EXPLORING THE GEOSPACE FRONTIER: QUO VADIS?

Scientists from across the geospace domain participated in this NSF workshop to identify mechanisms for advancing space weather observations and prediction capabilities. The collective of nearly 100 space scientists reached a consensus that now is the time to invest in infrastructure and observational facilities to meet the societal need and scientific challenges posed by Space Weather. Workshop presenters outlined numerous observing strategies and platform concepts, each with the potential to transform space weather forecast capability in one or another domain. All considered it imperative to develop a conceptual community-wide NSF Major Research Equipment Facilities Construction (MREFC) proposal to bring these platform concepts together into an end-to-end (dedicated) space weather research facility. To develop this plan further, it was determined that we must, as a community-leading group, invest time to evaluate, prioritize, and scope the components of such a cross-cutting initiative.

Introduction

This report summarizes the discussion and findings from the NSF-supported “Exploring the Geospace Frontier: Quo Vadis?” Workshop held in Boulder, CO, May 25-27, 2016, and the community workshops organized subsequently by the NSF CEDAR, GEM and SHINE programs in June 20-24, 2016. These workshops were organized to help identify mechanisms for advancing space weather observation and prediction. The workshops placed a particular emphasis on crystallizing a comprehensive space weather research program at the NSF that closes critical observational and knowledge gaps, is responsive to societal needs, and elevates the discipline to a level commensurate with national priorities. The workshops focused on the scientific challenges and experimental infrastructure required for discovery research in the 21st century, with consideration for both basic and applied research driven by cutting edge observations of the Sun-Earth system. The path forward calls for new observing capabilities, integration across traditional disciplinary boundaries, and the formation of critical partnerships both within the NSF and with other agencies.

The Quo Vadis workshop attracted 97 registered participants representing all the subdisciplines of geospace. The format of the Boulder workshop was designed to maximize interaction and discussion. The workshop was divided into five sections. These sections included brief, individual presentations followed by moderated panel discussions. The workshop program is included as an appendix in this document. The individual presentations were accumulated and made available for review on the Quo Vadis website at https://www2.hao.ucar.edu/events/GeospaceFrontier2016. Presentations made subsequently at the GEM/CEDAR Quo Vadis workshop, which was conducted using a more traditional presentation-based format, are also available through the website. Workshop organizers also kept written records of the panel discussions.
The overall theme of the workshop can be summarized by the following questions: “If we had the resources, what would we (as a community) do to have the most impact?” The Quo Vadis workshop addressed the “we” in this question by assembling a broad community of investigators drawn from solar, interplanetary, magnetosphere, and geospace communities (i.e. SHINE, GEM, and CEDAR NSF programs) in an effort to defeat disciplinary stove-piping and to lay the groundwork for better collaboration within and across the Division, Directorate, and Foundation. It also addressed “impact” by emphasizing the dual goals (a la Pasteur’s quadrant [Stokes, 1997]) of discovery and applied research, both essential to space-weather research. Finally, the workshop took the first step in the process by defining observational needs and the ground-based instrumentation required to meet those needs.

The Goals and Objectives of the Workshop
Specifically, the goals and objectives for the Quo Vadis workshop were to:
1. position the NSF Geospace Program as the principal research arm of the National Space Weather Program;
2. determine key gaps in our understanding and observing capability of space weather phenomena and processes;
3. put forward a plan that will lead to discoveries and support communities impacted by space weather.

The Charge to the speakers
Quo Vadis was the start of a process to coordinate and advance space weather research within the Geospace Program at NSF with an emphasis on earth-based observing capabilities. This will likely be a multi-year effort with the focus primarily on NSF priorities, activities, and programs, i.e. to chart and approach earth-based observing for space weather research. The charge put forth to the speakers was to address three main questions:
- What major gaps in scientific understanding or engineering capability limit our ability to describe Sun-Earth connections?
- Where is discovery science likely to occur?
- How can we predict the occurrence of, and reaction to, space weather?
While most of the presentations made at the Quo Vadis? workshop were solicited, unsolicited presentations were also accepted. The workshop at GEM/CEDAR included only contributed presentations.

