Improving understanding and forecasts of space weather requires addressing scientific challenges within the network of physical processes that connect the Sun to society. The roadmap team identified the highest-priority areas within the Sun-Earth space-weather system whose advanced understanding is urgently needed. The roadmap recommends actions towards such advanced understanding, focusing on the general infrastructure to support research as well as on specific concepts for instrumentation to meet scientific needs.

General recommendations:

Research: observational, computational, and theoretical needs

a) Advance the international Sun-Earth system observatory along with models to improve forecasts based on understanding of real-world events through the development of innovative approaches to data incorporation, including data-driving, data assimilation, and ensemble modeling;
b) Understand space weather origins at the Sun and their propagation in the heliosphere, initially prioritizing post-event solar eruption modeling to develop multi-day forecasts of geomagnetic disturbance times and strengths, after propagation through the heliosphere;
c) Understand the factors which control the generation of geomagnetically-induced currents (GICs) and of harsh radiation in geospace, involving the coupling of the solar wind disturbances to internal magnetospheric processes in the magnetosphere and the ionosphere below;
d) Develop a comprehensive space environment specification, first to aid scientific research and engineering designs, later to support forecasts.

Teaming: coordinated collaborative research environment

e) Quantify vulnerability of humans and of society's infrastructure for space weather by partnering with user groups;
f) Build test beds in which coordinated observing supports model development;
g) Standardize (meta-)data and product metrics, and harmonize access to data and model archives;
h) Optimize observational coverage of the Sun-society system.

Collaboration between agencies and communities

i) Implement open space-weather data and information policy;
j) Provide access to quality education & information materials;
k) Execute an international, inter-agency assessment of the state of the field on a 5-yr basis to adjust priorities and to guide international coordination;
l) Develop settings to transition research models to operations;
m) Partner with the weather and solid-Earth communities to share lessons learned.

The roadmap's research recommendations are expanded in three pathways (see reverse of this flier) that reflect a blend of the magnitude of societal impact, scientific need, technological feasibility, and likelihood of near-term success. Each pathway needs recommendations of preceding one(s) implemented to achieve full success, but can be initiated in parallel. The pathways are designed to meet the variety of differential needs of the user communities working with different types of impacts.

Differential needs and feasibilities

Recommendation for next steps towards meeting user needs, grouped to enable advances on phased paths.

Character of requirements

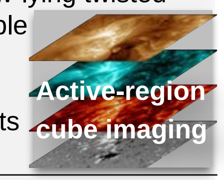
Needed product: / Most significant use:	Electrical systems — Geomagnetic variability protection of electrical & electronic systems	Navigation/Comm. — Ionospheric variability reliability of navigation and communication	(Aero)Space assets — Space particle environment anomaly resolution, and design specification
Knowledge of environment for system design	Pathway I	Pathway I	Pathway 2
Near-real time info and short-term forecasts	Pathway I	Pathway I	Pathways 2 & 3
1-2 day forecasts	Pathway I	Pathway I	Pathway 3

Concepts for priority new instrumentation for Pathways I,II,III

The recommendations in Pathways I, II, and III (see reverse of this flier) result in focus questions and associated concepts for new space missions and ground observatories that complement existing resources in the international Sun-Earth system observatory. For each pathway in order of priority:

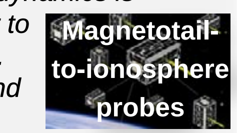
Pathway I-1: Quantify active-region magnetic structure for nascent coronal ejections.

Binocular vision for the corona. The quantitative description of the solar magnetic field in coronal mass ejections requires surface field maps plus stereoscopic coronal imaging at ~1 arcsec resolution. To forecast geomagnetic storm strengths more than 12 hrs ahead: EUV images from ~10°-20° off the Sun-Earth line matching those from Earth perspective, with contiguous coronagraph images.

