success rates that were determined in at least three different ways, e.g., collaborative proposals were counted as one proposal by the NSF budget office and as multiple proposals by the GS based on the number of collaborating institutions. For the targeted programs (CEDAR, GEM, SHINE), the denominator in success rates appear to have been determined by the number of proposals received in the fiscal year rather than on proposal actions. Use consistent criteria for identifying facilities. The committee learned late in the review about one Class 2 facility not previously identified to the committee by either Facilities PM serving during the review, perhaps because different GS staff have different ideas about what constitutes a facility. The committee recommends using the criteria given in Section 7.2 to differentiate facilities from PI-led research.

- As difficult as it may be to do so, the PRC recommends tracking M&O costs in grants and facilities awards. Maintain a database for the portion of the GS budget devoted to M&O. Ongoing M&O in the GS Grants programs (versus GS Facilities) diminishes the funds available for new research projects. The number of DASI and DASI-like projects is expected to increase in the future and tracking their M&O costs may appear in both grants and facilities programs. As discussed in the GS facilities chapter, such issues may in some cases bear on the quality of the facility-embedded research;
- Establish guidelines for determining the impacts of encumbering program resources for M&O of new facilities initiatives before committing future budget to them. For example, the peer review process for an innovative new DASI tends to generate a positive recommendation to fund it, but the reviewers are not necessarily considering the bigger picture: What other program investments will be impacted by taking on new continuing M&O costs for this project?
- GS often has to make difficult decisions; this portfolio review makes several recommendations to provide additional support in decision-making such as the Senior Reviews and the advisory groups for Class 1 facilities. Communicating the outcomes, rationale and impacts of decisions is an area where further developments and transparency are encouraged.

Appendix A. Committee Charge

National Science Foundation Directorate for Geosciences
Division of Atmospheric and Geospace Sciences

Review of the Geospace Section Portfolio

Charge to the Review Committee

February 18, 2015

Context

This review is motivated in part by priorities highlighted for the Geospace scientific community in the National Research Council's (NRC) Decadal Survey: *Solar and Space Physics – A Science for a Technological Society* (hereafter called the *Survey*) and by the current challenging outlook for the U.S. Federal budget.

The review is designed to examine the balance across the entire portfolio of activities supported by NSF's Geospace Section (GS) within the Division of Atmospheric and Geospace Sciences (AGS). The primary goal of this review, and of any resulting adjustments of the GS portfolio, is to ensure that investments in the GS science disciplines and respective facilities are properly aligned, both now and in the future, with the needs and priorities of the Geospace scientific community, in part as articulated in the Survey.

The following boundary conditions will be adopted for the review:

- All of the GS-funded activities should be considered together with the *Survey* recommendations: Core Programs of Aeronomy, Magnetospheric Physics, and Solar Terrestrial Research, focused programs CEDAR, GEM, and SHINE, elements of the new Space Weather Research & Instrumentation Program (CubeSats, space weather modeling, and other multi-user, space weather-related activities), components of the Geospace Facilities Program, such as the Incoherent Scatter Radar, Lidar Consortium, SuperDARN HF radars, and those activities specifically designed to enhance educational opportunities, diversity, and international participation.
- The review should be forward-looking focusing on the potential of all funded facilities, programs, and activities for delivering the desired science outcomes and capabilities (while taking into account respective past performances) and considering the value of funded activities in terms of both intellectual merit and broader impacts.
- The review should assume budget scenarios (to be provided by GS) to encompass the period from 2016 through 2025, and consider the costs of (i) continuing the existing observing capabilities and science-funded programs, as well as of (ii) new facilities and programs, including those recommended in the *Survey* and others the Review Committee may wish to introduce.
- The Committee's deliberations should take into consideration the national and international Geospace Sciences landscape and the consequences of its recommendations for domestic and international partnerships.

The Charge

The Committee is asked to construct its recommendations around two themes:

1. Recommend the *critical capabilities* needed over the period from 2016 to 2025 that would enable progress on the science program articulated in Chapter 1 of the *Survey*. These recommendations should encompass not only observational capabilities, but also theoretical, computational, and laboratory capabilities, as well as capabilities in research

support, workforce, and education.

