CONNECTING OUR STAR AND OUR HOME

High Altitude Observatory Implementation Plan

Abstract

This Implementation Plan outlines the steps required to maximize the return on our strategic planning efforts, benefiting HAO, the NCAR community, and the global solar-terrestrial physics community. It leverages HAO's historical strengths in solar spectropolarimetry, solar atmospheric dynamics, and terrestrial upper atmospheric physics to address scientific problems at the Sun-Earth connection. The plan details the roles of Strategic Working Groups (SWGs) and Science Task Groups (STGs) in driving core area efforts, developing instruments and models, and addressing specific scientific challenges. It emphasizes flexibility in participation due to limited base funding and highlights the alignment of these activities with HAO priorities to attract external funding. The plan also describes the operational structure, led by the HAO Director and key department heads, and the advisory framework, consisting of internal and external committees, to support and guide HAO's research and strategic initiatives.

HAO Staff

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Introduction

This Implementation Plan outlines the steps required to ensure the maximum return on that our strategic planning. A return that has benefits beyond HAO, into the NCAR community and the worldwide solar-terrestrial physics community.

As it stands, this implementation plan exploits the three historical bases of HAO science in solar spectropolarimetry, solar atmospheric dynamics, and terrestrial upper atmospheric physics to attack scientific problems at the crucial boundaries of the Sun-Earth connection. In addressing these problems, established in the strategic challenges and goals of the Strategic Plan, we will build observational and modeling capability that will actively involve the worldwide solar-terrestrial physics community.

HAO's staff will be challenged to participate in strategic working groups (SWGs) focused on core capabilities, including instrument and model development and analysis techniques to pursue the goals of the strategic plan. Additionally, more targeted and specific scientific problems will be addressed through ad hoc Science Task Groups (STGs). The SWGs, STGs, and core areas will form the scientific operating structure for the Laboratory and the basis for our budgetary planning. It is hoped that all staff will engage in pushing HAO and community science forward in addition to forming a concentrator for larger team proposal efforts. Early-career staff will be included in the SWGs, STGs, and core areas to facilitate career development when possible. The function of the *core capability* based SWGs is described below. We note that "*core capabilities*" are different from "core areas" described below. Namely, *core capabilities* refer to the critical elements necessary to achieve our goals, and core areas are where those capabilities are applied.

The limited nature of HAO's base budget requires considerable flexibility on the part of HAO's staff and visitors when participating in these working groups and task groups. *Not all working group and task group activities will obtain substantial levels of base funding.* As a result, staff and visitors should use best judgement when joining these efforts to make sure that their commitment is aligned with their funding profile. They should also bear in mind that the activities being undertaken are to build scientific capability that benefits the entire laboratory and the broader community—*it is anticipated that said the specific research activities will increase the likelihood of attracting external funding that is clearly aligned with the HAO priorities in the future*.

Grand Challenges and Goals

The strategic plan of the High Altitude Observatory (HAO) outlines detailed grand challenges and goals that are crucial to advancing our understanding of solar-terrestrial physics. These challenges include improving predictive capabilities for space weather, understanding solar variability and its effects on climate, and maintaining and upgrading observational facilities. To address these, HAO has set specific goals such as enhancing space weather prediction models, expanding knowledge of solar impacts on climate, advancing observational technologies, and fostering a collaborative research environment. The full details of these grand challenges and goals are comprehensively described in the strategic plan but for easy of reference we provide the high-level summaries here.

Grand Challenges

1. Identify the processes responsible for the origin and the evolution of solar magnetism.
2. Quantify the signatures of magnetism and the role of magnetic energy in the production of solar activity throughout the solar atmosphere to build a comprehensive understanding of solar atmospheric coupling and solar wind formation.
3. Explore the relationship between the solar plasma and magnetism that result in the measured distributions of electromagnetic radiation.
4. Determine the range of impact that solar variability can have on the coupled terrestrial atmosphere and the geospace environment along with lower atmosphere impacts on geospace.
5. Characterize coupling between different layers of the atmosphere-geospace system.
6. Explore the interactions between neutral and ionized gases within the extended geospace environment.