Workshop Presentations & Concept Quad Charts
The presentations from the workshop were collected and are available online in PDF format, attached to the conference agenda, and the presentation session webcasts can be found on the HAO YouTube Channel. These presentations provide an impressive array of potential observing platforms that can improve our understanding of Sun-Earth connections and lead to improved space weather forecasts. Along with these presentations, there are also mission-style quad charts available from this site. These quad charts provide a short description of the science motivation, challenges, resource requirements, and links for additional information.
Findings Of The First “Quo Vadis” Workshop

Why the Timing is Ideal - Societal Needs
It has become the policy of the United States to prepare for space weather events to minimize the extent of economic loss and human hardship – as recently mandated by Executive Order of the President of the United States. Regular, moderate space weather storms frequently affect navigation and communication systems, degrade electric power quality, interrupt satellite functions, and are hazardous to astronauts. Severe space storms have resulted in perturbations in high-voltage power and have caused loss of satellites through damaged electronics or increased orbital drag. For rare extreme events, the effects could be catastrophic with severe consequences for millions of people. As science and society increasingly recognize the impacts of space weather on the infrastructure of the global economy, interest in and dependence on space weather information and services grow [Baker and Lanzerotti, 2016]. The societal impacts of space weather can be minimized by designing less susceptible, more resilient technologies, combined with better environmental knowledge and more reliable forecasts.

Why the Timing is Ideal - Political Environment
In recent years, there has been a growing awareness of space weather impacts on critical infrastructure in the civilian, commercial, and military sectors. This awareness has led to action. The scientific community has developed guidance documents in the form of the 2012 Heliophysics Decadal Survey, and the 2015 COSPAR Space Weather Roadmap. At the national strategy level, to protect critical assets on the ground and in space, the NSF, NOAA, NASA and DOD have constructed a National Space Weather Strategy and a detailed Space Weather Action Plan (the “SWAP”). Within the NSF, we note the emphasis placed on space weather with the “Prediction of and Resilience against Extreme Events” (PREEVENTS) program created within the Directorate for Geosciences (GEO) and the recent review by the Atmospheric and Geospace Sciences (AGS) of their facility portfolio. Largely as a result of these activities and effective lobbying by our community as one voice, there is strong bipartisan support within Congress to improve the national space weather forecast capability.

Why NSF?
Space weather programs exist at multiple agencies (NSF, NASA, DoD, NOAA), with each program oriented toward the agency’s overarching mission. The DoD and NOAA (Space Weather Prediction Center-SWPC) are focused on operational capability, while the NSF and NASA (Living with a Star program) are oriented toward enhancing fundamental understanding. The NSF occupies a unique position in this landscape by virtue of the breadth of its mission. As articulated below, there exist major gaps in our basic understanding of the sun-Earth system that must be addressed if we are to realize a quantum advance in space weather prediction. These gaps span the disciplines of solar physics, magnetospheric physics, aeronomy, data science, cyberinfrastructure, and social science. A comprehensive NSF space weather program
built upon internal partnerships can fill this need. Such a program would have a substantial foundation-wide impact, while directly serving the public good.

The proposed program will require a sustained 20 to 30 year effort and a substantial investment in new infrastructure well beyond the reach of the current NSF Geospace Section budget. In terms of economic impact, episodic space weather events have caused damages in the range of billions of dollars to public and commercial infrastructure. These damages are projected to be in the trillions for a major geomagnetic storm [National Research Council, 2008 Report].

The space weather enterprise has already identified targets for fundamental research advancements that fall outside the missions of NASA and NOAA. The Quo Vadis? attendees urged the NSF to don the mantle as the primary research partner in this enterprise, as this type of effort fits squarely in their mission. Ground based technologies are innovative, have lower risk associated with them, engage students of multiple disciplines, and can make significant advancements in understanding space weather.

**Why a Major Research Equipment and Facilities Construction (MREFC) Project?**

To enable space weather discoveries and advance prediction of events, a major investment in observing capability is required. The Quo Vadis? Attendees identified that such a space weather research facility will need to address the generation, propagation, transference, and dissipation of solar disturbances. These four areas are key to understanding space weather events and, more importantly, to predict their behavior.