2. Recommend the *balance of investments* in the new and in existing facilities, grants programs, and other activities that would optimally implement the *Survey* recommendations and achieve the goals of the Geospace Section as articulated in the *AGS Draft Goals and Objectives Document* (including NRC/BASC Review, 2014) and the GEO/Advisory Committee Document "*Dynamic Earth: GEO Imperatives & Frontiers 2015-2020*" (NSF, 2014). These recommendations may include closure or divestment of some facilities, as well as termination of programs and other activities, and/or new investments enabled as a result. The overall portfolio must fit within the budgetary constraints provided to the Committee.

It is important that the Portfolio Review Committee considers not only what new activities need to be introduced or accomplished, but also what activities and capabilities will be potentially lost in enabling these new activities and discontinuing current activities.

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

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

The Committee will be a sub-committee of the Directorate for Geosciences Advisory Committee (AC/GEO). The Committee is asked to provide its recommendations by September 2015 for presentation to the AC/GEO, so NSF can consider them in formulating the FY 2017 Budget Request.

Portfolio Review Timeline

The timeline for this review is based on the desire for its results to inform on the input into the Fiscal Year 2017 budget process, and it is constrained by the needs to be initiated and reported to the GEO/Advisory Committee that meets in April/May and October/November each year.

The timeline for the Portfolio Review is as follows:

- Finalize PR Committee membership (12-14 members; January 2015)
- Develop criteria and strategy (January-February 2015)
- GEO/Front Office approves the PR Charge and formation of PR Committee (Feb 2015)
- Kick-off teleconference with GS/PR Committee (February 2015)
- Collect data and begin assessment (February – March, 2015)
- First PR Committee face-to-face meeting at NSF (March 2015)
- Visiting selected facility sites (tentative; February – May, 2015)
- Seeking community input via emails and workshops (March – June 2015)
- PR Committee drafts their report (June - August 2015)
- Second PR Committee face-to-face meeting at NSF (August 2015)
- Submit GS Portfolio Review Report to GEO/Advisory Committee (September 2015)
- GEO/Advisory Committee reviews the GS/PR Report (October 2015)
- GS programs response to the PR Committee Report (November 2015)
- Final (revised if necessary) GS/PR Report released (December 2015)

The detailed schedule for the Portfolio Review will be updated as events occur, milestones reached, and the process evolves.

Appendix B. Committee Membership

William Lotko (Chair), Dartmouth College

Joshua Semeter (AC/GEO liaison), Boston University

Daniel N. Baker, University of Colorado - Boulder

William Bristow (resigned May 2015), University of Alaska - Fairbanks

Jorge Chau, Leibniz-Institute of Atmospheric Physics (Germany)

Christina Cohen, California Institute of Technology

Sarah Gibson, High Altitude Observatory, National Center for Atmospheric Research

Joseph Huba (appointed May 2015), Naval Research Laboratory

Mona Kessel, NASA/HQ and GSFC

Delores Knipp, University of Colorado - Boulder

Louis Lanzerotti, New Jersey Institute of Technology

Patricia Reiff, Rice University

Alan Rodger, Formerly British Antarctic Survey

Howard Singer, NOAA/Space Weather Prediction Center

Appendix C. RFIs to Facility PIs

C1. Request for Information sent to all ISR PIs (AMISRs, AO, JRO, MH, Sondrestrom)

Examination: ISR Facilities:

Technical capabilities

1. Describe the current capabilities of your ISR facility for addressing key science goals and key science challenges described in the recent Decadal Report for solar and space physics, indicating recent improvements/modernizations.
2. Describe the essential technical/engineering features and capabilities of your ISR facility, and why these are essential for your facility.
3. How do these features and capabilities compare to state-of-the-art astronomical and other radio capabilities, nationally and internationally?
4. Has your facility conducted an independent review of its technical capabilities? If so when, and the outcome? If not, why?
5. What international ISR facilities might be considered comparable to the capabilities of your facility?

Maintenance and operations

6. What is the current Maintenance and Operations (M&O) budget of your ISR facility and how has it changed in the last five years? What is your total ISR budget if different than your M&O budget?
7. Does your facility receive funding from sources other than NSF Geoscience facilities (GF)? If so, how is the funding distributed among funding sources and main activities at your facility (M&O, Research, Solar/Mag/Aeronomy areas, ...)
8. What fraction of your yearly ISR budget is devoted solely to M&O and what fraction is devoted to science, technology upgrades, and related, respectively?

Strategic planning

9. How often does your facility update its strategic plan?
10. If more funding were available to your facility, how much would you require, where would it be invested and what would be the benefit for the US Geospace community?
11. Has your facility interacted with other similar facilities in the last 5 years?
12. Have you considered applying to medium sized grants in the last five years to develop your facilities? If not, why not?
13. What are the biggest risks to the continued operation of the facility and how are they being mitigated?