Goals

I. Solve critical problems of solar-terrestrial physics.
II. Improve capabilities to assess space weather and space climate hazards.
III. Develop, deploy, and maintain state-of-the-art observational facilities and science data services.
IV. Advance and support sophisticated models of the Sun-Earth system.
V. Identify, develop, and transfer critical knowledge of the Sun-Earth system to the community, the public, and other stakeholders.
VI. Educate and mentor a talented group of undergraduate and graduate students.
VII. Educate and mentor a talented group of postdocs and early-career solar-terrestrial scientists.

Strategic Working and Task Groups

The strategic working groups (SWGs) and strategic task groups (STGs) play distinct but complementary roles in advancing the High Altitude Observatory's mission. SWGs are structured around the foundational capabilities of HAO, supporting the community as they address long-term, critical problems within the Sun-Earth discipline. These groups are permanent, with defined charters and memberships, including broader community involvement, and are led internally by HAO-appointed leaders. They support efforts in core areas, manage projects, develop web content, and engage the community through workshops and outreach initiatives. In contrast, STGs are ad hoc and flexible, forming annually based on immediate strategic challenges and needs. These groups are funded through a competitive internal process, addressing specific, short-term problems with the aim of building broader capabilities. Unlike the permanent SWGs, STGs are temporary, dissolving after their objectives are met, ensuring responsiveness and adaptability to evolving research priorities.

Strategic Working Groups

SWGs are developed around core capabilities and will be focused on supporting the community in tackling tough, fundamental physical problems with a desire that outcomes help build capability across the Sun-Earth discipline. The SWGs will support core areas (see below) to help advance strategic priorities of the lab, establish their own charter and membership (which may include external members) with internal leadership appointed by the HAO Director. SWGs will hold meetings, engage broader community input, and specifically use visitor funds, post-doctoral, and affiliate scientist positions within HAO. Group leads will provide overarching project management, develop web content around their activities, provide input into group members year-end reviews, and be responsible for reporting activities around the effort.

The set of current HAO SWGs comprise:

- Geospace Community Modeling
    - A group dedicated to the development and maintenance of HAO's leadership and heritage in community geospace modeling activities.
    - Leaders: Gang Lu, Hanli Liu
- Data Assimilation Across Disciplines
    - A group dedicated to the development and utilization of best practices in data assimilation for the betterment of understanding that (ultimately) leads to better forecast skill across the geospace discipline.
    - Leaders: Nick Pedatella, Mausumi Dikpati
- Community Partnerships & Data Stewardship
    - A group charged with understanding who our community is, understanding community needs, ensuring effective interface to the community, and acting as a conduit to staff groups to implement tools and products as appropriate. This team is charged with overseeing HAO's data products, simulation output, website content (macro-level), user databases, metrics, etc. This group is also charged with developing a framework for one data interface, maintaining it, and cultivating a comprehensive list of HAO's community worldwide.
    - Leaders: Rebecca Centeno Elliott, Mike Galloy

Strategic Task Groups

STGs will develop around the strategic challenges stated above and will be focused on immediate strategic challenges and needs. In contrast to the SWGs, STGs are ad hoc and can form and be dissolved yearly, depending on relevance, needs, and outcomes. These focused groups will tackle specific problems and will be funded through an internal competitive process. Short proposals will be solicited yearly, and an advisory committee will review and provide the HAO Director with selection recommendations. A budget of base funds will be held to fund STGs, and a cadence of solicitation will be decided after a pilot program of one year. Although the available funds will vary year to year, this identified pot of funding will be at least $100k/year. STGs may leverage other types of funds, especially when aligned with other current programs. After the program is in place for one full year, the EAC will be asked to review its effectiveness.

