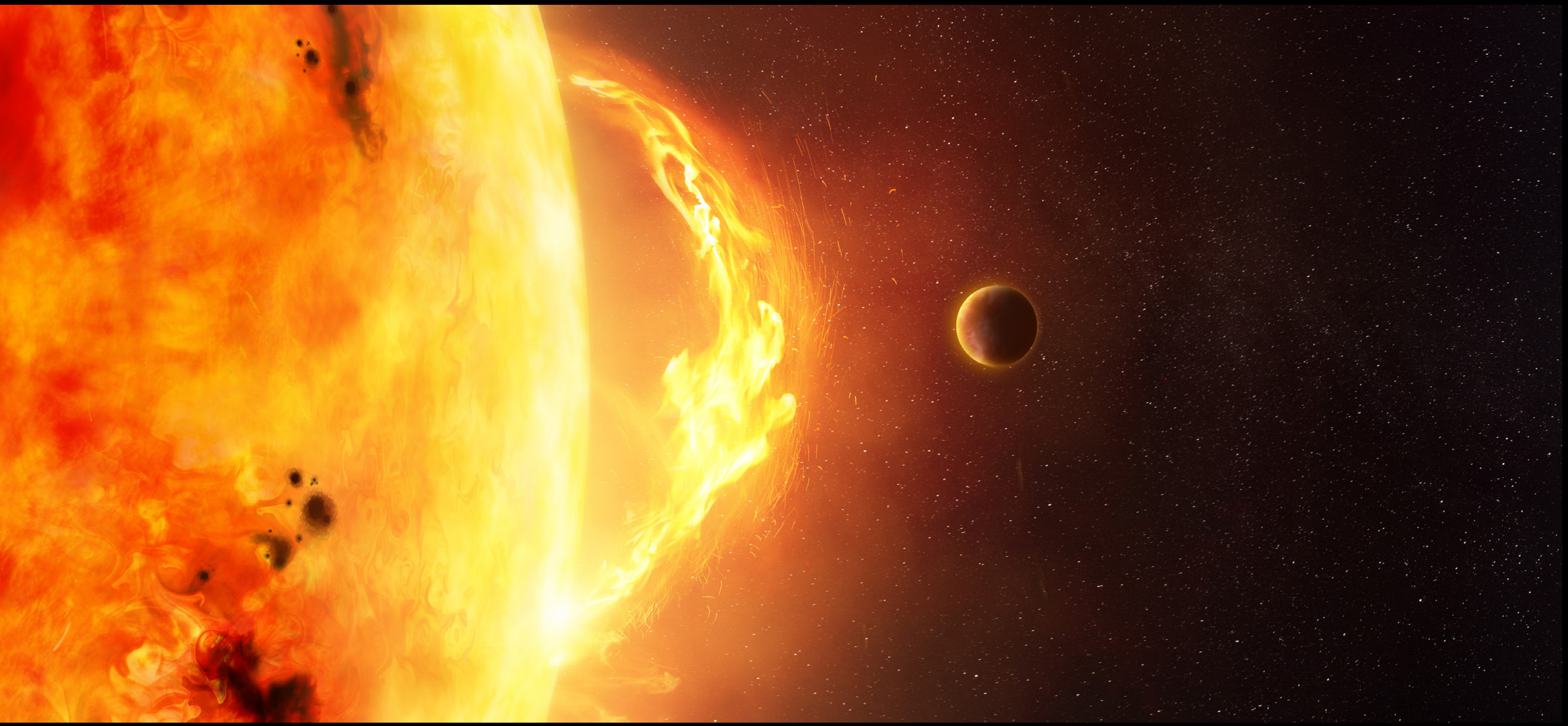
A REPORT TO NASA'S SPACE WEATHER SCIENCE APPLICATION PROGRAM

For the National Aeronautics and Space Administration (NASA)
Compiled by Johns Hopkins APL

SPACE WEATHER SCIENCE

AND OBSERVATION GAP ANALYSIS

December 2021



An illustration of an active Sun, including sun spots (dark regions) and a solar prominence, with a planet (not Earth; approximately Neptune or Uranus sized) to give scale to the size of the active regions and prominence. Such active regions are potential sources of solar eruptive events like flares and coronal mass ejections, which are important drivers of space weather.

COMMITTEE MEMBERS

Representing 16 institutions, from academia to space weather data end users

Operations/End Users:

Agencies: Doug Biesecker (NOAA/SWPC), M. Leila Mays (NASA/GSFC), Edward Semones (NASA/JSC), Stephen White (USAF/AFRL)

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Task Lead: George Ho (APL)