1. **Generation:** Chromospheric and coronal magnetic fields are the progenitors of space weather yet their growth, release of energy, and structure are poorly understood. In order to make short and long-term forecasts of solar eruptions we must developed the capability to measure and eventually model these fields.

2. **Propagation:** Once released, solar disturbances propagate and evolve through the interplanetary medium requiring more robust characterization and tracking than presently possible. A major source of error in the space weather prediction enterprise arises from the almost non-existent tracking and monitoring of disturbances as they travel through the interplanetary medium. We must develop capabilities to track or “sound” solar disturbances from the sun to the magnetosphere in order to develop a clearer picture of arrival time, strength of the disturbance at the magnetosphere (or whether that disturbance will miss), and the efficiency of energy transfer.

3. **Transference:** The capture or transference of a solar disturbance to the geospace system constitutes a geo-effective space weather event. Space weather events involve plasma and energy transport across geospace domains on varying temporal and spatial scales. Our understanding of the basic physics of scale-dependent energy exchange and plasma transport remains incomplete and speculative. We do not currently have the observational capabilities to measure the plasma across the vast range of interacting
scales present in the magnetosphere-ionosphere-thermosphere system. To advance our basic system-level understanding and improve our predictive capabilities requires observations from dense globally distributed sensor networks deployed both on ground and in space, with a parallel effort aimed at physics-based data assimilation.

4. **Dissipation:** The majority of space weather energy captured by the near-space environment is dissipated in the upper atmosphere, only to be redistributed through pathways that rely on inadequate knowledge of the thermosphere neutral gas properties and its interaction with the ionosphere plasma. The neutral gas component of the weakly ionized upper atmosphere above 100 km altitude is inadequately observed and consequently poorly understood. It absorbs most of the energy deposited by a space weather disturbance, redistributes that energy in unknown pathways, and poses the greatest uncertainty to satellite drag. We must make coordinated, regional and well-resolved measurements of both the neutral and plasma properties from 100-250 km altitude to advance our understanding of how space weather energy is deposited and distributed throughout the near-space environment.

Only a cross-community MREFC-class facility can address all four of these key science topics collectively. It will provide a focal point for the community under the banner of advancing our knowledge of the solar and geospace environments with a view to significant improvements in space weather knowledge and prediction. Such a notional multi-component, multi-community geospace facility is embodied in the traceability matrix below.

<table>
<thead>
<tr>
<th>Science topic</th>
<th>Observational gap</th>
<th>Potential Facility Component(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation: Coronal and chromospheric Magnetism</td>
<td>Magnetic and energetic inputs at base of system.</td>
<td>CoSMO1, FASR2, SPRING3</td>
</tr>
<tr>
<td>Propagation: Interplanetary Space</td>
<td>The “93-million mile gap”</td>
<td>VHF Space Weather Radar4</td>
</tr>
<tr>
<td>Transference: Geospace plasma and energy sources</td>
<td>Undersampled in space and time</td>
<td>Ground and Space Distributed Sensor Networks5</td>
</tr>
<tr>
<td>Dissipation: Upper Atmosphere plasma-neutral</td>
<td>Neutral and plasma observations above 100 km</td>
<td>OASIS6</td>
</tr>
</tbody>
</table>

1 Coronal and Solar Magnetism Observatory - [https://www2.hao.ucar.edu/](https://www2.hao.ucar.edu/)
3 SPRING
4 Geospace radar facility - [https://www.overleaf.com/read/vcxkkvwszqxb/](https://www.overleaf.com/read/vcxkkvwszqxb/)
5 Sensor Networks - [https://www2.hao.ucar.edu/events/GeospaceFrontierAgenda](https://www2.hao.ucar.edu/events/GeospaceFrontierAgenda)
6 Observatory for Atmosphere-Space Interaction Studies - [http://rsss.ece.illinois.edu/files/OASIS](http://rsss.ece.illinois.edu/files/OASIS)
Potential Partners in the Foundation

Mathematical and Physical Sciences (MPS)
(MPS/AST) In more basic research terms, space weather can address the habitability question for earth and for other stellar/planetary systems. As exoplanet exploration continues there is an understanding that a subset of exoplanets (with magnetic fields) likely experience a similar buffeting from their host star. We anticipate that the research conducted as part of the cutting-edge observing system being covered here is also applicable to those systems, with appropriate scaling.

