

The National Solar Observatory and Ground-Based Solar Observations: Essential Components of the National Space Weather Strategy

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Executive Summary

In response to the *National Space Weather Strategy* and *National Space Weather Action Plan* issued by the National Science and Technology Council, the National Solar Observatory has identified the following actions that could be taken in partnership with the research community and national industry:

- Refurbish the <u>GONG</u> network with enhanced space weather relevant data products and ensure its continuity for another 10 years (Action #1).
- Proceed with the definition phase of the <u>SPRING</u> network that will replace the <u>GONG</u> network and the <u>SOLIS</u> instrument suite (Actions #2 & #5).
- Evaluate fast readout detectors with multiplexing capabilities specifically designed for accurate measurements of the solar magnetic fields. Such detectors will further enhance the magnetic sensitivity of <u>DKIST</u> (Action #3).
- Develop improved spectral-line inversion techniques and associated data products to enable a more precise description of the magnetic processes that will be observed with <u>DKIST</u> and that are responsible for space weather (Action #4).
- Develop a lightweight solar magnetograph concept that is easily adapted to mediumsize space missions for advanced space weather measurements (Action #6).

1. Introduction

In October 2015, the National Science and Technology Council (NSTC) published two documents prescribing the Federal government approach to protecting the nation from the deleterious effects of space weather. These documents, the *National Space Weather Strategy*¹ and the *National Space Weather Action Plan*² (herein *Action Plan*), outline a number of recommendations to enhance and improve the ability of society to understand, forecast, and mitigate the effects of phenomena in outer space that are able to harm modern technological systems.

¹ <u>https://www.whitehouse.gov/sites/default/files/microsites/ostp/final_nationalspaceweatherstrategy_20151028.pdf</u> ² <u>https://www.whitehouse.gov/sites/default/files/microsites/ostp/final_nationalspaceweatheractionplan_20151028.pdf</u>

This White Paper discusses how the existing and future assets and facilities of the National Solar Observatory (NSO) can be an essential component of the *Action Plan*. The facilities of the NSO's Integrated Synoptic Program (NISP) are already available with cost-effective components that provide key inputs to many space-weather modeling efforts. With its unprecedented spatial resolution and sensitivity, the 4-meter aperture Daniel K. Inouye Solar Telescope (DKIST) under construction in Hawai'i will produce transformational observations of the physical processes underlying space-weather phenomena. We outline here a vision for consolidating and improving the contribution of the NSO to the National Space Weather Strategy in partnership with the national and international solar physics research communities.

The Federal approach includes six strategic goals, of which NSO can substantially contribute to two, namely No. 5: *Improve Space-Weather Services through Advancing Understanding and Forecasting*, and No. 6: *Increase International Cooperation*. The *Action Plan* document further refines objectives for all of the strategic goals, with the most relevant for this White Paper being:

- **5.3** Establish and Sustain a Baseline Observational Capability for Space-Weather Operations.
- **5.4** Improve Forecasting Lead-Time and Accuracy.
- **5.5** Enhance Fundamental Understanding of Space Weather and Its Drivers to Develop and Continually Improve Predictive Models.
- **6.2** Increase Engagement with the International Community on Observation Infrastructure, Data Sharing, Numerical Modeling, and Scientific Research.

This White Paper includes strategic actions which the National Solar Observatory could carry out, provided there is sufficient community and agency interest as well as funding support.

2. NSO's Contributions to Section 5.3: "Establish and Sustain a Baseline Observational Capability for Space-Weather Operations."

The Action Plan document states that:

5.3.4 DOC and DOD, in coordination with NSF, will sustain or enhance ground-based solar imaging, including solar magnetic field and H-alpha data for operational forecasting.

Deliverable: Achieve sustained measurement and data continuity for at least 10 years.

Timeline: Continuous

NSO currently contributes to this specific action by regularly performing relevant ground-based observations as part of the NISP mission. Compared to similar observations made from space, ground-based data have some clear advantages:

• Lower Cost – Space platforms typically require several hundreds of millions of dollars to develop, launch, and operate, while similar ground-based system costs are generally many times less.