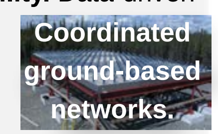


3D mapping of solar field involved in eruptions. Knowing the low-lying twisted filament configuration and its embedding field in the cores of unstable active regions is key to feeding heliospheric propagation models. Mapping the multi-thermal plasma and field at and above the solar surface at high-resolution (~0.2 arcsec) before and after solar events provides critical information to determine what is en-route to Earth.

Pathway I-2: Solar wind-magnetosphere-ionosphere coupling inducing strong GICs.



Magnetotail-to-ionosphere probes for GICs. *Magnetospheric dynamics is particularly poorly understood in the transition region from dipolar to tail-like magnetic field lines and in the auroral acceleration region. Squadrons of small, inexpensive satellites for probing particles and fields in these regions will provide the coverage needed to understand how magnetospheric instabilities generate strong geomagnetically-induced currents (GICs) and how ionospheric conditions can control their appearance.*



Coordinated networks for geomagnetic and ionospheric variability. Data-driven approaches in the ionospheric modeling need comprehensive observational input. Data sets from coordinated global networks of ground-based instruments (magnetometers, GPS receivers, ionospheric radars and auroral imagers) supported by satellite observations of ionospheric and thermospheric conditions will help to search the best solutions for data assimilation to better understand ionospheric densities and currents.

Pathway I-3: Global corona to drive models for the solar-wind plasma and field.

Mapping the global solar field. Dynamic modeling of the heliosphere requires more complete coverage of the solar surface magnetic field, specifically of the high-latitude and far-side areas. The Solar Orbiter will provide a first exploration of these regions, with later investments in, e.g., an L5 research observatory, to be assessed.

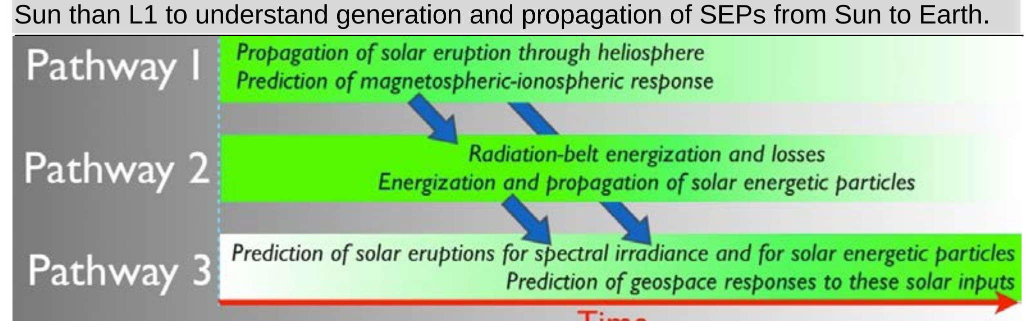
Determination of the foundation of the heliospheric field. Observations and models of the global solar coronal field are needed to drive heliospheric plasma and magnetic field models of eruptions en route to Earth. Coronal polarimetry (such as explored by DKIST) is needed as input to data-driven corona-heliosphere models.

Pathway I-4: Quantification of the state of the magnetosphere-ionosphere system.

Auroral imaging. Changes in the size of the auroral oval uniquely indicate start and end times of (sub-)storm processes. Together with in-situ measurements (above), auroral imaging thus enables characterization of the magnetosphere-ionosphere system when combined with ground-based array data (e.g., by SuperDARN and -MAG networks) for ionospheric electric fields, currents, and conductances.

*Pathway II: **Dynamic radiation belt modeling*** Combine space- and ground-based observations of solar wind, particle populations within the magnetosphere, and ground-based magnetometer and ionospheric networks into radiation-belt models.

*Pathway III: **Solar energetic particles (SEPs) in the Sun-Earth system.*** Obtain in-situ multi-point observations of SEPs off the Sun–Earth line and possibly closer to the Sun than L1 to understand generation and propagation of SEPs from Sun to Earth.