Core Areas

The core areas serve as the focal points of our efforts, facilitating robust community interaction and collaboration within the High Altitude Observatory. These programs are integral to supporting the initiatives of both the Strategic Working Groups (SWGs) and Strategic Task Groups (STGs), ensuring that our collective efforts are aligned and impactful. The six core areas encompass the full spectrum of science conducted by the observatory, including observations, theoretical research, and modeling of the Sun and Earth. By addressing broad scientific challenges, these core areas foster a comprehensive and dynamic approach to advancing our understanding of the Sun-Earth system.

The six core areas are:

- Observations: MLSO/COSMO/FPIN
- Space-based Mission Work
- Spectropolarimetry
- Solar Modeling Suite
- Geospace Atmosphere System
- WACCM-X

Observations: MLSO/COSMO/FPIN

Delivery of the COronal and Solar Magnetism Observatory (COSMO) is this core area's highest priority. Significant funding from the NSF for the COSMO Site and Design Advancement (COSADA) program has led to major progress toward the realization of this goal and reducing risk. Progress has been made in building the COSMO community – largely by leveraging observations from current MLSO instruments, UCoMP and K-Cor to cement the case for COSMO and to demonstrate its utility in fundamental synoptic science and for significantly advancing our understanding of space weather processes. A kickoff UCoMP users meeting brought scientists from around the world to HAO in September 2023, and we plan to continue these community building efforts through further workshops and the dissemination of MLSO data and analysis tools (the next one will be in Spring-Summer of 2025). In addition, we have active COSMO engagement from NCAR/UCAR's Government Relations and Communications offices. We report on all these efforts and receive recommendations for COSMO telescope design and community engagement from a COSMO Steering Committee that is made up of external members.

Internally, we hold biweekly UCoMP science lunches and are actively promoting the involvement of early career scientists in MLSO science and operations. Moving forward, an important goal is to clarify and strengthen the connections between MLSO and COSMO and to develop and communicate our vision for HAO solar ground-based observations. Another goal is to continue supporting solar eclipses via MLSO observations and exploring how eclipses can advance instrumentation.

We are working on expanding the thermospheric and mesospheric wind observation network to understand the inputs to the ionosphere thermosphere from above and below. HAO is operating, augmenting, and updating our Fabry Perot interferometer network. We added an FPI at Korhogo, Ivory Coast for equatorial dynamics study. We will propose to build and deploy four FPIs in the high Arctic to the equator to form meridional chain in Europe/Africa sector and mid and low latitude longitudinal networks to study migrating and nonmigrating tides and to track geomagnetic storm disturbances from high to low latitudes. One of the four FPIs will be at MLSO. The MLSO FPI is particularly important for understanding vertical coupling between the lower atmosphere and the ionosphere and thermosphere. The MLSO FPI combined with observations from Korhogo Ivory Coast, South America, and Southeast Asia will help determine nonmigrating tides in the equatorial region, which are known to modulate the ionosphere equatorial dynamo. The topic is of great interest for space weather and NCAR global model development, such as the Whole Atmosphere Community Climate Model (WACCM), and its extension into the ionosphere and thermosphere (WACCM-X) and the Multiscale Atmosphere-Geospace Environment Model (MAGE).

Space-based Mission Work

Leadership in space-based mission opportunities are becoming a higher priority in HAO's portfolio and new partnerships with industry, academia, and government agencies play a large role in facilitating our presence in space. We have a unique position of enhancing the synergies between ground-based and space-based solar observatories. Current collaborations include two NASA Heliophysics Small Explorer (SMEX) missions: PUNCH (launched in 2025) and CMEx (led by HAO, selected for Phase A in 2023), the WindCube cubesat (led by HAO, selected for launch 2026), CLARO (small mission concept in development, led by HAO), and several coronagraph opportunities. Future opportunities include instrumentation on NASA MIDEX and Decadal missions as well as smaller Mission of Opportunity (MoO) missions.