- Repairable With very rare exceptions it is not possible to repair space platforms when they suffer failures. This is especially true for operational solar missions, which are typically inserted into orbits (such as geosynchronous or Lagrangian point orbits) far beyond near-Earth altitudes.
- Upgradable The inaccessible nature of space platforms also precludes the ability to improve systems with new technology.
- Higher Data Rates Deep space data return rates are generally many times slower and far more expensive than what is achievable with current Internet technology.
- Less Vulnerable to Space Weather All space missions are inherently exposed to space weather. Ground-based systems are shielded by the Earth's atmosphere and magnetosphere.
- Long continuity Continuing ground-based observations of many space weather drivers extend decades prior to the space age. Such observations bridge periods when space observations may not be available.

As a major disadvantage, ground-based instruments are wavelength limited, precluding observations of some solar phenomena. This disadvantage, however, can be partially mitigated by ground observations at radio wavelengths and also by using spectrum lines formed above the solar surface. For example, the NSO's daily ground-based observations of coronal holes (the main sources of high-speed solar wind) starting in 1974 were for decades the only regular source of coronal hole information.

NSO has operated the Global Oscillation Network Group (GONG) facility since 1995. GONG comprises six observing stations around the world in California, Hawai'i, Australia, India, Spain and Chile, and provides observations of the full-disk solar longitudinal magnetic field component, Doppler velocity, and H-alpha intensity every minute, 24/7, with nearly continual temporal coverage (median daily observing fraction of 0.91). While originally developed for helioseismology, GONG magnetic field and H-alpha data are now essential inputs to the Space Weather Prediction Service Center (SWPC) forecast models, the US Air Force Research Laboratory (AFRL) ADAPT model of the solar magnetic field, the US Air Force 557th Weather Wing forecasts, and the NASA Goddard Community Coordinated Modeling Center (CCMC) suite of models. This NSO activity has resulted in intermittent funding support for operations from the US Air Force, DOC/NOAA, and NASA/Heliophysics. In addition, the NSF has included a potential FY 2016 budgetary line item for GONG refurbishment to improve the operational capabilities of the network and ensure its continuity for an additional 10 to 15 years. The current plan for this opportunity is to replace obsolete components, improve the measurements of the solar magnetic field by increasing measurement accuracy, and to add the capability of measuring the Doppler shift of the H-alpha spectral line to measure the progression of filament activations in the chromosphere that frequently precede powerful coronal mass ejections (CMEs).

NSO also operates SOLIS (Synoptic Optical Long-term Investigations of the Sun), an instrument package comprising a vector spectromagnetograph (VSM), a full-disk patrol (FDP), and an integrated sunlight spectrometer (ISS). The VSM provides daily, basic measurements of the strength and direction of the Sun's magnetic field that are vital for forecasting the activity that causes space weather. Recently, the VSM has been upgraded to regularly provide unique measurements of the magnetic field at a height where magnetic forces dominate over other plasma forces. This development will allow improved models of the geo-effectiveness of CMEs (see discussion below). The FDP provides high-cadence full-disk images of the Sun corresponding to different heights in solar atmosphere, including the chromospheric H-alpha and He I lines, needed to determine the morphology and evolution of solar flares and associated activity. The ISS provides spectra of the Sun summed over the entire solar disk. The ISS data are helpful in interpreting solar irradiance space measurements that serve as input for Earth climate models.

NSO Strategic Action #1

NSO, through continuing operations of GONG and SOLIS, significantly contributes to action 5.3.4. Ensuring GONG functionality for one more decade requires replacement of aging components and new operational capabilities available only if the funding line for GONG refurbishment proposed in the FY 2016 President's Budget Request is realized. NSO's GONG refurbishment plans are ready to execute.

The Action Plan anticipates new instrumentation for space weather observations:

5.3.9 DOC, in coordination with NASA, DOD, and NSF, will produce a plan for deployment of new operational space-weather-observing assets to provide the baseline measurements outlined above. The plan will prioritize and define the required fidelity, cadence, and latency of ground-based and space-based measurements.

