



## The Geospace Environment Modeling Program Need, Goals, Accomplishments, Implementation<sup>†</sup>



The Geospace Environment Modeling Program was initiated in 1991 as an NSF targeted research program with the scientific 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’).” Progress in achieving this fundamental objective has been truly impressive. Leveraged support for the GEM program encompassing ground-based polar observations, analysis of in-situ satellite measurements and model development has produced new capabilities and many scientific discoveries. We now have a much deeper understanding of geospace as a system. Several global, physics-based models have been developed and are routinely used to predict the large-scale response of geospace to solar wind driving. Empirical statistical models for key parameters of space climatology have been developed and are widely used by the research community. Results from these models have proven to be invaluable in the interpretation of sparse observations from ground- and space-based measurement platforms. The models also enable controlled numerical experiments that provide novel physical insights into the coupled behavior of the geospace system.

The GEM program has thus come far in delivering on its original promise, though not without tweaks in its original master plan. The program’s observational plan envisioned extensive networks of NSF-sponsored ground-based instruments serving as primary data sources for diagnosing global magnetospheric behavior. These deployed networks continue to be important assets for geospace research, but good science makes use of all relevant data. The advent of NASA’s International Solar-Terrestrial Program and its evolution into the Heliophysics System Observatory made measurements from satellite constellations readily accessible soon after GEM’s inauguration. Today GEM fully embraces the use of ground-based and satellite-borne measurements, to the extent that the program has become a model for cooperative NSF-NASA research in geospace science.

The strongly coupled nature of the geospace system also required a midcourse correction in GEM’s approach to model development—from the initially envisioned modular approach, involving assembly of subcomponents into a geospace general circulation model, to advancement of magnetohydrodynamic spine models. The spine models are progressively improved by embedding new physics, either in the underlying mathematical framework, by coupling to models with other essential physics or through boundary conditions that couple other regions and their effects into the dynamics of the spine model. Evolution of these models is mature but far from complete. The progressively improving fidelity of atmospheric weather and climate models, combined with advanced measurement techniques that enable model validation and data assimilation while promoting scientific discovery, are apropos of the current trajectory of GEM program research.

From its modest origins, the GEM Program has tripled its community participation, mainly as a consequence of the program’s novel and adaptive approach in addressing forefront science and by successfully promoting professional development of students and early-career scientists. NSF resources for the GEM program are even more highly leveraged today due to the program’s success in coordinating national and international geospace research and in hosting a vibrant, open forum for timely and critical scientific discussions. This success has been accompanied by an expansion in scope well beyond the program’s defining terms of reference. At the same time, the GEM program continues with a strong sense of purpose and coherence.

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## 1 Purpose, Audience and Scope of the White Paper

This White Paper on the status of the GEM Program was solicited by Dr. Ray Walker, the Program Director for Magnetospheric Physics in the NSF Division of Atmospheric and Geospace Sciences Division. Upon arriving at NSF in early 2012, he asked the GEM community to answer several key questions in a concise document: Why is a GEM program needed, and what are its goals? What has the program accomplished? How will it achieve its goals going forward?

The White Paper is intended for two audiences: 1) NSF Atmospheric and Geospace Sciences program directors, together with program administrators at partnering agencies, who would like to understand the goals, achievements and value of a GEM program and the resources needed to ensure its future success; and 2) GEM scientists who participate in making the program successful, both scientifically and organizationally.

This document consolidates the ideas of many people into a strategy for how to maintain the GEM program's focus on its grand vision for scientific advancement – the advancing dot on the horizon. The mission of the GEM program is to ensure that this vision is realized. The program's guiding principles are:

**Vision:** Accurate prediction of the geospace environment.

**Mission:** Develop physical understanding of the large-scale organization and dynamics of the geospace environment from observations, theory and increasingly realistic models.

Subsequent sections explain why the need for geospace environment modeling is greater today than when the GEM program was first initiated and why an *evolving* GEM program is essential in meeting this need. The goals of the GEM program are well aligned with current national scientific priorities, not surprisingly, because GEM program science has informed national interests. The program's success is largely a consequence of its ability to regenerate and rapidly adapt its scientific focus on timely and critical problems in geospace environment modeling that emerge from new data, discoveries and progress in scientific understanding. Perspectives on how the GEM program evolved its unique mode of organization and why the program has become a magnet for collective scientific inquiry are highlighted. The White Paper is forward-looking and provides a plan for realizing short- and long-term scientific goals through synergies among observational, theoretical and modeling approaches, ongoing strategic planning and coordinated community action on emerging scientific issues.