Spectropolarimetry

The magnetism of our Sun and its evolution at various temporal scales, spanning from minutes to decades, is responsible for all phenomena of space weather and space climate that have a direct impact on Earth. HAO has a long heritage of observational studies of solar magnetism through the modeling and interpretation of the polarization signatures of magnetic fields in the solar spectrum. Scientists at HAO, in close collaboration with the wider domestic and international heliophysics communities, advance this field by developing new spectropolarimetric instruments for both ground-based and space-borne observations of solar magnetism (e.g., the DKIST/ViSP, ChroMag, UCoMP, CMEx, CLARO), through the theoretical investigation and improved numerical modeling of the Sun's polarized spectrum, and by exploiting new computational capabilities to develop state-of-the-art inversion tools that can decipher the polarization signatures of the solar spectrum to infer the thermodynamic and magnetic properties of the solar atmosphere.

Solar Modeling Suite

HAO develops models to study solar eruptions including processes such as flux emergence in the convection zone, evolution of active regions, flares and CME initiation and propagation of CMEs through the inner heliosphere. For this purpose, HAO uses a combination of models, including a (M)HD shallow-water model (tachocline dynamics), MURaM (upper convection zone to lower corona, including detailed radiation transport in local domain), MFE (lower corona to heliosphere, local and global) and GAMERA (propagation of CMEs through inner heliosphere). HAO also models the physical mechanisms that translate solar magnetic and plasma properties into spectropolarimetric observables (e.g. CLE, Hanle-RT), allowing direct comparison of simulations which allow for modeling of physical details and the comparison with observations through the forward modeling of solar synthetic observables. With the development and incorporation of data-driving and data-assimilation into these MHD models using observations of the solar atmosphere at multiple heights, HAO aims to determine the realistic magnetic field evolutions of solar eruptive events, which provide the critically important information for predicting their space weather impact.

Geospace Atmosphere System

As part of our efforts to develop a whole geospace model we will collaborate with the community on the development of a simulation system capable of modeling the coupled magnetosphere, ionosphere, thermosphere and lower atmosphere. This modeling system will have resolution to examine the roles mesoscale structures have in the dynamic response of geospace to solar wind and radiation driving conditions. Drawing upon the data assimilation and atmospheric modeling capabilities throughout NSF NCAR our efforts will also be able to examine the relative importance of the system response to driving from the solar wind and forcing from the atmosphere. Our efforts will draw up NSF NCAR's existing infrastructure in modeling, software engineering, and high-performance computing to create a truly open-source system with community researchers not just using the model but contributing to its development.

WACCM-X

As a joint effort of NCAR's Community Earth System Model (CESM) and the System for Integrated Modeling of the Atmosphere (SIMA), the new species-dependent spectral element dynamical core and regirding scheme have been developed, and will be part of the upcoming CESM3 release, scheduled for FY25. The new development enables high-resolution, ~25 km horizontally, capabilities and the study of the multiscale processes in the whole atmosphere system. A whole atmosphere nature run using the high-resolution capability has been completed and used to support upcoming NASA missions and will provide abilities needed for analysis of their observations. Further capability development is under way to incorporate field-line based ionospheric dynamo module into WACCM-X.

WACCM-X has been used as the physics model, along with the DART ensemble Kalman filter, to assimilate the meteorological, middle and upper atmosphere observations for accurate specification and research forecast of the mesosphere, thermosphere and ionosphere. The WACCM-X+DART system will be used to regularly produce atmospheric reanalysis products. As a key partner of the NASA CGS DRIVE Center and SWORD Space Weather Center of Excellence, we will work with our community collaborators to advance community modeling capabilities and space weather forecasting. This includes building WACCM-X into the MAGE modeling system and advancing existing data assimilation capabilities in WACCM-X. We will work closely with CESM, SIMA, MAGE and SWORD and continue supporting the community usage of WACCM-X model and its data products.

Connections to NCAR

We will maintain synergistic activities within CESM and have contributed to SIMA multi-laboratory program to continue development on WACCM and WACCM-X, which is leading the way to a unified model of the Geospace environment across a wide range of temporal scales. The WACCM-WACCMX/MPAS developments will provide us the opportunity to run a whole atmosphere model with a non-hydrostatic dynamical core. These activities will be performed in collaboration with the Atmospheric Chemistry Modeling and Observation (ACOM), Climate and Global Dynamics (CGD), and Mesoscale and Microscale Meteorology (MMM) laboratories of NCAR. In coming years, the data assimilation methodologies being developed in the Computational Information Systems (CISL) and Mesoscale and Microscale Meteorology (MMM) laboratories can help us to use ionospheric and solar observations to move space weather forecasting along a critical upgrade path, as is being done for terrestrial weather forecasting.