Deliverable: Complete prioritized plan to provide baseline space-weather observations

Timeline: Within 2 years of the publication of this Action Plan

In addition to a refurbished GONG, NSO is involved in an international collaboration aimed at developing the next-generation solar observing network. This network, known as SPRING (Solar Physics Research Integrated Network Group), would replace both the 1980's technology GONG and the 1990's technology SOLIS. SPRING is envisioned to provide vector magnetic field and Doppler velocity measurements in multiple wavelength bands that will sample the solar atmosphere at a number of different physical heights. A novel target for SPRING relevant to space weather modeling will be the synoptic measurements of the vector magnetic field in solar filaments, the core structures of many CMEs. This has the potential to greatly improve the input boundary conditions that drive the simulations that underlie space weather forecasts. SPRING would provide a flexible observing infrastructure, utilizing a design that would allow a number of different instruments for specific observations with fewer compromises; the freedom to match the instrument set with the site characteristics; and an additional ability to cope with evolving technology and funding scenarios. SPRING is necessarily an international

project. The study phase has been led by the Kiepenheuer-Instut für Sonnenphysik (KIS) in Germany, where the science requirements are being written and instrumental concepts are being developed in collaboration with NSO and other international (mostly European) partners.

NSO Strategic Action #2

NSO will provide the necessary experience and leadership to define a new world-wide synoptic network, SPRING, targeted at producing space-weather relevant data: from vector magnetic field descriptions of the massive cores of many coronal mass ejections to improved far-side images of the magnetic activity on the Sun.

3. NSO's Contributions to Section 5.4: "Improve Forecasting Lead-Time and Accuracy."

Useful space weather predictions require an improved forecasting lead-time, consequently, the *Action Plan* document proposes:

5.4.2 NASA, DOC, DOD, and NSF will support the development of novel sensor technologies and instrumentation to improve forecasting lead-time and accuracy.

Deliverable: Complete assessment of technology needs

<u>Timeline</u>: Within 1 year of the publication of this Action Plan

When the Sun is quiet, it has long been possible to forecast solar wind properties at Earth with useful accuracy. But the most severe geomagnetic storms are produced by unpredictable, fast, massive CMEs with strong, southward-directed magnetic fields. Currently, the magnetic field inside a CME cannot be measured since the outer, coronal parts of CMEs are too faint to measure with today's instrumental sensitivities. DKIST will provide the highest coronal sensitivity yet available due to its large 4-meter aperture and advanced instrumentation and may intermittently observe the magnetic field direction of CMEs erupting near the solar limb.

The inner, dense core regions of many CMEs are observable against the solar disk facing Earth and are more amenable to accurate magnetic field and velocity determinations. Mapping the magnetic field of solar filaments that populate many CME cores during an ejection is expected to improve modeling of their evolution in interplanetary space, and to provide strong clues about the field orientation upon arrival at Earth. These measurements are best made with chromospheric lines and at high polarimetric sensitivities. Achieving high sensitivity requires optimization of many instrumental properties, but especially the detector. Routine measurements performed in a synoptic manner by a SPRING-type network, or at high spatial resolution by DKIST, will enormously benefit from bi-dimensional detectors specifically tailored for polarimetric measurements. Such detectors should have two principal properties: fast readout rates and multiplexing capabilities in each pixel. Detectors combining some of these properties exist in various forms (in the US and Europe) and recent advances in detector technology are truly remarkable, but no optimized detector has been developed yet for precise magnetic field observations relevant to space weather.

Optimized detectors will enhance the polarimetric capabilities of a SPRING-type network and the DKIST facility, and NSO has all the necessary expertise to lead the development and evaluation of such specialized detectors. These detectors will make accessible polarimetric sensitivities well below current specifications to the DKIST, providing access to magnetic regimes never observed in stars.

NSO Strategic Action #3

Continuous improvements of sensor technology have helped to achieve higher magnetic field sensitivities with existing telescopes, but no specific detector optimized for such measurements has been developed. Through a partnership with national industry and other research institutions, NSO proposes to develop fast readout detectors with multiplexing capabilities.

The development of metrics needed to improve the quality of space weather observations is proposed in the *Action Plan*:

5.4.3 NASA, DOC, DOD, and NSF will prioritize and identify needs for improved coverage, timeliness, data rate, and data quality for space-weather observations, and opportunities to address these needs through collaborations with academia, the private sector, and international community.