Social, Behavioral and Economic Science (SBE)
As the economic and societal impact of space weather events is growing, as highlighted in the news and National Academy reports, an important part of any MREFC venture is effective communication with the general public and economic decision makers.

Computer Information Science and Engineering (CISE)
With a cross-community facility of the scale considered and the complexity of the data integration and assimilation problem at hand it is likely that advanced methods will be required for data handling, transfer and interpretation - such as pattern recognition techniques, compressed sensing techniques, and related methods drawn from estimation and optimization theory.

Directorate for Engineering (ENG)
With the scale and complexity of the instrumentation efforts, including the construction and fabrication of the buildings and enclosures for those instruments, we anticipate that some interest in these facilities will live within ENG.

Potential Agency and International Partners

Significant scientific problems require substantial resources to address. Space weather prediction and mitigation is of this scale, having to cover the terrestrial globe and span the vast reaches of the heliosphere between Earth and the Sun. The problems posed by space weather may be too large in scope to be addressed with a single MREFC or even a single federal agency. Although NSF will take the research lead, a hallmark of the 2013 Decadal Survey, the 2015 SWAP, and the 2016 Executive Order (Coordinating Efforts to Prepare the Nation for Space Weather Events) is an emphasis on interagency and international cooperation. An initial investment by the NSF in a comprehensive strategy to combat space weather could catalyze further investments by other agencies as well as international partners, the MREFC process being the gold standard for vetting. Some of the most obvious partners in this effort are listed below.
NASA: NASA has a long and fruitful history of collaboration with ground-based instrumentation in pursuit of common scientific goals. Two examples are the planetary radar project based at the Arecibo Radio Observatory and the all-sky imager (ASI) array deployed in support of THEMIS. Future missions, including flagship missions such as the Geospace Dynamics Connections (GDC), would be complementary and could be deeply entwined with the project being envisioned here.

NOAA: As a goal of this project being the acquisition of scientific expertise in pursuit of a space-weather forecast capabilities, partnership with the NOAA/NWS Space Weather Prediction Center will occur early in project planning. Filling the observing gaps identified in this report parallels the kind of instrument development effort that ultimately made meteorological forecasts accurate and actionable. The exchange from research to operations and operations to research will also be a logical engagement with NOAA.

DoD: Critical DoD systems are susceptible to moderate and severe space weather effects including satellite-based communication, navigation, and imaging systems as well as ground-based radars, especially over-the-horizon radars, and most every service that relies on HF radio signals. Efforts are underway already to make these systems more resilient. The proposed MREFC effort would provide an umbrella for coordinating these efforts. At the same time, DoD partners have considerable expertise in constructing large facilities which could be tapped when the project instrumentation is being designed and constructed.

International: the NSF Geospace Section already has close ties with space science programs in other countries, most notably in Canada (home of RISR-C and RISR-N), the EISCAT member nations, Greenland, and Peru. Coordination between the MREFC effort envisaged here and complementary efforts in other countries, EISCAT-3D and the Equatorial MU radar to name two already underway, could lay the groundwork for a truly global space-weather observatory while optimizing the use of limited financial and human resources.

Next Steps

In order to carry this project to the next level we recommend the formation of a small steering committee to organize a series of meetings to complete the mission scoping exercise. This steering committee should have representation from the four science topics identified in Potential Facility Description Subsection. We envision that each science topic will convene a short 1-2 day meeting drawing upon experts from the field to conduct a more detailed discussion of the priorities, scope and initial cost estimates of their components of the MREFC facility. Once these meetings are completed representatives from these working groups along with the steering committee will meet to aggregate the information and produce the initial concept study of the comprehensive space weather research facility.
References


Workshop Organizers (in alphabetical order)

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