In its development of instrumentation projects, HAO frequently benefits from the workshop facilities and expertise of the Earth Observing Laboratory (EOL). With total solar eclipse field campaigns, we aspire to open aircraft-based solar observation to our community on a regular basis as an alternate means of validating new instrumentation.

The Earth System Predictability Across Timescales (ESPAT) initiative, led by NSF NCAR, is a comprehensive effort to accelerate scientific progress in understanding the predictability of the coupled Earth system including solar and geospace processes, with the ultimate goal of enhancing societal resilience to natural hazards such as hurricanes, wildfires, and space weather events. These space weather events can significantly disrupt satellite operations, communications, navigation, and power infrastructure, posing risks to national security and the global economy. ESPAT emphasizes the need for breakthroughs in observations, data assimilation, modeling, and integration of AI and machine learning, as well as convergence research that brings together physical, computational, and social sciences in collaboration with government, academic, and operational partners. Among the initiative’s grand challenges are understanding interactions across the Sun-Earth system, determining how Earth system variability affects geospace predictability, and exploring how processes across scales shape atmosphere-geospace interactions.

Crucially, ESPAT advocates for user-informed and co-developed approaches to ensure that scientific advances lead to actionable insights and decision-making tools that support preparedness, response, and long-term resilience planning.

Convergence approaches aim to deeply integrate expertise across disciplines, sectors, and users, drawing on knowledge from natural, social, engineering, and computational sciences. In support of this, the NSF NCAR Directorate is developing a Convergence Science Program (CSP) to strengthen NSF NCAR's leadership in enabling and advancing convergence research in the field of Earth Systems Sciences. Convergence approaches closely align with the Decadal survey for solar and space physics (heliophysics) 2024-2033, which recognizes that integration across disciplines and with users will be key to improving the usability and relevance of predictability research across a range of timescales, including those related to solar activity and geospace variability. In response, HAO plans to develop convergence research efforts in collaboration with the NSF NCAR CSP over the coming years.

NSF NCAR envisions a future where AI and ML are integral to Earth system research at the organization, accelerating scientific discovery and improving our ability to understand and predict complex Earth system processes. Through collaborative engagement with the community, NSF NCAR is developing a comprehensive roadmap for the Community AI ecosystem that democratizes and accelerates innovation in AI capabilities for Earth System Science (ESS). This ecosystem will enable researchers across domains, including solar and geospacer physics, to effectively harness AI to advance our understanding of the Earth system while ensuring reproducibility, scalability, and broad accessibility of AI methods for the Earth System community. HAO contributes to and is a partner in this effort, advancing machine learning efforts occurring within the Lab.

Operational Structure

The operational structure of the High Altitude Observatory (HAO) is designed to facilitate efficient leadership and coordination across its various scientific and administrative functions. At the helm is the HAO Director, who provides overall strategic direction and oversight. Supporting the Director are the heads of key departments: Instrumentation, the Mauna Loa Solar Observatory (MLSO), the Lead Administrator, and the two science sections—Solar and Geospace. The Solar Frontiers section focuses on research and observations related to the Sun, while the Geospace Frontiers section concentrates on the Earth's atmospheric and space environment. This organizational framework ensures a cohesive approach to managing HAO's scientific initiatives and operational needs.

Advisory Committees

To support the operation and strategic direction of the High Altitude Observatory (HAO), a robust advisory framework is in place, consisting of both internal and external committees. The internal advisory committees, comprising HAO staff and leadership, focus on operational efficiency, scientific priorities, and internal policy development. Meanwhile, external advisory committees, which include distinguished scientists and experts from the broader scientific community, provide critical external perspectives, ensure alignment with the latest scientific advancements, and help foster collaborations. Together, these advisory committees play a vital role in guiding HAO's research endeavors, promoting excellence, and maintaining HAO's leadership in solar and geospace sciences.