Understanding space weather to shield society

2014/10/24

An international, interdisciplinary roadmap to advance the scientific understanding of the Sun-Earth connections leading to space weather, on behalf of COSPAR and the International Living With a Star program

https://cosparhq.cnes.fr/scientific-structure/cospar-scientific-roadmaps
http://tinyurl.com/swxrm

Recommendations in brief:

a) **Advance the international Sun-Earth system observatory along with models and innovative approaches to data incorporation;**
b) **Understand space weather origins at the Sun and their propagation in the heliosphere;**
c) **Understand the factors controlling the geospace response;**
d) **Develop a comprehensive space environment specification;**

e) **Quantify societal vulnerability;**
f) **Build test beds in which coordinated observing supports model development;**
g) **Standardize (meta-)data and product metrics, and harmonize access to data and model archives;**
h) **Optimize observational coverage of the Sun-society system;**

i) **Implement an open space-weather data and information policy;**
j) **Provide access to quality education & information materials;**
k) **Assess the state of the field on a 5-yr basis to adjust priorities and to guide international coordination;**
l) **Develop settings to transition research models to operations;**
m) **Strengthen partnerships to share lessons-learned.**

Highest-priority research areas to improve space weather information:

1. **Quantify active-region magnetic structure to model nascent coronal mass ejections;**
2. **Understand solar wind-magnetosphere-ionosphere coupling dynamics inducing strong currents;**
3. **Know the global coronal field to drive models of the solar-wind plasma and magnetic field from Sun to Earth;**
4. **Learn to quantify the state of the coupled magnetosphere-ionosphere system;**
5. **Understand the radiation belts through dynamic observation-based modeling;**
6. **Understand solar energetic particles throughout the Sun-Earth system.**

The roadmap's research recommendations (a) to (d) [see other side] are expanded into three pathways that reflect a blend of scientific need, technological feasibility, and likelihood of near-term success. Each pathway needs recommendations of preceding one(s) implemented to achieve full success, but can be initiated in parallel. Recommendations within each pathway are grouped into actions that can be taken now, soon, or on a few-year timescale, each listed in priority order within such group.

Pathway I recommendations

to obtain forecasts more than 12 hrs ahead of the magnetic structure of incoming coronal mass ejections to improve alerts for geomagnetic disturbances and strong GICs, related ionospheric variability, and geospace energetic particles

Maintain existing essential capabilities:

- solar magnetic maps (ground-based, SDO), EUV/X-ray images at arcsec and few-second res. (SDO; Hinode), and solar spectral irradiance observations;
- solar coronagraphy, best from multiple perspectives (L1: SoHO; and well off Sun-Earth line: STEREO);
- in-situ measurements of solar-wind plasma and magnetic field at, or upstream of, Sun-Earth L1 (ACE, SoHO; DSCOVR);
- for several years, continue to measure the interaction across the bowshock-magnetopause (as now with Cluster/ARTEMIS/THEMIS; soon with MMS), to better understand wind-magnetosphere coupling;
- satellite measurements of magnetospheric magnetic and electric fields, plasma parameters, soft auroral and trapped energetic particle fluxes (e.g. Van-Allen Probes, LANL satellites, GOES, ELECTRO-L, POES, DMSP);
- ground-based sensors for solar, heliospheric, magnetospheric, and iono-/thermo-/mesospheric data to complement satellite data.

Model capability, archival research, or data infrastructure:

- near-real time, observation-driven 3D solar active-region models of the magnetic field to assess destabilization and to estimate energies;
- data-driven models for the global solar surface–coronal field;
- data-driven ensemble models for the magnetized solar wind;
- data assimilation techniques for the global ionosphere-magnetosphere-atmosphere system using ground & space data for nowcasts and near-term forecasts of geomagnetic & ionospheric variability, making optimal use of select locations where laboratory-like test beds exist or can be efficiently developed;
- coordinated system-level research into large-scale rapid morphological changes in Earth's magnetotail and embedded energetic particle populations;
- system-level study of the mechanisms of the particle transport/acceleration/losses driving currents and pressure profiles in the inner magnetosphere;
- stimulate research to improve global geospace modeling beyond the MHD approximation (kinetic, hybrid, ...);
- develop the ability to use solar chromospheric and coronal polarimetry to guide full-Sun corona-to-heliosphere field models.