## 2 Geospace Environment Modeling: Need and Value

The National Research Council's 2012 Report on a Decadal Strategy for Solar and Space Physics identifies important touchstones for future directions in geospace research, with specific directives for geospace environment modeling appearing in the report's top two science goals:

Decadal Goal 1: Determine the origins of the Sun's activity and *predict the variations in the space environment.*

GEM advances the ability to predict and diagnose the state of the geospace environment – an essential capability for a space-reliant, spacefaring and technologically advanced society. Most space weather effects are manifest in the geospace environment.

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

GEM advances our understanding of the external and internal processes that produce the large-scale organization and dynamics of the geospace system.

The Decadal Strategy also advocates Guiding Principles and Programmatic Challenges that inform GEM research:

*“To make transformational scientific progress, the Sun, Earth, and heliosphere must be studied as a coupled system.”*

GEM provides a holistic treatment of the solar wind–magnetosphere–ionosphere–thermosphere interaction. GEM research is providing new insights into the coupled system.

*“To understand the coupled system requires that each subdiscipline be able to make measurable advances in achieving its key science goals.”*

Understanding is demonstrated by prediction which is enabled by modeling, which is informed and constrained by theory and observations. GEM embodies these principles.

*“Success across the entire field requires that the various elements of solar and space physics research programs—the enabling foundation comprising theory, modeling, data analysis, innovation, and education, as well as ground-based facilities and small-, medium-, and large-class space missions—be deployed with careful attention both to the mix of assets and to the schedule (cadence) that optimizes their utility over time.”*

GEM transcends national and program boundaries and integrates observations, data, theory and modeling approaches in advancing scientific understanding of the geospace environment. Development of reliable, first-principles models sharpens our scientific questions about the geospace environment and motivates, justifies and optimizes new observational capabilities and data exploitation.

### 3 Why is a GEM Program needed?

Concerted efforts are required to realize the Decadal Strategy’s goals and guiding principles. A GEM program is needed to engage, coordinate and support broad community participation in:

- An open and frank forum for discussing progress and challenges in geospace research;
- Timely identification and resolution of critical, emerging scientific issues in geospace environment modeling;
- National and international coordination of geospace research;
- Integration of diverse theoretical, computational, and observational expertise in developing and advancing comprehensive predictive capabilities;
- Model validation and comparison;
- Consolidation of knowledge (and models) of the geospace system and dissemination for possible transition to an operational environment where it can benefit society; and
- Professional development for students and early-career researchers with interest in GEM.

The GEM Program is an “*existing, enabling program*” of the NSF Division of Atmospheric and Geospace Sciences. As discussed in Section 6 on Program Implementation, in the language of the Decadal Survey it can be brought to “*full fruition ... to realize scientific discoveries from existing data, build more comprehensive models, make theoretical breakthroughs, and innovate*” with new program elements enabled by the DRIVE initiative of the 2012 Decadal Survey:

*“The survey committee recommends 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.”*

## 4 GEM Program: Goals

The overarching goal of the GEM program is to explore, understand, and ultimately predict the dynamics of the geospace system by advancing increasingly realistic numerical simulations, including global and specialized regional models, and capabilities for synoptic observations. This overarching goal includes the following elements:

- Develop an integrated physical understanding of the geospace dynamical system;
- Develop the scientific understanding of geospace processes required for accurate prediction;
- Advance modeling capabilities, including metrics and validation of first-principles and empirical models, and promote the broader use of models;
- Advance innovative observational capabilities, especially synoptic measurements including ground-based measurements, to improve scientific understanding, facilitate data assimilation and test key elements of models;
- Promote a vibrant community of geospace scientists to accomplish program goals; and
- Prepare and develop the next generation of geospace researchers.