C2. Request for Information sent to AMPERE PI

Examination: Ampere Facility:

Technical capabilities

1. Describe the current capabilities of the AMPERE Facility products for addressing key science goals and key science challenges described in the recent Decadal Report for solar and space physics, indicating recent developments.

Maintenance and operations

2. What fraction of the NSF AMPERE Facility yearly budget is devoted solely to producing and maintaining the current data products, and what fraction is devoted to developing new products, science, and other activities, respectively? How have these budgets changed over the last five years?
3. What is the total yearly funding for AMPERE, and what are other sources and amounts of funding for routine operations, developing new products, science, and other activities, respectively?
4. Approximately how is AMPERE effort and budget split between providing products for space weather and for novel science research?

Strategic planning

5. What is the plan for AMPERE developments? How often is this plan updated?
6. If more funding were available to AMPERE, how much would be required, where would it be invested and what would be the benefit for the US Geospace community?
7. Are there plans to integrate AMPERE data with other data sets to produce further value-added products?
8. What are the biggest risks to the continued operation of the AMPERE facility? How are they being mitigated?

C3. Request for Information sent to SuperMAG PI

Examination: SuperMAG Facility

Technical capabilities

1. Describe the current capabilities of the SuperMAG facility products for addressing key science goals and key science challenges described in the recent Decadal Report for solar and space physics, indicating recent developments?

Maintenance and operations

2. What fraction of the NSF SuperMAG facility yearly budget is devoted solely to producing and maintaining the current data products, and what fraction is devoted to developing new products, science, data archiving, and other activities, respectively? How have these budgets changed over the last five years?
3. What is the total yearly funding for SuperMAG, and what are other sources and amounts of funding for routine operations, developing new products, science, data archiving, and other activities, respectively?
4. Approximately how is SuperMAG facility effort and budget split between providing products for space weather and for novel science research?

Strategic planning

5. What is the plan for SuperMAG developments? How often is this plan updated?
6. If more funding were available to SuperMAG, how much would be required, where would it be invested and what would be the benefit for the US Geospace community?
7. Are there plans to integrated SuperMAG data with other data sets to produce further value-added products?
8. What are the biggest risks to the continued operation of SuperMAG? How are they being mitigated?

C3. Request for Information sent to SuperDARN PI

Examination: SuperDARN Facilities:

Technical capabilities

1. Describe the current capabilities of SuperDARN (the U.S. components and the international component) for addressing key science goals and key science challenges described in the recent Decadal Report for solar and space physics, indicating recent improvements/modernizations.
2. Can the US SuperDARN facilities be rank-ordered by their contribution to the science defined in the Decadal Review?
3. How do the technical/engineering features and capabilities of U.S. SuperDARN radars compare to state-of-the-art astronomical and other radio capabilities, nationally and internationally?
4. How much progress has been made since 2004 (Avery Report) in gaining a more firm scientific understanding of the source and behavior of the irregularities upon which the SuperDARN backscatter relies for its results?

Maintenance and operations

5. How are the individual U.S. radars coordinated and managed for the US Geoscience community?
6. What fraction of the NSF U.S. SuperDARN yearly budget is devoted solely to M&O, and what fraction is devoted to science, technology upgrades, and related, respectively? How have these budgets changed over the last five years?
7. What is the total yearly funding of the U.S. SuperDARN? What are other sources and amounts of funding for M&O, science, technology upgrades, data archiving and other activities, respectively?
8. How much of the SuperDARN data is used for near-real time space weather activities?

Strategic planning

9. Does the U.S. component of the SuperDARN consortium have a strategic plan? If so, how often is it updated?
10. If more funding were available to SuperDARN, how much would be required, where would it be invested, and what would be the benefit for the US Geospace community?
11. What are the biggest risks to the continued operation of the facility? How are they being mitigated?

C4. Request for Information sent to CCMC PI

Examination: CCMC Facility

Technical capabilities

1. Describe the current capabilities of the CCMC for addressing key science goals and key science challenges described in the recent Decadal Report for solar and space physics, indicating recent developments?
2. Describe the decision process used to incorporate models into CCMC. Describe the decision process for the termination of support for models.
3. Describe the relationship for coordination with model development at HAO.
4. Describe how the current suite of models at CCMC compares with other models, both in the USA and internationally.