Deployment of new/additional instrumentation:

- binocular imaging of the solar corona at ~1-arcsecond and at least 1-min. resolution with ~10–20˚ separation between perspectives;
- observe the solar vector-field at and near the surface and the overlying corona at <200-km resolution to quantify ejection of compact and low-lying current systems from solar active regions;
- (define criteria for) expanded in-situ coverage of the auroral particle acceleration region and dipole-tail field transition region (building on MMS) to determine the magnetospheric state in current (THEMIS/Cluster) and future high-apogee constellations, using hosted payloads and cubesats where appropriate;
- (define needs, then) increase ground- and space-based instrumentation to complement satellite data of the magnetospheric and ionospheric variability, including geomagnetic input above 55˚ magnetic latitude, ideally with ionospheric measurements, and other ionospheric data to cover gaps (e.g., over oceans);
- an observatory to expand solar-surface magnetography to all latitudes and off the Sun-Earth line [starting with Solar Orbiter];
- large ground-based solar telescope(s) to perform multi-wavelength spectro-polarimetry to probe magnetized structures at a range of heights and scales in the solar atmosphere (incl. DKIST);
- optical monitors to measure global particle precipitation to be used in assimilation models for geomagnetic disturbances and ionospheric variability.

Pathway II recommendations

to understand the particle environments of (aero)space assets leading to improved environmental specification and near-real-time conditions

With the Pathway-I requirements implemented:

Maintain existing essential capabilities:

- LEO to GEO observations of electron and ion populations (hard/~MeV and soft/~keV; e.g., GOES, ...,), and of the magnetospheric field, to support improved particle-environment nowcasts;
- maintain a complement of spacecraft with high resolution particle and field measurements (such as the Van Allen Probes).

Model capability, archival research, or data infrastructure:

- specify the frequency distributions for fluences of energetic particle populations [solar-energetic, radiation-belt, and galactic cosmic-ray particles] for a variety of orbital conditions, and maintain archives of past conditions;
- develop, and experiment with, assimilative integrated models for radiation-belt particles towards forecast development including ionosphere, thermosphere and magnetosphere and below, and validate these based on archival data.

Deployment of new/additional instrumentation:

- deploy high- and low-energy particle and electro-magnetic field instruments to ensure dense spatial coverage from low-Earth orbits to geo-stationary orbits and long-term coverage of environment variability (incl., e.g., JAXA's ERG).

Pathway III recommendations

to enable pre-event forecasts of solar flares and coronal mass ejections, and related solar energetic particle [SEP] storms for near-Earth satellites, astronauts, ionospheric conditions, and polar-route aviation, including all-clear conditions.

Maintain existing essential capabilities (in addition to Pathway-I list):