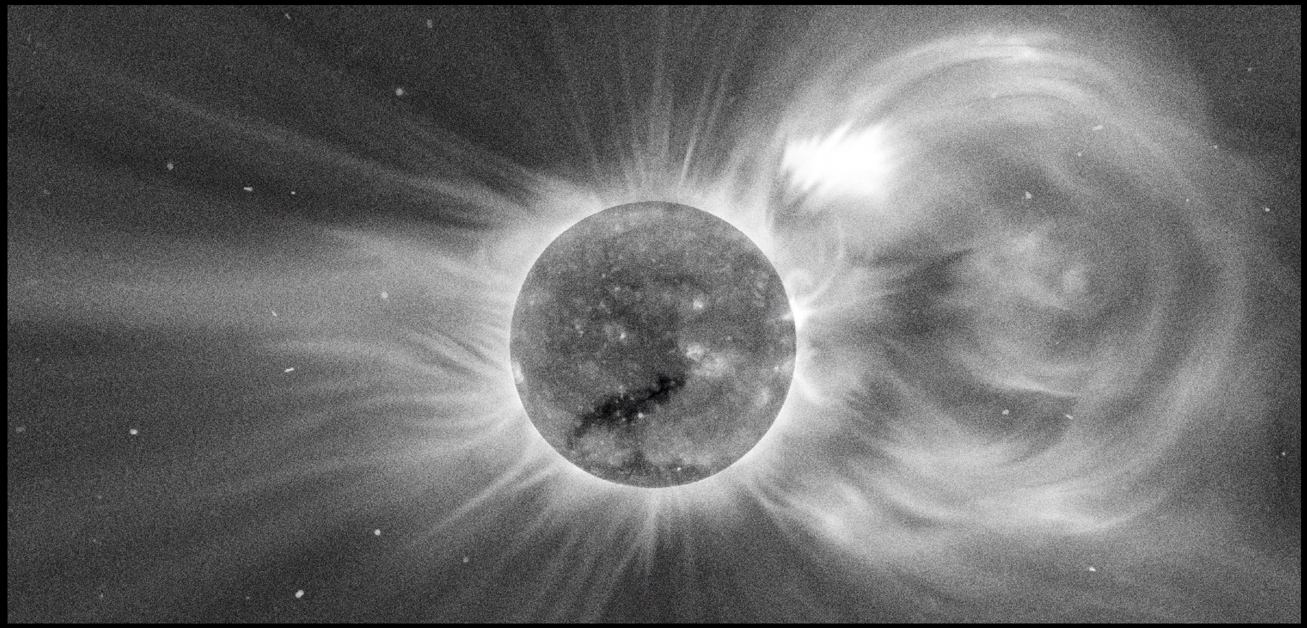
SUMMARY OF KEY FINDINGS

This document summarizes the key findings of a gap analysis conducted by APL for NASA about the state of space weather science and observations. Note that the explicit task from NASA specified space-based observations only be considered in the context of improved space weather predictive capabilities and the science of space weather. The full report, which was presented to NASA's Space Weather Science Application Program, can be found here:

> https://science.nasa.gov/science-pink/s3fs-public/atoms/files/GapAnalysisReport_full_final.pdf

The gap analysis report was compiled by a committee of space weather experts from academia, government, the commercial sector, and the space weather operational and end-user community. APL thanks them for their coordinated and thoughtful efforts to produce this analysis.

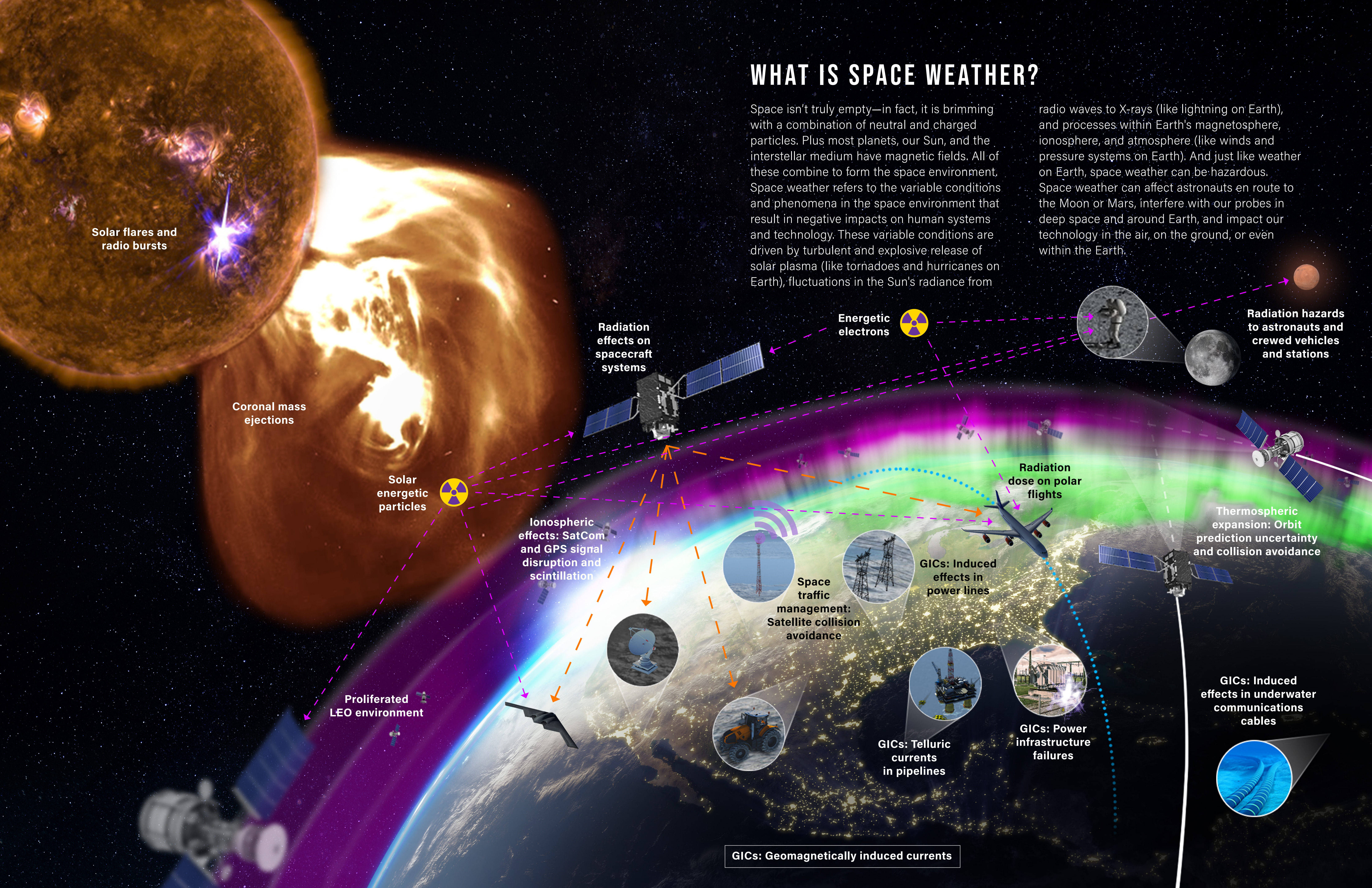
The gap analysis committee found that we can significantly improve our space weather prediction capabilities by using existing technology on an expanded network of space weather observatories in various strategic Earth and solar orbits. The space environment operates as a system-of-systems, and a system-of-systems approach is also needed to gather concurrent validated measurements from key observatories, process data, drive predictive models, and deliver products to space weather end users all with little delay time. A long-term strategy is required to close observational gaps that includes partnering federal agencies with one another and also with commercial satellite operators and international agencies. New technologies and capabilities should also be leveraged, such as expanded launch vehicle options and rideshare opportunities; small satellite technology; low-latency global satellite communication networks; open-access datasets as well as cloud computing and machine learning capabilities; and hosted payloads in proliferated low Earth orbit (LEO) and beyond.