Maintenance and operations

5. Describe how and by whom the priorities and the success criteria of CCMC are set each year.
6. Provide information as to how often the various models are used each year. Provide a breakdown between inside NASA and other users.
7. What fraction of the NSF-contributed CCMC yearly budget is devoted to maintaining the current suite of models, ingesting new models, setting up and running models for external scientists, science research by CCMC-funded staff, model archiving and other activities, respectively? How have these budgets changed over the last five years?
8. What is the total yearly funding for CCMC, and what are the other sources and amounts of funding for maintaining the current suite of models, ingesting new models, setting up and running models for external scientists, science research by CCMC-funded staff, model archiving and other activities, respectively.
9. Are there any CCMC facility activities that could be considered for space weather in contrast to novel science research?

Strategic planning

10. What is the plan for CCMC developments? How often is this plan updated?
11. If more funding were available to CCMC, how much would be required, where would it be invested and what would be the benefit for the US Geospace community?
12. What are the biggest risks to the continued operation of CCMC? How are these being mitigated?

C5. Request for Information sent to CRRL PI

Examination: Lidar Facilities:

Technical capabilities

1. Describe the current capabilities of the set of LIDAR installations for addressing key science goals and key science challenges described in the recent Decadal Report for solar and space physics, indicating recent improvements/modernizations.
2. Can the LIDAR installations be rank-ordered by their contribution to the science defined in the Decadal Review?
3. Describe the coordination process for current individual PI-led LIDAR instruments to obtain optimum research return.
4. What are international LIDAR capabilities, and how do they compare to the U.S. capabilities?

Maintenance and operations

5. What fraction of the NSF U.S. LIDAR yearly budget is devoted solely to M&O, and what fraction is devoted to science, technology upgrades, and related, respectively? How have these budgets changed over the last five years?
6. What is the total yearly funding of the LIDAR groups and what are other sources and amounts of funding for M&O, science, technology upgrades, data archiving and other activities, respectively?

Strategic planning

7. Does the LIDAR PI-group have a strategic plan? If so, how often is it updated?
8. If more funding were available to the LIDAR PI-group, how much would be required, where would it be invested, and what would be the benefit for the US Geospace community?
9. What are the biggest risks to the continued operation of the PI-led LIDAR facility group? How are they being mitigated?

C5. Request for Information sent to LISN PI

<u>Request for Information for LISN Facilities</u>

Technical capabilities

1. Describe the current and any proposed capabilities of LISN (the U.S. components and the international components) for addressing key science goals (Chapter 1) and key science challenges (Chapter 2) described in the 2013 Decadal Survey Report for solar and space physics, indicating any recent or proposed improvements and modernizations in capabilities.

2. How do the technical/engineering features and capabilities of the U.S. component of LISN compare to similar or related state-of-the-art capabilities, nationally and internationally?

3. Describe the coordination process for current and any proposed LISN instruments to obtain optimum research return for the US geospace science community.

4. Please quantify the contribution to the design, build and deployment of the non-US partners in the LISN project.

Maintenance and operations

5. We understand that NSF may not yet have decided or allocated yearly budgets for LISN. What are the proposed future yearly budgets from NSF starting with FY16? Please indicate the total proposed yearly budget and separate line items for LISN M&O, LISN science and LISN technology upgrades? Describe very briefly the nature of the proposed science and technology upgrades. What is the yearly budget for data storage and distribution to users (if these are not a part of M&O)? How have the estimates for these budgets changed over the last five years? What was the projected M&O budget included in the MRI proposal for LISN?

6. What other sources and amounts of funding for M&O, science, technology upgrades, data archiving and other activities is LISN receiving from international partners and any non-NSF US partners?

7. How much of the LISN data are used for near-real time space weather activities?

Strategic planning

8. Does the U.S. component of LISN have a strategic plan? If so, how often is it updated? What is the projected lifetime of LISN?
9. If more funding were available to LISN, how much would be required, where would it be invested, and what would be the benefit for the US geospace science community?
10. What are the biggest risks to the continued operation of the facility? How are they being mitigated?