## 5 GEM Program: Background and Accomplishments

### *History and Early Organization*

Following a three-year definition and planning phase, the GEM program was initiated in 1991 as an NSF targeted research program of the Geosciences Directorate with the goal to develop a community Geospace General Circulation Model (GGCM). The envisioned model would test scientific understanding and demonstrate mastery of magnetospheric physics. The approach to GGCM development evolved from the initial concept of a modular assembly of GGCM component models to the present implementation in which the best MHD “spine” models are advanced through addition of increasingly realistic non-MHD physics.

When GEM was conceived ground-based measurements (together with the first generation of space-borne auroral imagers) provided the only means of obtaining an instantaneous global view of magnetospheric dynamics through their reflection in high-latitude ionospheric dynamics. As a result ground-based measurements, especially those from global and regional arrays of instruments particularly in the Arctic and Antarctic, played an important role within GEM and continue to be essential in investigating the global dynamics of relevance to GEM.

Since a system is built from the sum of its parts, initially GEM was organized into a series of temporally overlapping campaigns that focused attention on areas of the magnetosphere important to understanding global dynamics. The four campaigns addressed Boundary Layers, the Tail and Substorms, the Inner Magnetosphere and Storms, and Ionosphere-Magnetosphere Coupling. These campaigns focused their efforts on answering outstanding questions important to building the GGCM. After the conclusion of the initial campaigns GEM reorganized itself into a set of ongoing research areas based on these campaign areas. These research areas organize finite-lived focus groups that address a question or area of topical importance.

From the outset, GEM has held a week-long summer workshop at which researchers gather to collaborate, discuss the latest developments, and plan for future work. These workshops have come to define GEM and its unique approach to collaborative science. To many these workshops are GEM, and the meeting has become an important annual gathering for magnetospheric physicists, both US and international. Later the summer workshops were supplemented with a day of GEM mini-workshops held in conjunction with the AGU Meeting each December. The success of the

GEM workshops depends on the research, collaboration and planning done between workshops, and on the workshop organizers' insistence that focus groups structure their activities in a workshop mode of presentation and open discussion. International participants note that no other world forum is as effective as the GEM program in coordinating ground-based measurements and science.

### *Innovations and Accomplishments*

After more than two decades of focused collaborative research, GEM's scientific accomplishments and its major innovations in methods of collaborative science, scientific modeling, and methods of training and mentoring are legion. To do full justice to these accomplishments, or even to list all the major ones, in a short document such as this is impossible. Instead we highlight an illustrative set of examples of GEM's major accomplishments, many of which were enabled by GEM's workshop approach to collaborative science. The first list focuses on innovations in collaborative science, modeling, and training that have enabled GEM's scientific success. The second list provides an example of a major scientific accomplishment from each of GEM's research areas.

### *Overarching and Organizational*

1. *GEM Challenges*: A unique mode of community interaction and research; facilitates model validation and collections of observations; capacity for high-impact science (e.g., reconnection challenge) The GEM challenges have resulted in some of the most highly cited papers in the field.
2. *Coordinated observations*: Especially ground-based measurements and their synthesis with current and past spacecraft measurements; GEM participants fostered coordination between ground-based and THEMIS measurements; conjunction studies between the Van Allen Probes and THEMIS will likely also be coordinated at GEM workshops.
3. Finite-term scientific campaigns and *rapid response focus groups*: A new focused, collaborative, and efficient mode of scientific inquiry.
4. *Lively community forum* for:
  - Identification of the most important and timely topics for community research: What's hot?
  - Resolving competing paradigms and/or controversial issues spanning all areas of geospace; open discussion of issues, e.g., partial ring-current timing during storms; timing of SW entry, ionospheric outflow during storms; importance of plasmasphere morphology, especially for radiation belt dynamics; MI gap region; in-out vs out-in substorm initiation received greatest attention at GEM workshops; origin of energetic particles in the cusp; origin of ionospheric convection transients and traveling convection vortices.
  - CCMC validation and metrics of models describing various aspects of the solar wind – magnetosphere – ionosphere interaction. GEM is CCMC's de facto forum.
5. *Vibrant professional development* and education: Prepares the next generation of geospace scientists; provides opportunities for them to exercise leadership roles, e.g., in student-led workshop elements. GEM-supported students have become leaders in the GEM program and the broader space physics community and are recognized, e.g., as AGU Scarf and Macelwane awardees, NSF Career Awardees and NRC Decadal Survey Panelists.
6. Large-scope *comprehensive community modeling* efforts: Spawned CISM (NSF), SWMF (MURI/LWS-NSF), OpenGGCM (LWS-NSF); code coupling, computational advances, "under-the-hood" software development; addition of new physics to large-scale codes.

