NOAA Space Weather Follow On (SWFO) Program

The SOLAR-1 Product Validation Process

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NOAA/Space Weather Observations (SWO)

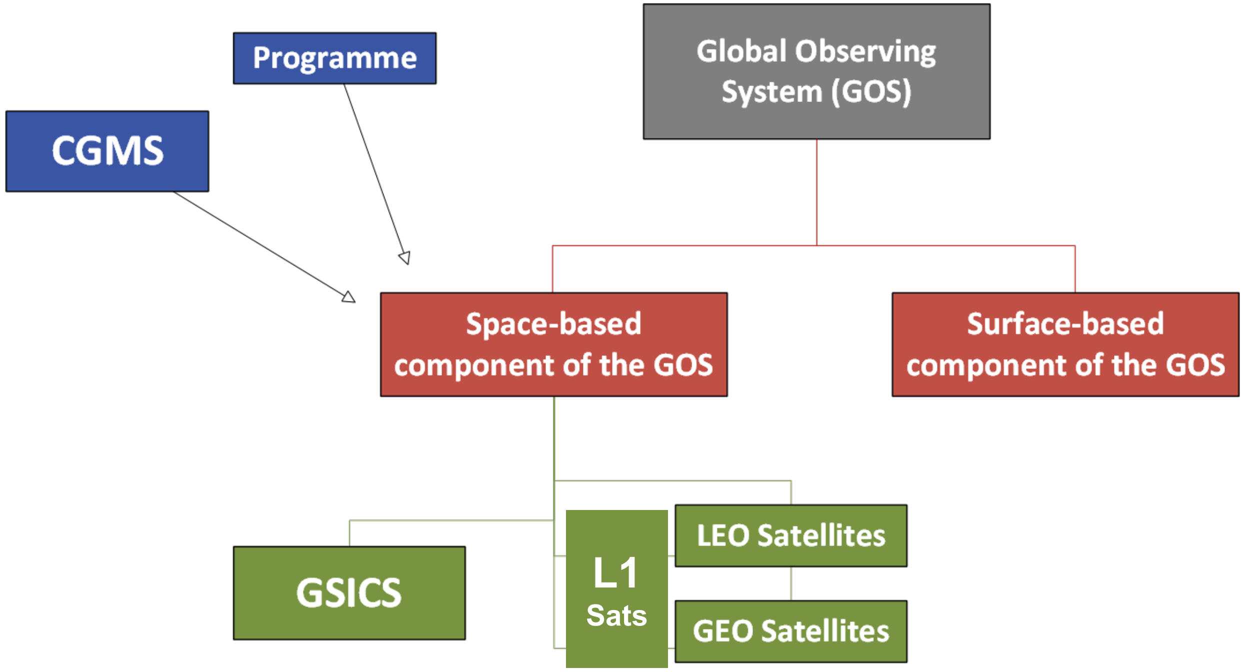
GSICS Global Space-based Inter-Calibration System

GLOBAL SPACE-BASED INTER-CALIBRATION SYSTEM ANNUAL MEETING

23-27 MARCH 2026, OTTAWA, CANADA

Relevance to GSICS

1. <u>The upstream boundary</u>: The solar wind upstream of the Earth is an important boundary condition for space weather at terrestrial environments (magnetosphere, ionosphere, thermosphere).
   - Therefore, it is important to monitor the solar and solar-wind states and consider them as drivers of space weather conditions at geospace environments.
   - SOLAR-1/SWiPS, MAG: SW/IMF measurements are regularly used as external drivers of models of the GEO and LEO environments
   - SOLAR-1/STIS: suprathermal particle data can be used as a precursor for SEP events at GEO and lower altitudes.
2. <u>Intercalibration of satellite measurements at L1</u>: the advent of multiple platforms at L1 enables the development of methods of quantitative comparisons of corresponding datasets.
   - There are now six solar wind monitoring spacecraft orbiting the Sun-Earth L1 point: recently launched SOLAR-1, IMAP, Aditya-L1, and the earlier ACE, DSCOVR, and Wind. There is a significant need for intercalibration of plasma/IMF/particle-flux data for operational as well as science objectives.