Deliverable: Develop a report with priorities and recommendations

Timeline: Within 1 year of the publication of this Action Plan and every year thereafter, as necessary

The NSO maintains a vigorous scientific and technical staff that has been performing research in the solar physical processes that underlie space weather since the 1950s. The staff is constantly developing improved instrumentation, observational programs, and analysis techniques to advance our knowledge of the Sun and space weather. The collective experience of the NSO in these areas is available to the community and the agencies to help prepare studies of the needs and most useful data sets for space weather. Existing collaborations include NOAA, US Air Force, NASA and international partners.

4. NSO's Contributions to Section 5.5: "Enhance Fundamental Understanding of Space Weather and Its Drivers to Develop and Continually Improve Predictive Models."

Space weather is a developing area of research that needs quantitative and qualitative progress in our understanding of the physics behind its fundamental sources before robust predictions can be routinely available. To this end, three related actions targeted at enhancing our knowledge of these space weather sources are proposed in the *Action Plan*.

5.5.1_NSF and NASA, in collaboration with DOC and DOD, will lead an annual effort to prioritize and identify opportunities for research and development (R&D) to enhance the understanding of space weather and its sources. These activities will be coordinated with existing National-level and scientific studies. This effort will include modeling, developing, and testing models of the coupled sun-Earth system and quantifying the long- and short- term variability of space weather.

Deliverable: Document R&D priorities

<u>Timeline</u>: Within 1 year of the release of this Action Plan and every year thereafter, as necessary

5.5.2 NASA, NSF, and DOD will identify and support basic research opportunities that seek to advance understanding of solar processes and how the sun's activity connects to and drives changes on Earth and its near-space environment.

Deliverable: Announce and provide financial awards that enhance basic research in this area

Timeline: Within 1 year and sustained thereafter

5.5.3 NASA, DOC, and DOD will identify and support research opportunities that seek to address targeted operational space-weather needs.

Deliverable: Announce and provide financial awards that enhance basic research in this area

Timeline: Within 1 year and sustained thereafter

NSO has more than six decades of experience and leadership in these precise research areas, and has long provided instrumentation, analysis software, observing programs, research projects and data products to both the research community and mission agencies. The accumulated experience of hundreds of years of researcher effort in solar physics and space weather origins is available to the relevant agencies as they formulate their plans for future research and development.

To promote improvements in space weather predictive modeling, the NSO Integrated Synoptic Program (NISP) scientific staff is already developing innovative observations and data products. Recent efforts have centered on data quality improvement, determination and propagation of observational uncertainties to prediction reliability, and to provide more physically meaningful boundary conditions. NSO scientific personnel will continue close collaborations with the modeling community in order to focus limited resources where they will provide the most benefit to modelers.

Some developmental data products provided by the NISP should lead to improvements in existing space weather models. For example, most space weather predictive models rely on observations of the line-of-sight component of the photospheric magnetic field as an input boundary condition. This is well known to be far from optimum for at least two reasons. On the one hand the photosphere is a region where plasma forces overcome magnetic forces, and the

magnetic field measured at this layer is not well suited as input to extrapolation methods that assume magnetic forces are dominant. Measurements made higher up, in the chromosphere and above, are a more ideal input boundary for extrapolation. Such measurements are routinely being done by the SOLIS/VSM but are not yet fully exploited. Second, one would ideally introduce into these models either the radial (instead of the longitudinal) component of the magnetic field, or, better yet, the full vector as input. Further work is needed to develop existing heliospheric models to the point where they can assimilate such data—an interesting example being the adaptive models developed by the US Air Force that includes NSO participation. Close coordination among all of the involved parties is needed to make progress in this fundamental area.