7. *National Space Weather Program*: Successfully advocated for its establishment and continues to promote basic research to understand space weather, space climatology and their predictability.

#### Select Scientific Highlights by Research Area

Examples of outstanding scientific achievements within each of GEM's five Research Areas are highlighted below. Many other major scientific advances for which GEM can take credit appear in a supplementary document (<http://www-ssc.igpp.ucla.edu/gem/whitepaper2013/accomplishments.pdf>).

- Importance of Hall MHD physics in reconnection, independent of model choice (*RA: Global Geospace Circulation Model*)
- Differentiation of magnetospheric modes of convection (*RA: Tail and Substorms*)
- Modeling and analysis of feedback processes in the inner magnetosphere, including effects of self-consistent magnetic and electric fields and wave-particle interactions on plasmaspheric, ring-current and radiation-belt dynamics (*RA: Inner Magnetosphere and Storms*)
- Importance of bow shock and foreshock processes in driving transients in dayside convection and identification of the modes and physics of solar wind entry through boundary layers (*RA: Dayside Interactions*)
- Role of MI gap-region physics and ionospheric outflows in geospace dynamics (*RA: Magnetosphere-Ionosphere Coupling*)
- Differentiation of two major types of storms with systematically different phenomenology: CME-driven storms with GIC, SEP, large Dst, and shifted inner radiation belts and high-speed-stream-driven storms with outer-radiation-belt killer electrons and hot-plasma spacecraft charging (*Overarching*)

## 6 GEM Program: Implementation

GEM program goals are achieved via a grass-roots collaborative engagement of the community, with a focus on forefront issues of geospace science. As detailed below, implementation of this strategy requires coordinated action, drawing from existing best practices along with new approaches. Information about the current program organization is available at the GEM Program wiki ([http://www-ssc.igpp.ucla.edu/gemwiki/index.php/Main\\_Page](http://www-ssc.igpp.ucla.edu/gemwiki/index.php/Main_Page)).

### *Community Engagement*

The semi-annual GEM workshops (a one-week long summer workshop and a one-day mini-workshop on the Sunday before the Fall AGU meeting) are unique venues for discussing and conducting science in a collaborative, open and spirited forum. They engage US and international scientists as well as students. The GEM workshops organize community activities around critical problems in GEM science and collaborative efforts in solving them. These workshops are of utmost importance for:

- Identification, initiation and conduct of high-impact challenge campaigns;
- Integration of NSF-funded observations and modeling with other US and international research programs;
- Mentoring, training, and education of students and early-career scientists;
- Coordinated investigations of the coupled geospace system (proactively leading collaborations with interested members of the CEDAR and SHINE communities); and
- Dissemination of research progress.

## Research Coordination

GEM research activities are coordinated by Research Area (RA) Coordinators, two for each research area identified below. RA Coordinators are charged with the following responsibilities.

- Develop and periodically update a concise statement of scope and goals for each RA.
- In consultation with the broader GEM research community, identify and articulate science targets for community study via limited-term Focus Groups (FGs) that concurrently investigate timely problems in each of five overlapping Research Areas:
  - Solar Wind – Magnetosphere Interaction (SWMI);
  - Magnetotail and Plasma Sheet (MPS);
  - Inner MAGnetosphere (IMAG);
  - Magnetosphere – Ionosphere Coupling (MIC); and
  - Global System Modeling (GSM).

The previously defined research areas have been retitled in the above list so as to reflect their current scope more accurately. Henceforth, they will be so designated.

- Identify geospace system-level problems and science targets that cross research areas.
- Invite prospective Focus Group leaders to float ideas for new focus groups.
- Develop selection criteria for Focus Groups that are consistent with program goals and with the scope and goals of the research area. Focus group selection criteria are updated and clarified as needed to ensure alignment with the goals of each research area. RA Coordinators do not participate in focus group proposals so as to maintain an impartial selection process.