Appendix D. PI Diversity Data by GS Grants Program

Table D1. AER Awardees by gender and ethnicity, 2010-2014

PIs 2010-14		Asian	Black/AA[1]	Hispanic	Multi-Racial	Unknown	White	Total	**Fraction of awards**
Female	Actions	23	0	0	0	10	30	63	
	Awards	10	0	0	0	3	17	30	**0.16**
	Funding Rate	0.43				0.30		0.48	
Male	Actions	47	1	13	0	13	243	317	
	Awards	20	1	6	0	4	116	147	**0.80**
	Funding Rate	0.43	1.00	0.46		0.31		0.46	
Unknown	Actions	1	0	0	0	18	5	24	
	Awards	0	0	0	0	5	2	7	**0.04**
	Funding Rate	0				0.28	0.40	0.29	
Total	Actions	71	1	13	0	41	278	404	
	Awards	30	1	6	0	12	135	184	
	Funding Rate	**0.42**	**1.00**	**0.46**	**N/A**	**0.29**	**0.49**	**0.46**	
Fraction of total awards		**0.16**	**0.01**	**0.03**	**0.00**	**0.07**	**0.73**		

[1] AA (African American)

Table D2. AER Awardees by gender and ethnicity, 2005-2009

PIs 2005-09		Asian	Black/AA[1]	Hispanic	Multi-Racial	Unknown	White	Total	**Fraction of awards**
Female	Actions	16	2	0	0	6	30	54	
	Awards	7	2	0	0	3	15	27	**0.14**
	Funding Rate	0.44			0	0.00	0.50	0.50	
Male	Actions	52	12	20	2	16	336	438	
	Awards	14	6	5	1	3	141	170	**0.85**
	Funding Rate	0.27	0.50	0.25	0.50	0.19	0.42	0.39	
Unknown	Actions	1	0	0	0	5	6	12	
	Awards	0	0	0	0	1	1	2	**0.01**
	Funding Rate					0.20		0.17	
Total	Actions	69	14	20	2	27	372	504	
	Awards	21	8	5	1	7	157	199	
	Funding Rate	**0.30**	**0.57**	**0.25**	**0.50**	**0.33**	**0.42**	**0.39**	
Fraction of total awards		**0.11**	**0.04**	**0.03**	**0.01**	**0.04**	**0.79**		

[1] AA (African American)

Table D3. MAG Awardees by Gender and Ethnicity, 2010-2014

PIs 2010-14		Asian	Black/AA[1]	Hispanic	Multi-Racial	Unknown	White	Total	**Fraction of awards**
Female	Actions	40	3	0	0	2	32	77	
	Awards	14	3	0	0	1	9	27	**0.18**
	Funding Rate	0.35	1.00			0.50		0.35	
Male	Actions	88	6	7	1	26	192	306	
	Awards	28	2	3	1	11	77	114	**0.77**
	Funding Rate	0.32	0.33	0.43	1.00	0.42		0.37	
Unknown	Actions	7	0	0	0	17	3	27	
	Awards	0	0	0	0	6	1	7	**0.05**
	Funding Rate	0				0.35	0.33	0.26	
Total	Actions	135	9	7	1	45	227	410	
	Awards	42	5	3	1	18	87	148	
	Funding Rate	**0.31**	**0.56**	**0.43**	**1.00**	**0.40**	**0.38**	0.36	
Fraction of total awards		**0.28**	**0.03**	**0.02**	**0.01**	**0.12**	**0.59**		

[1] AA (African American)

Table D4. MAG Awardees by Gender and Ethnicity, 2005-2009

PIs 2005-09		Asian	Black/AA[1]	Hispanic	Multi-Racial	Unknown	White	Total	**Fraction of awards**
Female	Actions	12	0	0	0	1	23	36	
	Awards	4	0	0	0	0	13	17	**0.11**
	Funding Rate	0.33			0	0.00	0.57	0.47	
Male	Actions	95	8	8	1	21	214	347	
	Awards	34	3	2	0	10	88	137	**0.87**
	Funding Rate	0.36	0.38	0.25	0.00	0.48	0.41	0.39	
Unknown	Actions	4	0	0	0	8	4	16	
	Awards	0	0	0	0	3	1	4	**0.03**
	Funding Rate	0				0.38	0.25	0.25	
Total	Actions	111	8	8	1	30	241	399	
	Awards	38	3	2	0	13	102	158	
	Funding Rate	**0.34**	**0.38**	**0.25**	**0.00**	**0.33**	**0.42**	**0.40**	
Fraction of total awards		**0.24**	**0.02**	**0.01**	**0.00**	**0.08**	**0.65**		

[1] AA (African American)