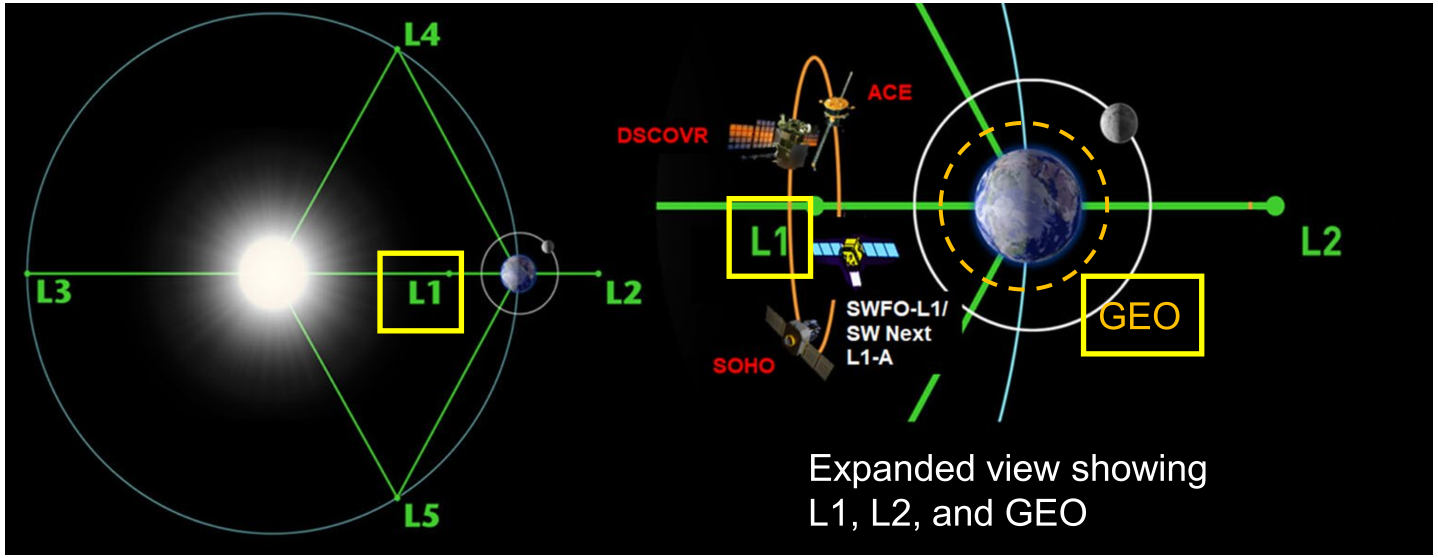


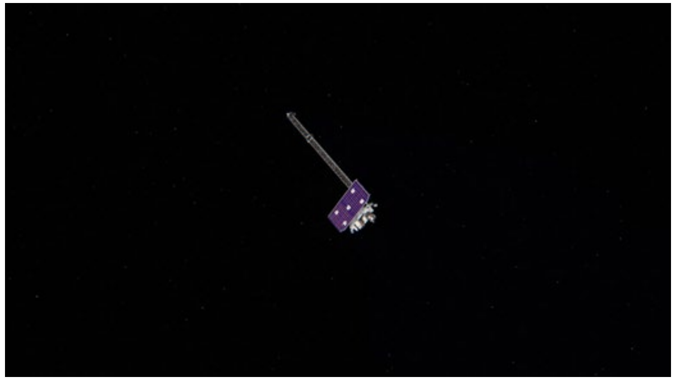
The Space Weather Follow On Program

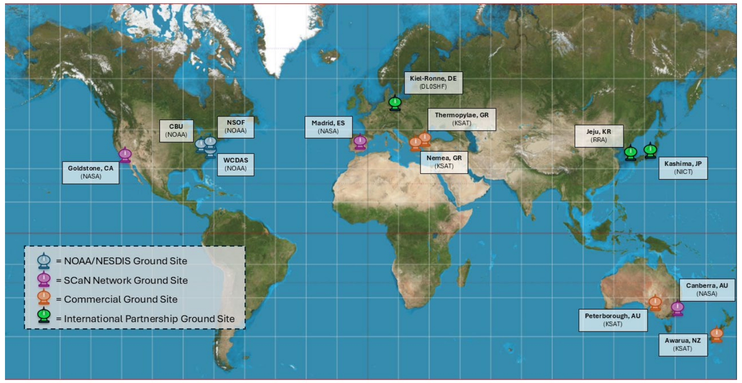
- A NOAA-NASA program for space weather, SWFO has been designed to provide critical solar and heliospheric data to both operational users (forecasters, satellite operators, others) and retrospective ones (scientists, other developers).

- SWFO is operating from two orbits:
  - GEO: The Compact Coronagraph-1 (**CCOR-1**) on the GOES-19 satellite launched on June 25, 2024.
  - Sun-Earth Lagrange 1 (L1) point: The SWFO-Lagrange 1 (**SWFO-L1**) Observatory launched on September 24, 2025 as a rideshare with NASA's IMAP and CGO. After reaching orbit, it was renamed Space weather Observations at L1 to Advance Readiness 1 (**SOLAR-1**).