The sudden eruption of Sept. 10, 2017. The fastest (>11 million kilometers per hour) eruption in 13 years occurred at the waning end of the weakest solar cycle in 100 years, reminding us that a potentially devastating space weather event can occur at any time.

WHAT IS SPACE WEATHER?

Space isn't truly empty—in fact, it is brimming with a combination of neutral and charged particles. Plus most planets, our Sun, and the interstellar medium have magnetic fields. All of these combine to form the space environment. Space weather refers to the variable conditions and phenomena in the space environment that result in negative impacts on human systems and technology. These variable conditions are driven by turbulent and explosive release of solar plasma (like tornadoes and hurricanes on Earth), fluctuations in the Sun's radiance from radio waves to X-rays (like lightning on Earth), and processes within Earth's magnetosphere, ionosphere, and atmosphere (like winds and pressure systems on Earth). And just like weather on Earth, space weather can be hazardous. Space weather can affect astronauts en route to the Moon or Mars, interfere with our probes in deep space and around Earth, and impact our technology in the air, on the ground, or even within the Earth.



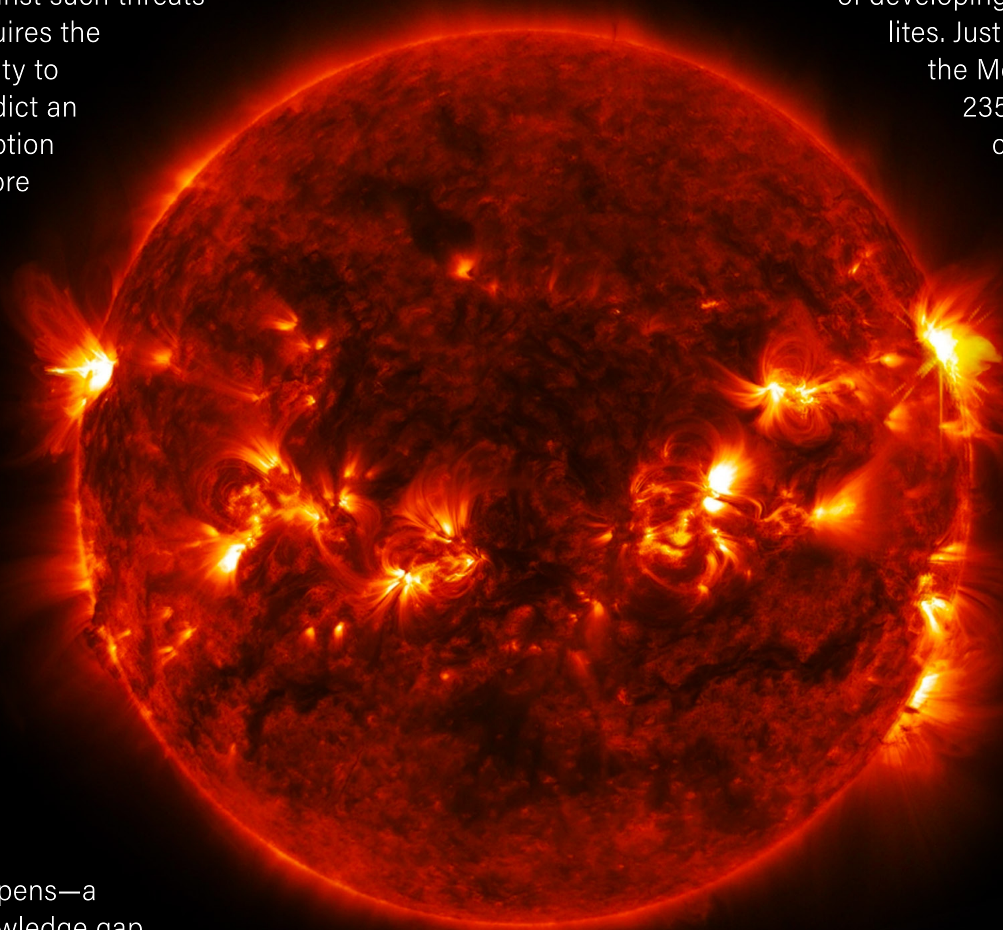
WHY DO WE CARE?

As humanity becomes more reliant on satellite technology for key aspects of daily life on Earth, as we become increasingly dependent on electrical power and high-altitude travel, and as we venture farther into our solar system more frequently, space weather plays an increasingly important role in the success of our species. Our space-, air-, and ground-based technologies are all susceptible to space weather, and space weather represents the only known natural disaster capable of affecting the entire contiguous United States and Alaska and Hawaii, as well as space-based infrastructure, in a single major event. Such an event would have major economic consequences, too. A 2017 study by Oughton et al. estimates that a U.S.-wide electricity transmission failure due to a space weather event could affect anywhere between 8% and 66% of the U.S. population with an associated economic impact of about $4.4 billion to $35.4 billion per day.[1]

Space weather affects satellite communication signals and GPS availability and accuracy. Heating and expansion of the uppermost layers of Earth's atmosphere result in increased satellite drag, uncertainty in orbit tracking and prediction, and increased likelihood of on-orbit collisions. Radiation in the form of X-rays and energetic particles pose a hazard to humans in spacecraft and in aircraft over polar regions. Radiation also is a major hazard to the satellites we rely on, resulting in system failures and degraded operational lifetimes. During the most intense geomagnetic storms, space weather can even affect our power grid, potentially resulting in damage to infrastructure and even large-scale power outages, as occurred in March 1989 in Quebec, Canada.

Such considerations have led the U.S. government to pass the PROSWIFT Act (public law 116-181), making its official policy to prepare for and protect against the social and economic impacts of space weather phenomena by supporting actions to improve space weather prediction. Several parts of the U.S. government (including FEMA) are working to inform the public about (and prepare it for) space weather's ability to disrupt our power grid and communications systems.