Table D5. STR Awardees by Gender and Ethnicity, 2010-2014

PIs 2010-14		Asian	Black/AA[1]	Hispanic	Multi-Racial	Unknown	White	Total	**Fraction of awards**
Female	Actions	21	1	5	0	11	35	73	
	Awards	2	0	2	0	2	10	16	**0.11**
	Funding Rate	0.10	0.00	.4		0.18		0.47	
Male	Actions	64	2	2	3	15	226	312	
	Awards	18	0	2	3	4	82	137	**0.87**
	Funding Rate	0.28	0.00	1.00	1.00	0.27		0.39	
Unknown	Actions	5	0	0	0	35	3	16	
	Awards	0	0	0	0	9	0	4	**0.03**
	Funding Rate	0				0.26	0.00	0.25	
Total	Actions	90	3	7	3	61	264	399	
	Awards	20	0	4	3	15	92	158	
	Funding Rate	**0.22**	**0.00**	**0.57**	**1.00**	**0.25**	**0.35**	**0.40**	
Fraction of total awards		**0.14**	**0.00**	**0.03**	**0.02**	**0.10**	**0.62**		

[1] AA (African American)

Table D6. STR Awardees by Gender and Ethnicity, 2005-2009

PIs 2005-09		Asian	Black/AA[1]	Hispanic	Multi-Racial	Unknown	White	Total	**Fraction of awards**
Female	Actions	25	0	3	0	4	41	73	
	Awards	7	0	2	0	2	17	28	**0.22**
	Funding Rate	0.28			0	0.00	0.41	0.38	
Male	Actions	79	1	0	2	12	214	308	
	Awards	19	0	0	1	3	74	97	**0.77**
	Funding Rate	0.24	0.00		0.50	0.25	0.35	0.31	
Unknown	Actions	0	0	0	0	8	0	8	
	Awards	0	0	0	0	1	0	1	**0.01**
	Funding Rate					0.13		0.13	
Total	Actions	104	1	3	2	24	255	389	
	Awards	26	0	2	1	6	91	126	
	Funding Rate	**0.25**	**0.00**	**0.67**	**0.50**	**0.33**	**0.36**	**0.32**	
Fraction of total awards		**0.21**	**0.00**	**0.02**	**0.01**	**0.05**	**0.72**		

[1] AA (African American)

Appendix E. Summary of GS CubeSat Missions

IN ORBIT | AWAITING LAUNCH | NEW PROJECT

Mission, Launch	Leading Organizations	Science	Spacecraft Status	Comments
RAX 2010 , 2011	U Michigan SRI	Ionospheric plasma regularities	1 of 2 S/C operated 18 months; mission complete	30 Events, Data: rax.sri.com/raxdata.html
DICE 2011	Utah State U ASTRA LLC	Storm time E-fields, plasma density	E-field boom did not de-ploy; mission complete	Data archive not found
CINEMA 2012	UC Berkeley	Ring current dynamics	Early comm failure	Some magnetic field data
CSWWE 2012	CU Boulder	Outer rad belt, solar energetic electron and protons	Full operations; mission complete; 24 months	Data at NSSDC with Van Allen Probes
FIREBIRD I, II 2013, 2015	UNH, Montana State U Aerospace	Relativistic electron microbursts	All SC operational	Collecting Data
FIREFLY 2013 and FIRESTATION	Siena College, NASA/GSFC	Terrestrial gamma ray flashes	S/C operational; mission nearing completion	~60 Events Captured
EXOCUBE 2015	U Wisconsin, Cal Poly, U Illinois Scientific Solutions	Exospheric morphology, dynamics	Antenna did not deploy	First light mass spectrometer measurement
CADRE	U Michigan, NRL	Thermospheric dynamics	Awaiting Launch	
LAICE	V Tech, U Ill, Aero Corp, NWRA	Atmospheric gravity waves	Launch expected 2016	
OPAL	USU, HISS (U. Maryland East Shore)	Neutral temp profiles 90-140 km alt	Launch expected 2016	
QBUS	U Michigan, CU Boulder, Stanford, U del Turabo, Draper Lab	In situ lower thermospheric observa-tion, spectrometer	Project underway 2014; Launch expected 2018	4 CubeSats to European QB50 Project
ELFIN	UCLA, Aerospace Corp	Relativistic particle PA distributions	Project underway 2014	
IT SPINS	JHU/APL, Montana State Um SRI	UV nightglow radiance from O^+ recomb	Initial funding	
TRYAD	UA Huntsville, Auburn	Terrestrial gamma-ray Flashes	Initial funding	
ISX	Cal Poly, SRI	Ionospheric scintillation	Initial funding	