- SWFO is providing the following products:
  - Coronal imagery to enable early situational awareness for forecasting
  - Solar wind and interplanetary magnetic field (IMF) measurements to drive geospace models.
  - Suprathermal particle flux measurements to be used in improving estimates of CME arrival times.

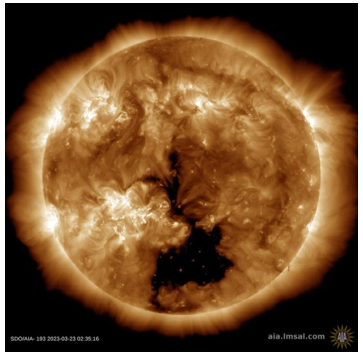


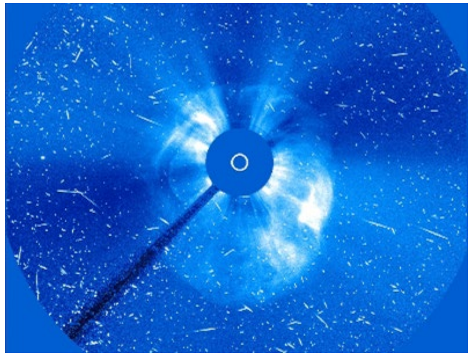


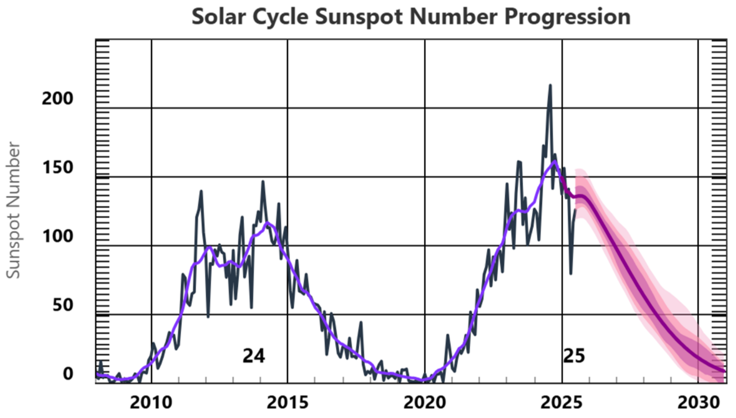


Operational Perspective: Space Weather Readiness

- Real-time, accurate solar imagery and heliospheric in situ measurements are among the critical data needed in SWPC and other SpWx forecast centers. NOAA's satellite programs are designed to provide such operational data to SWPC forecasters and real-time users.
- Further, for research objectives, such programs can provide reference measurements for solar, heliospheric, and geospace analysis and modeling. Data from key locations (in particular, Lagrange 1) are useful for driving or validating NWP models.
- Further, the R2O process enables these models to be transitioned to operations following thorough validation in testbed and proving-ground facilities at NOAA and NASA.