For NASA, space weather concerns reach to its very core—its space exploration charter. Highly energetic particles, accelerated by solar eruptive events, can impact the health—and potentially even the lives—of astronauts on the Moon, Mars, or anywhere in between. Radiation on the Moon can reach dangerous levels within minutes of an eruption on the Sun, leaving little time for astronauts to seek shelter. Guarding against such threats requires the ability to predict an eruption before it happens—a knowledge gap that this report sought to address. Solid scientific understanding of space weather conditions across the immense space between the Sun and Mars is the only way to safeguard humanity's sojourns to Mars and beyond.



The current state of our predictive capability for space weather is largely restricted by limited data from space weather stations and observatories, both ground- and space-based. Two obstacles we face in meeting these challenges are the enormity of space and the cost and complexity of developing and deploying satellites. Just between Earth and the Moon, there are 235 million-billion cubic kilometers of space—enough to fit 215,000 Earths into! That space grows even more when we consider the solar environment. However, scientists know where and when different types of space weather are most relevant, and a network of future space weather observatories can be strategically developed and deployed.

> *The effects of severe space weather on the electric power grid, satellites and satellite communications and information, aviation operations, astronauts living and working in space, and space-based position, navigation, and timing systems could have significant societal, economic, national security, and health impacts.*
>
> *– PROSWIFT Act, U.S. Public Law 116-181, section 60601. Space Weather*

[1] *E. J. Oughton, A. Skelton, R. B. Horne, A. W. P. Thomson, and C. T. Gaunt, "Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure," Space Weather, vol. 15, no. 1, pp. 65–83, 2017, https://doi.org/10.1002/2016SW001491.*

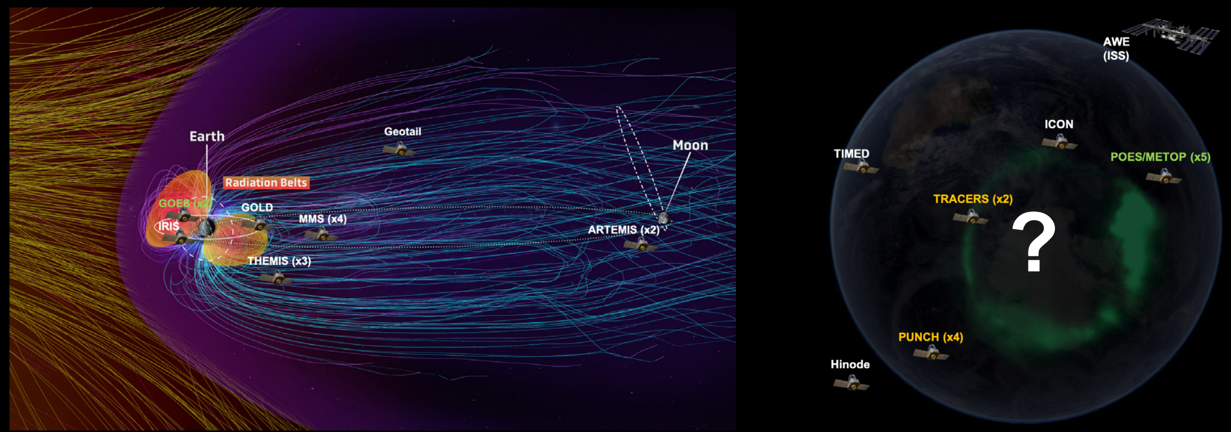
WHERE DO WE STAND?

State of U.S. Terrestrial Weather circa 1960

The gap analysis report identified gaps in our knowledge and measurement abilities for all regions of space that lie between us and the Sun, from the solar surface and atmosphere to the inner heliosphere and through to the "last mile" (the space within 1 million kilometers of Earth) and into our own magnetosphere.

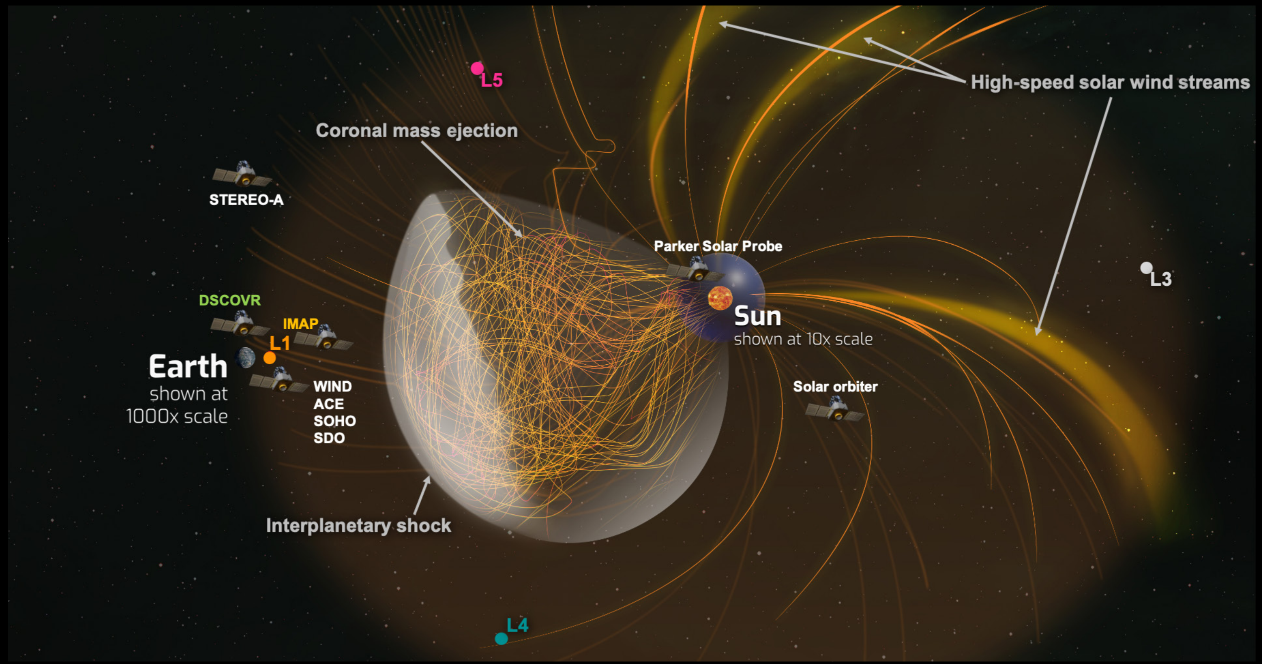
Our current ability to predict space weather is in many ways like our ability to predict terrestrial weather was several decades ago, before global weather station networks and satellite imagery and observations were available. With only sparse and often partial weather stations and observatories available, predicting space weather today is something like asking a forecaster to predict tornado activity in Kansas given only weather data from stations in New York City and Los Angeles—an area that spans 2,800 miles (~4,500 kilometers).