## Strategic Planning

To promote ongoing strategic planning, a Research Area Council is charged with coordinating focus group studies of the individual research areas, while promoting research of the geospace system as a whole. The Council consists of the Research Area Coordinators, the Steering Committee Chair and Chair-Elect and the liaisons to the CEDAR and SHINE Programs. It meets at least once per year, separately from the greater GEM steering committee of which it is a subcommittee. Its primary responsibilities are to:

- Define near-term GEM program goals and ensure their alignment with the program vision and mission.
- Collect, discuss and report progress during the current year in addressing science questions relevant to the coupled geospace system.
- Identify new and continuing system-level science questions that cut across research areas.
- Communicate progress and problems in global system modeling and observing to FG leaders and solicit their feedback on emerging geospace science issues. RA Coordinators are encouraged to hold two annual telecons with their respective Focus Group Leaders.
- Identify deficiencies in models and observations and gaps in understanding in each RA.

As described in the GEM bylaws on the GEM Wiki (referenced above), a GEM Steering Committee (SC) oversees all GEM activities, except funding. This oversight includes, for example, program organization, decisions on focus group proposals and research initiatives emerging from the RA council. Voting members of the SC consist of the Chair, Chair-elect, 4 science community representatives, the RA Coordinators and the GEM meeting organizer. Nonvoting members of the SC include student representatives (2), the GEM communications coordinator(s), liaisons to NASA, NOAA, CEDAR and SHINE, international liaisons, and the GEM program manager.

### Resource Priorities

The success of the GEM program requires resources to plan and coordinate program activities and to conduct core GEM research projects. Funding from the NSF is used to facilitate:

- Program participation by students and early-career scientists;
- Logistics and travel support (mainly for students) for GEM workshops;
- Ongoing development and use of geospace models; and
- Data analysis for model development and validation.

Core GEM research projects span:

- Observational, theoretical, and model developments;
- Community campaigns and challenges; and
- Investigator-led, forefront science investigations that advance GEM goals.

### Future Opportunities and Initiatives

Growing interest in GEM research has been accompanied by increasing proposal pressure on already oversubscribed resources. The GEM program is a supplement to the NSF's base program in geospace science, and its funding is—and should remain—separate from base program funding. As highlighted in item 6 under “Innovations and Accomplishments”, the GEM community in the past has successfully developed additional resources to support GEM research. The recommendations of the 2012 Decadal Strategy's DRIVE initiative provide potential new opportunities to augment core GEM research and program infrastructure. Transforming these opportunities into funded program elements will require leadership in developing compelling initiatives and proposals and the NSF budgetary discretion to support them. Some will likely require cross-agency partnerships.

It would be particularly desirable to initiate a new research element involving collaborative, multi-institutional and multidisciplinary team research. Creation of a science center devoted to GEM-related research, as envisioned in the DRIVE Venture thrust, provides one model for organizing such team projects, but other models that build on the GEM program's existing organization might support a more adaptive program structure, with minimal institutional inertia.

This White Paper closes with ideas on how new funding for the Decadal Strategy's DRIVE initiative could enhance experimental and theoretical assets manifest in the GEM program and enable it to achieve “full fruition.”