Appendix F. Membership in EISCAT: Categories and Conditions

The appendix provides a brief overview of the membership type and conditions. The elements taken directly from the EISCAT regulations are in inverted commas. Much further details are provided in the EISCAT Blue Book.[28]

"Two levels of EISCAT membership are available: Associate and Affiliate. Associate members make a long-term financial commitment at a national level. This membership provides immediate access to all Common Program (CP) measurements, and greater influence on the operation and future direction of EISCAT. Affiliate members have a shorter-term and smaller financial commitment, gain immediate access to the Common Program and are normally individual institutions rather than national programs."

Generic requirement

"New Associates and Affiliates need to demonstrate scientific competence on an international level and must be prepared to contribute their scientific expertise to the association. They are expected to carry out or fund basic research that is published in internationally accepted scientific journals and/or to have an independent external scientific evaluation system in place."

Associates

"EISCAT Associates enable the basic conditions for running the Association, take full responsibility for the Association and determine the overall direction of its development. "They are expected to make a significant initial payment into the Association, which is used to achieve the Association's scientific and strategic goals, to contribute to the EISCAT system's operational costs, maintenance and decommissioning in a proportion that is related to their initial payment and that allows that the minimum required operation costs be covered by the Associates. An Associate's long-term commitment is five years on a rolling basis, i.e., they must give five years' notice before leaving the Association. At present the initial payment of a new Associate ideally corresponds to at least 5% of the total investment currently planned for new EISCAT instruments." EISCAT is planning a major investment into the new EISCAT-3D system that is equivalent to approximately 1100 MSEK (118M€, ~130M$). Therefore 5% represents about $6.5M (May 2013 costs).

"The Associates decide on a common observing program and on data formats. They have access to the archived data of the Association. Their observing time is guaranteed according to a time-share formula developed by the Association. Associates are normally National Research Councils, their equivalents, or major national institutions."

Current Associate Members include Norway, Sweden, Finland, Japan, Canada and the UK.

Affiliates

"EISCAT Affiliates can join the Association with a smaller financial contribution and with less responsibility and other commitments. The observing time of Affiliates is guaranteed by an Association time-share formula. Affiliates have access to the archived data of the Association. The expected minimum payment of an Affiliate to the Association covers the cost of observing time for an Affiliate to run at least one independent observational campaign per year." This corresponds to a

[28] www.eiscat.se/eiscat2014/eiscat-bluebook-draft-2015-version-2014-04-02/view

minimum fee equivalent to 100K SEK (€11K, ~$12K) (2014 costs). "Affiliates will normally be individual institutions or foundations".

Current Affiliate Members are Russia, France and Ukraine. Korea may join in the near future.

"The EISCAT Associates establish the governing EISCAT Council and its committees. Affiliates have vested membership in the EISCAT Science Advisory Committee and observer status in Council."

In 2014, the EISCAT Associates paid between ~170k$ and 667k$ per annum to the M&O of EISCAT and this contribution provided between 10-30% of EISCAT Special Time.

The distribution of time on EISCAT is

Special Program Time: 51%

Common Program Time: 38%

Peer Review Time (openly competed): 8%

EISCAT Time for development: 2%

Appendix G. List of ACRONYMS

AAGS: Antarctic Astrophysics and Geospace Sciences program
ACR: Anomalous Cosmic Rays
AER: AERonomy
AGS: Atmospheric and Geospace Sciences
AIM: Atmosphere-Ionosphere-Magnetosphere
AIMI: Atmosphere-Ionosphere-Magnetosphere Interactions
AFOSR: Air Force Office of Scientific Research
AMISR: Advanced Modular Incoherent Scatter Radar
AMPERE: Active Magnetosphere and Planetary Electrodynamics Response Experiment
ASP: Advanced Studies Program
AST: ASTronomical sciences
ATST: Advance Technology Solar Telescope
BBSO: Big Bear Solar Observatory
CCMC: Community Coordinated Modeling Center
CEDAR: Coupling, Energetics, and Dynamics of Atmospheric Regions
CISL: Computational and Information Systems Laboratory
CISM: Center for Integrated Space weather Modeling
CME: Coronal Mass Injection
COSMO: COronal Solar Magnetism Observatory
COSTEM: Committee on Science, Technology, Engineering, and Mathematics
COV: Committee of Visitors
CRRL: Consortium of Resonance and Rayleigh Lidars
DASI: Distributive Array of Science Instruments
DKIST: Daniel K. Inouye Solar Telescope
DRIVE: Diversify, Realize, Integrate, Venture, Educate
DoD: Department of Defense
DPP: Division of Polar Programs
DS: Decadal Survey
DURIP: Defense University Research Instrumentation Program
EISCAT: European Incoherent SCAtter Scientific Association
ELF: Extremely Low Frequency
ENA: Energetic Neutral Atoms
EPSCoR: Experimental Program to Stimulate Competitive Research
FASR: Frequency Agile Solar Radiotelescope
FDSS: Faculty Development in the Space Sciences
FPI: Fabry-Perot Interferometer
GEM: Geospace Environment Modeling
GBO: Ground Based Observatory