Current State: Geospace

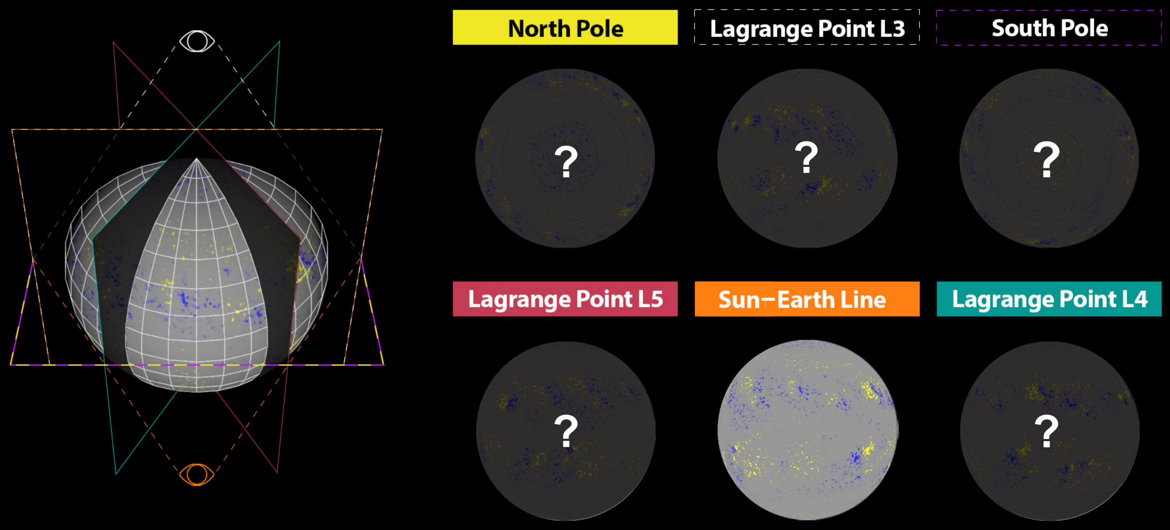


Current operational (in white) and in-development (in orange) NASA (and NOAA/European Space Agency [ESA] in green) missions that provide key measurements for space weather prediction. In geospace, around Earth, there are multiple critical blind spots, including the solar wind at the magnetopause, comprehensive ionospheric and thermospheric observatory networks in LEO, and dedicated radiation belt and charging environment monitors throughout the cislunar magnetosphere.

Current State: Solar/Heliospheric



Current operational (in white) and in-development (in orange) NASA (and NOAA in green) missions that provide key measurements for space weather prediction. For solar and heliospheric measurements, critical blind spots include observations around the entire Sun, multipoint in situ observations of the solar wind and energetic particle environment, and comprehensive observations of the solar irradiance and magnetic fields (magnetograms).

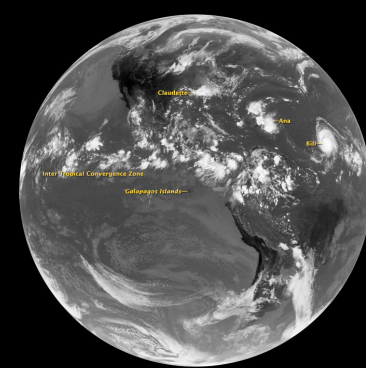


Currently, we only have observations from one perspective on the solar disk: from along the Sun-Earth line. We are mostly blind to activity over the remainder (majority) of the solar surface, impeding longer-term predictive capabilities.

WHERE DO WE NEED TO BE?

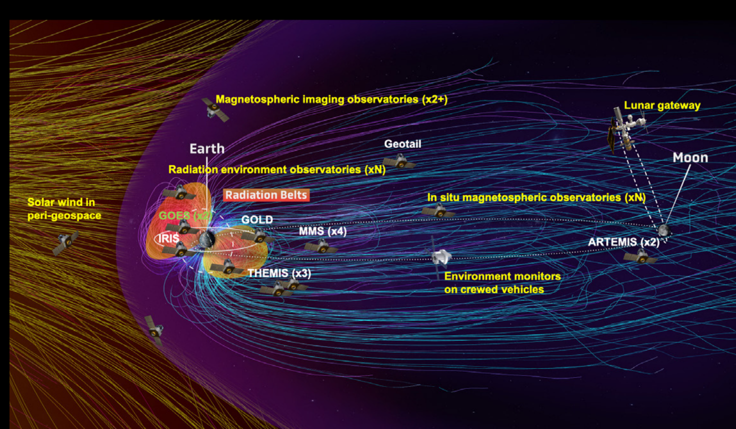
Current State of Global Terrestrial Weather

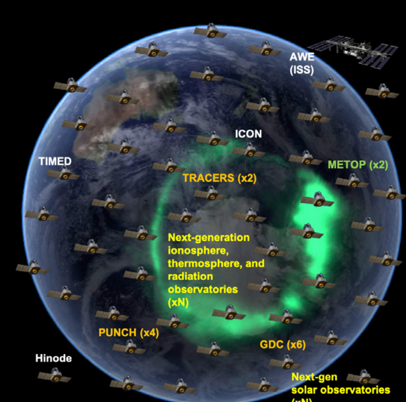
We need the ability to monitor and predict space weather just like we can for weather on Earth. We already have the technology available to significantly improve our ability to hindcast, nowcast, and forecast space weather in an effort to protect critical systems.