Internal

Director's Scientific Advisory Committee (DSAC)

To advise the HAO Director on strategic matters affecting the Laboratory, including scientific direction and community engagement. DSAC is advisory to the HAO director and shall be composed of a cross section of scientists and engineers, including senior, mid-level, and early-career. A sub-group of this committee will review proposals for Science Task Groups (STGs) and advise on selections. The Appointments Committee is a standing sub-committee of the DSAC.

HAO Appointments Committee (AC)

To advise the HAO Director on personnel matters, scientific appointments, and promotions.

HAO Instrumentation Advisory Committee (HIAC)

Advises the HAO Director on the priorities of HAO's Instrumentation program and provide scheduling and strategic oversight of the Instrumentation Group (IG) and Mauna Loa Solar Observatory (MLSO).

Line of Business (LOB)

The HAO LOB helps set the priorities that inform HAO strategic planning for funding sources beyond NSF base. The LOB is advisory to the HAO director and shall be composed of a cross section of scientists, including those working on instrumentation and modeling, and management. The LOB will conduct internal reviews of the HAO portfolio and evaluate the strategic direction in which the Lab is moving.

External

External Advisory Committee (EAC)

The EAC is charged with monitoring the progress of HAO's strategic programs and priorities, providing feedback on the direction of the work taken with respect to the broader community.

Mauna Loa Users Committee

Comprised of solar and space scientists whose charge is to provide a forum for the users of the MLSO facility, to give feedback and advice to HAO on the status, desired enhancements, and future new developments of the MLSO facility and operations. The Mauna Loa Observatory provides observations of the solar photosphere, chromosphere, and corona in order to understand the Sun's continuous release of plasma and energy into interplanetary space and the impacts at Earth.

COSMO Science Steering Committee (CSSC)

Advises the development and design of the COronal Solar Magnetism Observatory. The NCAR High Altitude Observatory, The University of Hawaii, and the University of Michigan, propose to build a COronal Solar Magnetism Observatory (COSMO) facility for use by the solar physics research community. The facility will take continuous daytime synoptic measurements of magnetic fields in the solar corona and chromosphere, to understand solar eruptive events that drive space weather, and to investigate long-term phenomena.

WACCM-X Advisory Committee (WAC)

The WAC is charged with the oversight of WACCM-X development.

Looking Further into the Future

The Strategic and Implantation Plans of HAO are meticulously aligned with the vision articulated in the recent Solar and Space Physics Decadal Survey, which aims to "discover the secrets of the local cosmos" and "expand and safeguard humanity's home in space." HAO's mission delineates precise trajectories for advancing discoveries in solar physics and geospace, while its dedication to safeguarding humanity's home in space is deeply embedded in the NSF NCAR's foundational principle of "science in service to society." The Decadal Survey emphasizes HAO's preeminence in solar and geospace research, citing the Mauna Loa Solar Observatory on multiple occasions and the Coronal Solar Magnetism Observatory (COSMO) project extensively. Despite COSMO not being selected as the foremost NSF mid-scale project recommendation, strategic avenues for progression are being actively investigated, including potential synergistic partnerships with the highest-ranking NSF MREFC category recommendation, ngGONG, which incorporates several coronagraphs designed by HAO. The Solar Panel report of the Decadal indicates that a collaborative endeavor between ngGONG and COSMO would effectively address the survey's pivotal scientific inquiries. With respect to geospace, WACCM-X received numerous citations, underscoring its vital function in propelling upper-atmosphere and space weather modeling. The survey's Recommendation 5-4 for a "Flagship Community Science Modeling Program" is exceptionally congruent with HAO's objectives for model development and its collaborative efforts with the NSF NCAR's ESPAT initiative. Through these concerted efforts, HAO remains at the vanguard of solar and space physics, spearheading innovation and fostering strategic alliances to further scientific discovery and societal resilience.