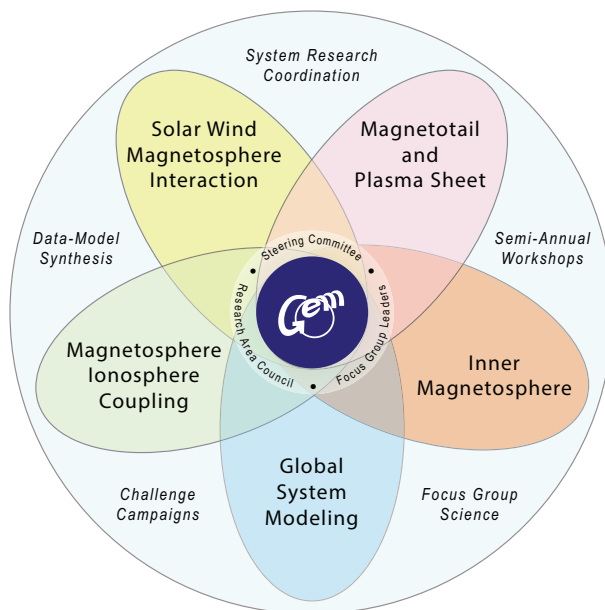
- *Diversify*: Develop innovative new measurement techniques and networks relevant to GEM, with deployments in ground-based networks and/or tiny satellite observing platforms.
- *Realize*: Augment community coordinated data exploitation in GEM forums, e.g., leading to data assimilation capabilities in GEM models.
- *Integrate*: Support GEM challenges that integrate team efforts, multidisciplinary analysis and cross-agency assets.
- *Venture*: GEM is Grand Challenge research *par excellence* and a virtual GEM Center, periodically re-envisioned, competed and funded as an NASA/NSF/NOAA partnership, would ensure its vitality and alignment with the programmatic goals of supporting agencies.
- *Educate*: Develop new program elements that contribute to graduate education and professional development, e.g., an (institutionally) floating version of NCAR's Advanced Study Program could be adapted to provide short-term training experience for graduate students and other researchers at geospace data and modeling centers, both national and international.



## 8 Summary and Next Steps

The GEM program has made great strides in delivering on its original promise. Its goals support the next decade's strategic priorities in solar and space physics. The program has developed an innovative organizational structure for rapidly exploiting new data and scientific breakthroughs to advance scientific understanding and modeling of the geospace environment and the coupled geospace system. It engages broad segments of the national and international geospace research community, and it is among the most highly leveraged programs sponsored by the NSF. The successful and popular GEM workshops are the primary forums for identifying and resolving the most important and timely topics in geospace environment science, modeling and observation and for promoting the professional development of early career scientists with interest in GEM.

The GEM Program is poised to achieve “full fruition” by exploiting new opportunities and ventures with cross-agency appeal. The next step in research planning is to mobilize the program's newly formed Research Area Council, which, in the coming months, will initiate the continuous strategic planning process outlined in the previous section. The Council will periodically assess progress in realizing the program vision, identify structural impediments to accurate prediction, and build and articulate community consensus for a progressive research strategy to ensure success.



**Caption.** Overlapping research areas of the GEM Program and collaborative activities it supports to advance our understanding of the geospace environment.

### Acronym Definition List

AGU: American Geophysical Union

CCMC: Community Coordinated Modeling Center

CEDAR: Coupling, Energetics, and Dynamics of Atmospheric Regions program, the upper-atmospheric counterpart to GEM

CISM: Center for Integrated Space Weather Modeling, an NSF-sponsored Science and Technology Center

CME: coronal mass ejection

DRIVE: Diversify, Realize, Integrate, Venture and Educate, a cross-agency initiative of the 2012 Decadal Strategy for Solar and Space Physics

Dst: disturbance storm time index from ground-based magnetometers

FG: Focus Group

GEM: Geospace Environment Modeling, the program for which this document is written

GGCM: Geospace General Circulation Model

GIC: geomagnetically induced currents

GSM: Global System Modeling, one of the GEM research areas

IMAG: Inner MAGnetosphere, one of the GEM research areas

LWS: Living With a Star, a program with the NASA Heliophysics Division

MHD: magnetohydrodynamic, often used in reference to a numerical model

MI: magnetosphere-ionosphere

MIC: Magnetosphere-Ionosphere Coupling, one of the GEM research areas

MPS: Magnetotail and Plasma Sheet, one of the GEM research areas

NASA: National Aeronautical and Space Administration

NCAR: National Center for Atmospheric Research

NOAA: National Oceanic and Atmospheric Administration

NRC: National Research Council

NSF: National Science Foundation

RA: research area

SC: Steering Committee

SEP: solar energetic particle

SHINE: Solar, Heliospheric, and INTERplanetary Environment program, the solar-system counterpart to GEM

SW: solar wind

SWMF: Space Weather Modeling Framework

SWMI: Solar Wind-Magnetosphere Interaction, one of the GEM research areas

THEMIS: Time History of Events and Macroscale Interactions during Substorms, a 5-spacecraft mission sponsored by NASA