By improving our understanding of how solar disturbances propagate and how the near-Earth space environment reacts to them, we can increase our forecast horizon and deliver more accurate and useful forecasts. With an expanded network of space weather stations and observatories, we can better predict the current and future states of the space environment relevant to known space weather hazards.

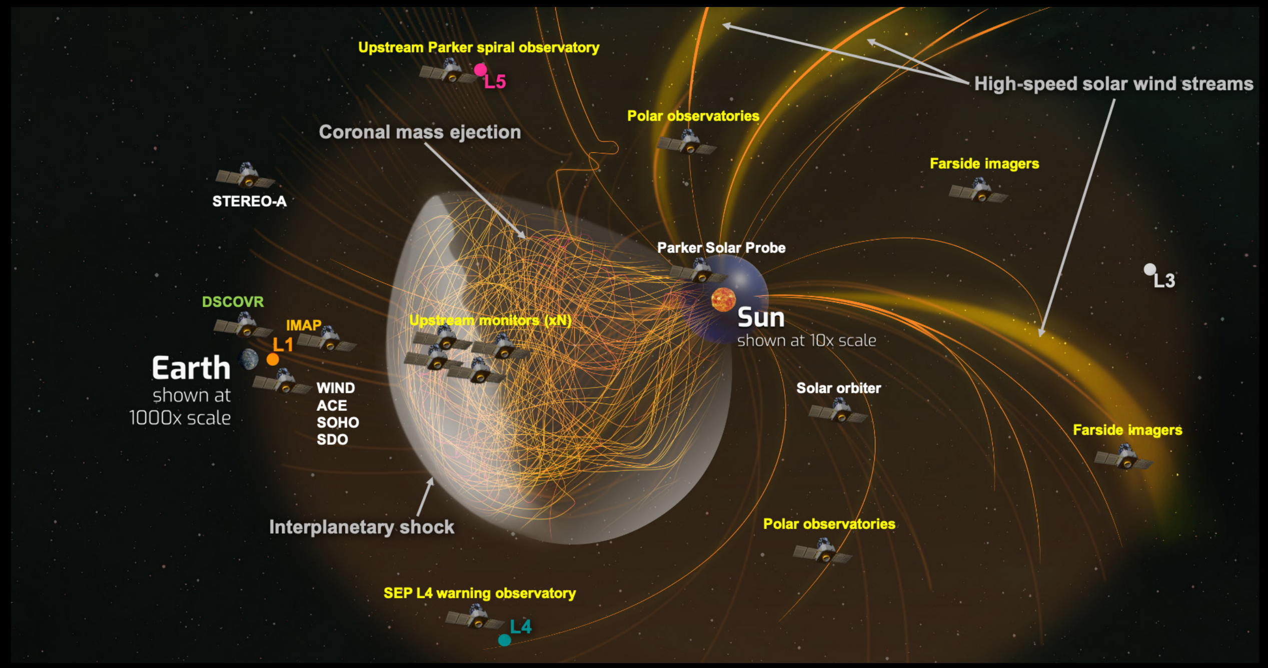
Critical Gaps: Geospace



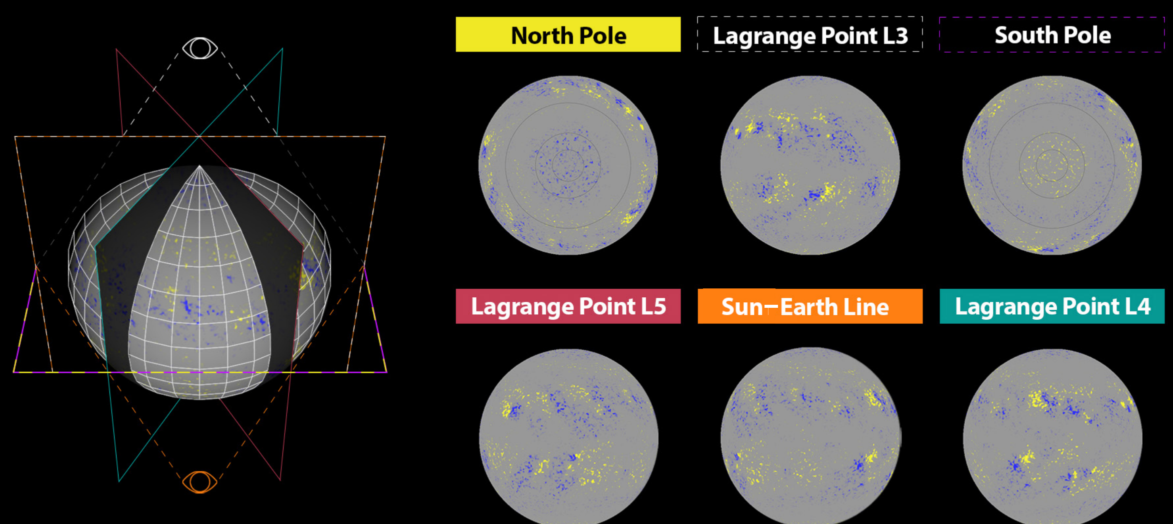


In geospace, around Earth, there are multiple critical blind spots including the solar wind at the magnetopause, comprehensive ionospheric and thermospheric observatory networks in LEO, and dedicated radiation belt and charging environment monitors throughout the cislunar magnetosphere. Observatories marked in yellow indicate identified observation gaps.

Critical Gaps: Solar/Heliospheric



Solar transients are both immense and highly complex magnetic structures. The magnetic field lines shown in this graphic are based on a physics-based simulation using the Grid Agnostic MHD for Extended Research Applications (GAMERA) model. The vast size difference between Earth and transients requires a multiscale measurement approach to capture the information necessary for successful and actionable space weather prediction. Observatories marked in yellow indicate identified observation gaps.



Full (4π) mapping of the magnetic field on the surface of the Sun. Closing this measurement gap will constitute a "quantum leap" in our ability to forecast the conditions within Sun–Earth space and around the heliosphere, much like the Geostationary Operational Environment Satellites (GOES) in geosynchronous orbit provide a global view of weather on Earth.