GCM: General Circulation Model
GCP: Grand Challenge Projects
GCR: Galactic Cosmic Ray
GIC: Geomagnetically Induced Currents
GONG: Global Oscillation Network Group
GS: Geospace Section
GSO: Geospace System Observatory
HAO: High Altitude Observatory
HF: High Frequency
HSO: Heliospheric System Observatory
IBEX: Interstellar Boundary EXplorer
ICON: Ionospheric CONnection explorer
IGS: Integrated Geospace Science
INSPIRE: Integrated NSF Support Promoting Interdisciplinary REsearch
ISR: Incoherent Scatter Radar
I-T: Ionosphere-Thermosphere
I&V: Innovation and Vitality
KP: Kitt Peak observatory
LISN: Low-latitude Ionospheric Sensor Network
LISM: Local InterStellar Medium
MAG: MAGnetosphere
MHD: MagnetoHydroDynamics
MLSO: Mauna Loa Solar Observatory
MMS: Magnetospheric Multiscale Mission
M&O: Management and Operations
MPS: Mathematical and Physical Sciences
MREFC: Major Research Equipment and Facilities Construction
MRI: Major Research Instrumentation program
MSIS: Mass Spectrometer and Incoherent Scatter radar model
MURI: Multidisciplinary University Research Initiative
NASA: National Aeronautics and Space Administration
NCEI: National Center of Environmental Information
NCEP: National Center for Environmental Prediction
NIST: National Institute of Standards and Technology
NCAR: National Center for Atmospheric Research
NOAA: National Oceanic and Atmospheric Administration
NRAO: National Radio Astronomy Observatory
NSF: National Science Foundation
NSO: National Solar Observatory
NWS: National Weather Service

O2R: Operations to Research
ONR: Office of Naval Research
OSTP: Office of Science and Technology Policy
PFISR: Poker Flat Incoherent Scatter Radar
PI: Principal Investigator
PLR: PoLaR programs
PRC: Portfolio Review Committee
R2O: Research to Operations
RISR-C: Resolute bay Incoherent Scatter Radar - Canada
RISR-N: Resolute bay Incoherent Scatter Radar - North face
R-MHD: Radiative MagnetoHydroDynamcis
S2I2: Software Infrastructure for Sustained Innovation
SEP: Solar Energetic Particles
SFO: San Fernando Observatory
SHINE: Solar Heliospheric and INterplanetary Environment
SOLIS: Synoptic Optical Long-term Investigation of the Sun
SP: Sacramento Peak observatory
SSP: Solar and Space Physics
STEM: Science, Technology, Engineering and Math
STEREO: Solar TErrestrial RElations Observatory
STC: Science Technology Center
STR: Solar-Terrestrial Relations
SWM: NASA/NSF Collaborative Space Weather Modeling
SWMI: Solar Wind Magnetosphere Interaction
SWPC: Space Weather Prediction Center
SWR: Space Weather Research
SuperDARN: Super Dual Auroral Radar Network
TEC: Total Electron Content
THEMIS: Time History of Events and Macroscale Interactions During Substorms
TIEGCM: Thermosphere Ionosphere Electrodynamics General Circulation Model
TSI: Total Solar Irradiance
UCAR: University Centers for Atmospheric Research
UV: UltraViolet
VLF: Very Low Frequency
VSO: Virtual Solar Observatory
WACCM: Whole Atmosphere Community Climate Model
WACCM-X: Whole Atmosphere Community Climate Model eXtended
WSO: Wilcox Solar Observatory
WPI: Wave-Particle Interaction