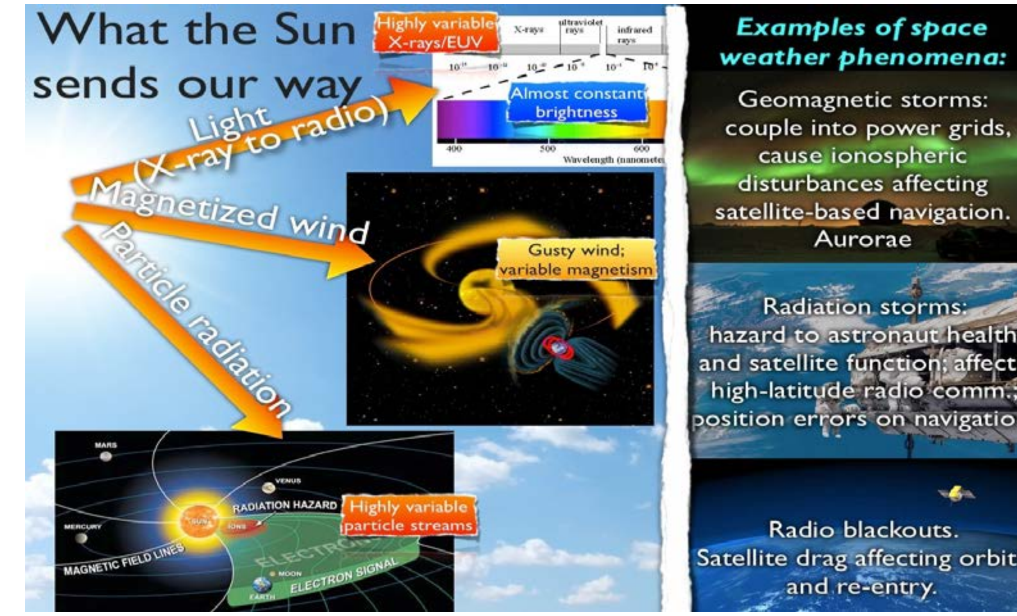
- solar X-ray observations (GOES);
- observe inner-heliospheric shocks at radio wavelengths;
- maintain for some years multi-point in-situ observations of SEPs on- and off Sun-Earth line throughout the inner heliosphere (e.g., L1, STEREO);
- maintain measurements of heavy ion composition (L1/ACE, STEREO; near-future: GOES-R).

Model capability, archival research, or data infrastructure:

- develop data-driven predictive modeling capability for field eruptions from the Sun through the inner heliosphere;
- investigate energetic particle energization and propagation in the inner heliosphere, aiming to develop at least probabilistic forecasting of SEP properties [cf. Pathway-I for heliospheric data-driven modeling];
- ensemble modeling of unstable active regions to understand energy conversions into bulk kinetic motion, photons, and particles.

Deployment of new/additional instrumentation:

- new multi-point in-situ observations of SEPs off Sun-Earth line throughout the inner heliosphere to understand population evolutions en route to Earth (e.g., Solar Orbiter, Solar Probe Plus);
- maintain and further develop ground– and space–based ionospheric observation platforms, complemented by space–based instrumentation to obtain electron density as a function of height and to fill observation gaps that now exist, such as over ocean areas.



Space weather is driven by changes in the Sun's magnetic field and by the consequences of that variability in Earth's magnetic field and upper atmosphere. This results in a variety of manifestations, including geomagnetic variability, energetic particles, and changes in Earth's uppermost atmosphere. All of these can affect society's technological infrastructures in different ways.

Space weather is generally mild but sometimes extreme: Mild space weather storms frequently affect navigation, degrade electric power quality, interrupts satellite functions, and are hazardous to astronaut health: all these impacts cost the global economy tens of billions of dollars each year. 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.

Societal interest in space weather grows rapidly: 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 grows rapidly. Apart from having societal relevance, understanding space weather is an exciting science revealing how the universe around us works.

Space weather is an international challenge: Significant scientific problems require substantial resources, with observations having to cover the terrestrial globe and span the vast reaches of the heliosphere between Earth and the Sun.

Mitigating against the impacts of space weather: Shielding society from space weather can be improved by designing less susceptible, more resilient technologies, combined with better environmental knowledge and more reliable forecasts. This roadmap outlines how we can achieve deeper understanding and better forecasts, recognizing that the expectations for space weather information differ between societal sectors, and that capabilities to observe or model space weather phenomena depend on available and anticipated technologies.

The existing observatories that cover much of the Sun-Earth system provide a unique starting point: Moderate investments to fill key capability gaps can enable scientific advances that could not be otherwise achieved, while at the same time providing a powerful base to meet many operational needs.