HOW DO WE CLOSE THE GAPS?

We have the ability to close the observation gaps and associated science gaps that currently prevent us from advancing our space weather forecasting capabilities throughout the inner heliosphere. Some of these gaps include:

Incomplete Coverage of the Sun and of the Inner Heliosphere

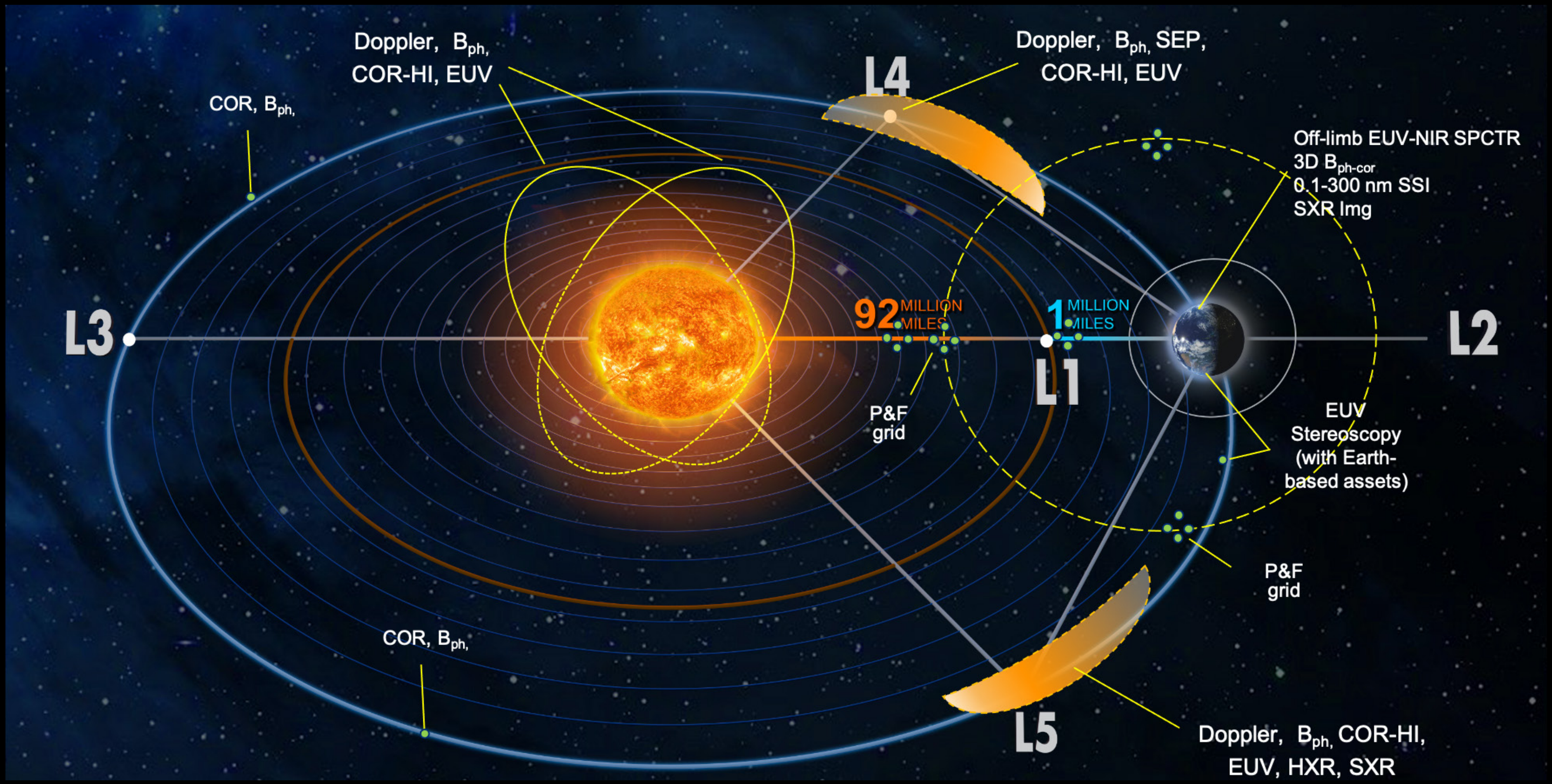
- Having only a single real-time view of the Sun leaves us blind to activity across most of the solar surface, yet this activity can still impact life on Earth, our robotic spacecraft, and future crewed missions to Mars and beyond.

Incomplete Coverage of the "Last Mile"

- Solar wind is turbulent and erratic, and our current monitoring spot from the Sun–Earth L1 point is too far away to accurately understand how Earth's magnetosphere, ionosphere, and atmosphere could respond.

Incomplete Coverage of Our Protective Cocoon

- With the end of NASA's Van Allen Probes mission in 2019, we no longer have key measurements to predict the current and future state of radiation in Earth's magnetosphere.
- We currently have insufficient coverage of the global ionosphere (satellite communications and GPS signals) and thermosphere (satellite drag and orbit prediction accuracy) systems.