This discussion assumes that inference of the magnetic field is made in a rather precise way from the corresponding solar observations. But also here one faces serious challenges that need further research. The magnetic fields on the Sun are inferred indirectly via their signature in the polarization of specific spectral lines. But the mapping between polarization in spectral lines and magnetic fields is far from trivial. This mapping needs to include fundamental atomic processes, plasma physics phenomena, and photon-matter interactions that in some cases are not yet well understood. NSO and other institutions, most prominently the High Altitude Observatory, National Center for Atmospheric Research (HAO/NCAR), have established collaborations to implement highly complex numerical codes that allow precise mapping between the polarization signatures and the magnetic fields. While some of the basic inference algorithms are well understood-Milne-Eddington or Local Thermodynamic Equilibrium inversions—other more realistic models need more basic research—Non-local Thermodynamic Equilibrium inversions and polarization induced by scattering processes and the Hanle effect, whose research concentrates almost exclusively in Europe. DKIST will be the first facility that will produce crucial observations of the tenuous solar corona with the required spatial resolution and sensitivity that will benefit from a community effort that makes transformational progress in these fields.

NSO Strategic Action #4

As part of a community effort, NSO will continue collaborating with our stakeholders and partners to further develop fundamental areas of research needed to consolidate space weather physics and its prediction capabilities. Areas that need special attention are the development of methods to incorporate chromospheric vector field measurements into heliospheric models, and numerically robust codes that translate polarization measurements into magnetic field vectors.

The novel character of this research makes these areas particularly appealing to graduate experiences and PhD programs.

5. NSO's Contributions to Section 6.2: "Increase Engagement with the International Community on Observation Infrastructure, Data Sharing, Numerical Modeling, and Scientific Research."

International cooperation in solar and solar-terrestrial research has been strong since the nineteen century. Such partnerships are natural given the global effects of the Sun and space weather. While some nations are more affected by space weather processes than others, interest has increased over the last few years in both developed and emerging countries. The *Action Plan* describes pathways to strengthen international collaborations in space weather research and proposes:

6.2.2 DOC and DOI, in coordination with NASA and NSF, will explore opportunities to leverage international partnerships to sustain baseline operational space-weather-observing capabilities.

Deliverable: Complete report on international partnerships

<u>Timeline</u>: Within 1 year of the publication of this Action Plan and every year thereafter

NSO has a long history of international cooperation dating to a time when other countries did not have competitive solar research facilities and used NSO's facilities for cutting-edge research. More recently, the GONG network has locations in Chile, Australia, India, and Spain, and could not operate without substantial support from these international partners. A group in Brazil is currently designing an instrument similar to the SOLIS/VSM with substantial input from NSO. The DKIST project involves instrumentation teams from Germany and the United Kingdom, and has strong ties to other European solar physics communities.

Finally, planning for the SPRING network is already heavily international, with the KIS (Germany) and the NSO currently developing the science requirements document and potential instrument concepts. These existing international partnerships facilitate the process of developing new paths to further collaborations for operational and research capabilities.

NSO Strategic Action #5

By the timeline proposed in 6.2.2, NSO will submit a proposal to the NSF describing the SPRING network, its value to space weather monitoring, potential costs and timeframe. The proposal will include a list of national and international partners built upon the GONG experience.

Via its leadership of the International Astronomical Union working group on Coordination of Synoptic Observations of the Sun, a broad international coordination of synoptic programs, the NSO is actively promoting the development of standards for data uniformity and identification of observational data necessary for a successful space weather forecast. Close coordination of the national programs will reduce unnecessary duplication of efforts to collect the data, and will improve the quality and uniformity of data products.

Other areas amenable to international partnerships are space missions that invariably attract the interest of other nations. The *Action Plan* explicitly mentions:

6.2.3 DOC and NASA will collaborate with academia, the private sector, and the international community to explore the potential benefits and costs of space-weather missions in orbits complementary to the sustained missions at the L1 Lagrangian point, which may include missions at the L5 Lagrangian point. Such missions may improve monitoring of CME properties and trajectories relative to Earth.

Deliverable: Complete analysis of space-weather missions in orbits complementary to sustained missions.