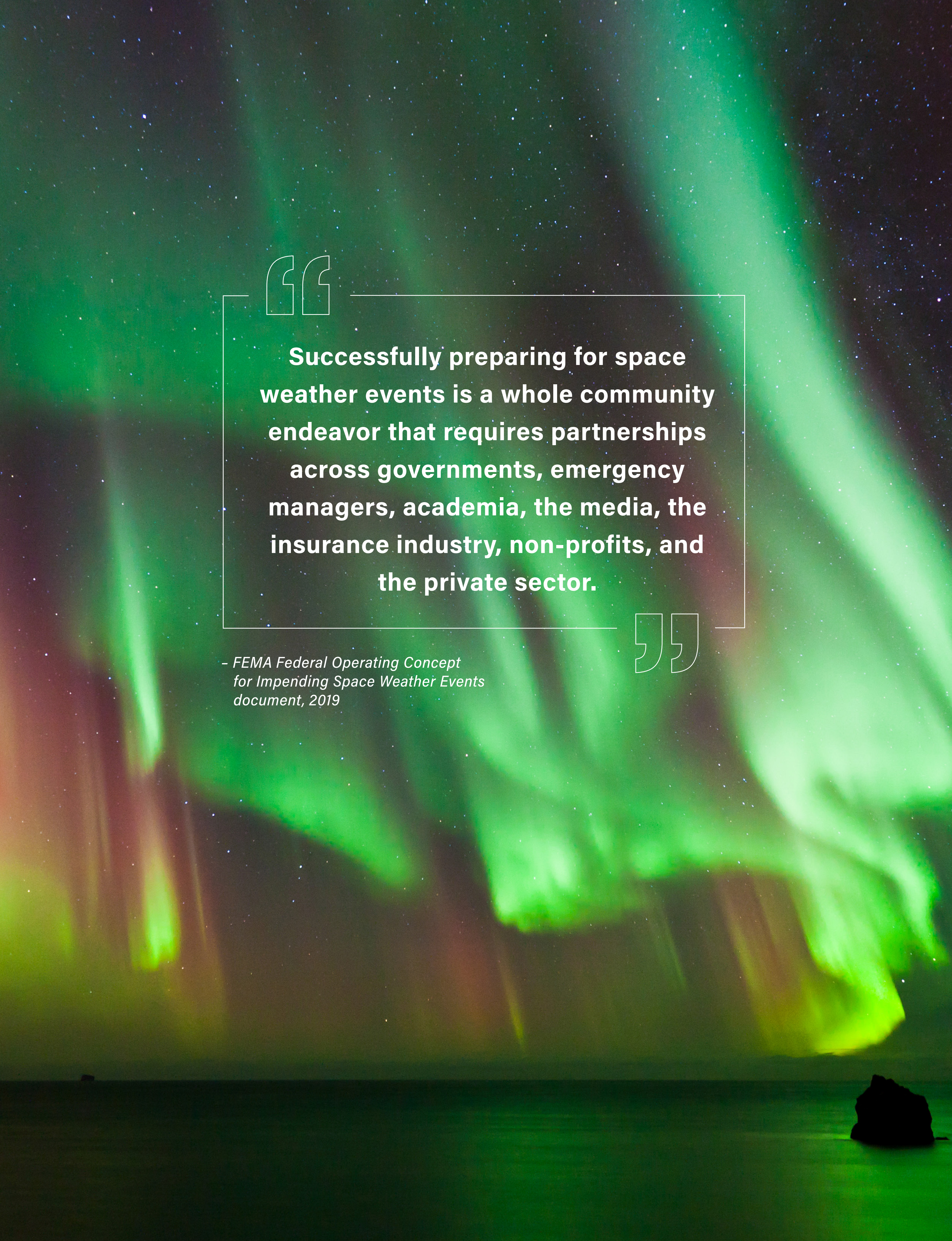


Graphic representation of the results of the gap analysis with respect to solar and heliospheric observational gaps. 'P&F grid' represents multipoint measurements of particles and fields that make up the in situ solar wind.

We can advance our understanding of space weather without needing new technologies or high-risk approaches—the technology already exists. We can do this by:

- Adopting a "systems approach" of concurrent measurements with a focused set of payloads and platforms from strategic locations
- Developing a long-term strategy of sustainable plans and resources to mitigate the gaps
- Leveraging and learning from "new space"—taking advantage of new opportunities like rideshares, hosted payloads, commercial launchers, and LEO satellite constellations
- Engaging the international community
- Establishing a standardized set of measurements that are fast, cost-effective, multipoint, and scalable
- Promoting open and accessible databases that contain space weather observation and anomaly data

The time to advance the science of space weather is now. As we become increasingly reliant on technologies that are susceptible to space weather events, and as we plan to send more crewed and uncrewed missions into space, we need to be able to predict and mitigate the effects of space weather now more than ever.



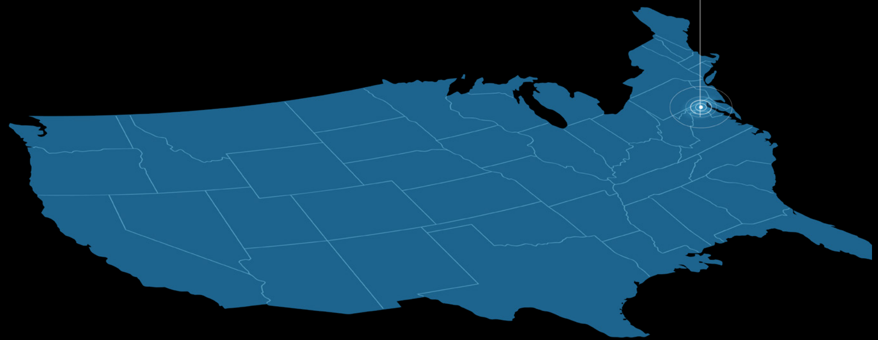
> **Successfully preparing for space weather events is a whole community endeavor that requires partnerships across governments, emergency managers, academia, the media, the insurance industry, non-profits, and the private sector.**

– FEMA Federal Operating Concept for Impending Space Weather Events document, 2019

CONCLUSION

As our technologies continue to advance and crewed and uncrewed missions travel farther into space more frequently, we become more susceptible to the effects of space weather—meaning we need to be able to monitor and predict it.

- The current state of our capabilities to monitor and predict space weather is similar to our capabilities to monitor and predict terrestrial weather several decades ago before we had global weather stations and satellite imagery.
- We can close the gaps in our space weather forecasting capabilities with technology that already exists.
- Closing the gaps will require a holistic and strategic approach with collaboration from government, academia, the private sector, and the international community.



ABOUT APL

For more than 75 years, the scientists and engineers at the Johns Hopkins University Applied Physics Laboratory (APL) have served as trusted advisors and technical experts to the government. Located in Laurel, Maryland, APL is the nation's largest university affiliated research center (UARC). APL makes critical contributions to NASA and international missions to meet the challenges of space science. Our work includes conducting research and space exploration; development and application of space science, engineering, and technology; and production of one-of-a-kind spacecraft, instruments, and subsystems. For more information, visit www.jhuapl.edu.

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