Timeline: Within 1 year of the publication of this Action Plan

NSO staff members have been involved in many past solar space missions, including Skylab, Spacelab 2, SMM, Yohkoh, SOHO, Stereo, SDO, IRIS, and TRACE, as Co-Is and collaborators to provide research support and planning advice. NSO also participates in the two upcoming solar missions under development, Solar Orbiter and Solar Probe Plus. The possibility of an L5 Lagrangian point mission is particularly attractive to NSO as it will provide exciting research capabilities in addition to the potential improvements to space weather forecasts. Our GONG network already provides the Earth's viewpoint from the ground. Combinations of the L1 and L5 Lagrangian viewpoints open a new set of research opportunities. Examples are stereo helioseismology, far-side imaging improvements, and stereo views of the magnetic field. The recent relocation of NSO headquarters to Boulder has resulted in a strong partnership between NSO and the Laboratory for Atmospheric and Space Physics (LASP). LASP has designed, fabricated, and operated a number of space missions, and NSO is developing a plan with LASP to provide a light-weight magnetograph. NSO has unique expertise in components key to lightweighted versions of existing magnetographs: from liquid crystal based polarization analyzers to ultrathin solid etalons for spectral recording. However, the adaptation of these technologies to future instrumentation requires a technology development. NSO is collaborating in the UKled Carrington L5 mission development, and its staff members are available to the agencies to explore a cost-benefit analysis of the concept.

NSO Strategic Action #6

NSO is actively developing light-weight magnetograph concepts that can be easily accommodated into medium-size space missions. We also continue to seek with interest our participation in future space weather relevant missions, in particular in areas such as data management and distribution.

6. Conclusion

The National Solar Observatory has been a leader in ground-based solar physics research and its space weather consequences for more than six decades. NSO accomplishments include the development, design, construction, and operation of several major facilities such as DKIST, GONG, SOLIS, the McMath-Pierce Solar Telescope, the Kitt Peak Vacuum Telescope, and the Dunn Solar Telescope, all of which have been provided to the international solar community for research. The US Air Force SOON solar monitoring facilities were designed and developed at NSO. NSO produces several data sets that are now being routinely used in space weather operational forecast systems. NSO is fully committed to serving society through fundamental solar physics research, and by obtaining the basic data needed to drive space weather forecasts. We will continue strengthening our role as a major (coordinating) center for ground-based solar and space weather related observations in the US and internationally.

NSO is prepared and qualified to be an active participant in the *National Space Weather Strategy* and *Action Plan*.

ACRONYM GLOSSARY

ADAPT	Air Force Data Assimilative Photospheric flux Transport
AFRL	Air Force Research Laboratory
AFWA	Air Force Weather Agency
AURA	Association of Universities for Research in Astronomy, Inc.
CCMC	Community Coordinated Modeling Center (NASA)
CME	Coronal Mass Ejection
DKIST	Daniel K. Inouye Solar Telescope (formerly the Advanced Technology Solar
	Telescope (ATST))
DOC	Department of Commerce (US)
DOD	Department of Defense (US)
EU	European Union
FDP	Full-Disk Patrol (NSO/SOLIS)
GONG	Global Oscillation Network Group (NSO)
HAO	High Altitude Observatory (NCAR)
IAU	International Astronomical Union
IRIS	Interface Region Imaging Spectrograph (NASA Small Explorer Mission (SMEX))
ISS	Integrated Sunlight Spectrometer (NSO/SOLIS)
KIS	Kiepenheuer-Instut für Sonnenphysik (Freiburg, Germany)
LASP	Laboratory for Atmospheric and Space Physics (University of Colorado)
NASA	National Aeronautic and Space Administration
NCAR	National Center for Atmospheric Research
NISP	NSO Integrated Synoptic Program
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NSO	National Solar Observatory
NSTC	National Science and Technology Council
SDO	Solar Dynamic Observatory
SMEX	Small Explorer Mission (NASA)
SMM	Solar Maximum Mission (NASA)
SOHO	Solar and Heliospheric Observatory (NASA)
SOLIS	Synoptic Optical Long-term Investigations of the Sun (NSO)
SOON	Solar Observing Optical Network (US Air Force)
SPRING	Solar Physics Research Integrated Network Group (European Union)
SWPC	Space Weather Prediction Service Center (NOAA)
TRACE	Transition Region And Coronal Explorer (NASA)
UK	United Kingdom
US	United States
VSM	Vector Spectromagnetograph (NSO/SOLIS)
Yohkoh	or "Sunbeam"; Solar Mission of the Japanese Institute of Space &
	Astronautical Science (ISAS)