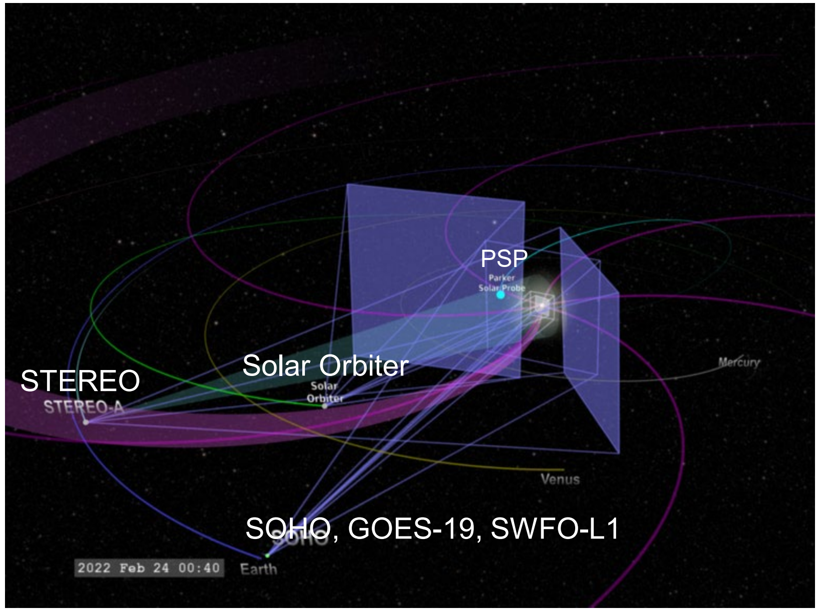


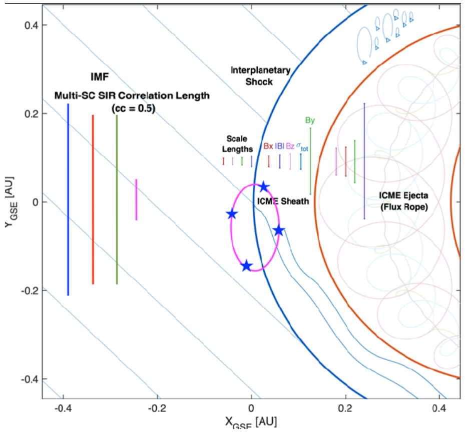


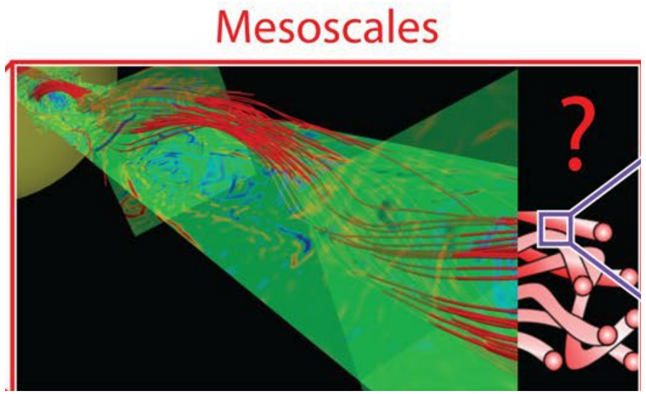


Research Perspective: The Need for Multi-Point Measurements in Solar/Heliospheric Studies

- Significance of coronal observations
  - A comprehensive set of solar observations (4π-steradian coverage in UV, VIS wavelengths) will advance the community's modeling capability of physical processes, energetics, and dynamics.
  - The observational backbone for such studies will be a long-term VIS and EUV monitoring on the Sun-Earth line such as the one supplied by NOAA's SWFO-L1 and GOES-R observatories. Their images are providing context for interpreting off-Sun-Earth line observations and quantifying space physics processes.
- Significance of solar wind measurements at Lagrange 1
  - A heliospheric constellation at L1 with *in situ* instrument suites will be useful in identifying and understanding CMEs, solar wind streams, other transients, and solar energetic particles (SEPs) and quantifying mesoscale structures, while increasing the accuracy of L1-based space weather forecasts.
  - This observational need has been discussed [e.g., Vourlidas+ 2021; WPs in DS2024: Allen+, Lugaz+, etc.].
  - While the community is planning for such constellations upstream of L1 and off the SEL, there are benefits from an "L1 swarm" using legacy and new missions (Aditya-L1, SWFO-L1, IMAP).
- Community recommendations on these topics including those for a HelioSystems Laboratory have been codified in the Decadal Survey for Solar and Space Physics (December 5, 2024).



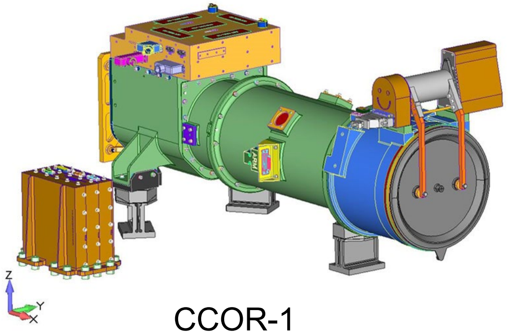




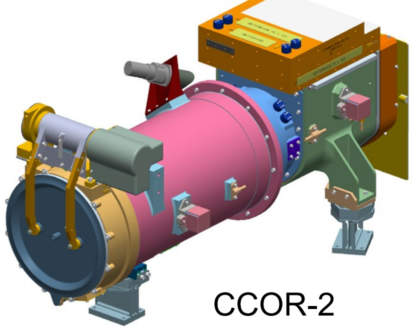
Above: current and near-term coronal imaging missions.
Below: Constellation measurements of a transient (here: a CME) [Lugaz+, 2022]; sampling a mesoscale structure [Allen+, 2022]

SWFO Instrumentation: Coronal Imagery

- SWFO is operating two Compact Coronagraphs (CCORs) with wide fields of view designed for CME detection and tracking.
- The nearly identical instruments are built by NRL and are based on a reduced-SWaP version of STEREO's COR1,2.



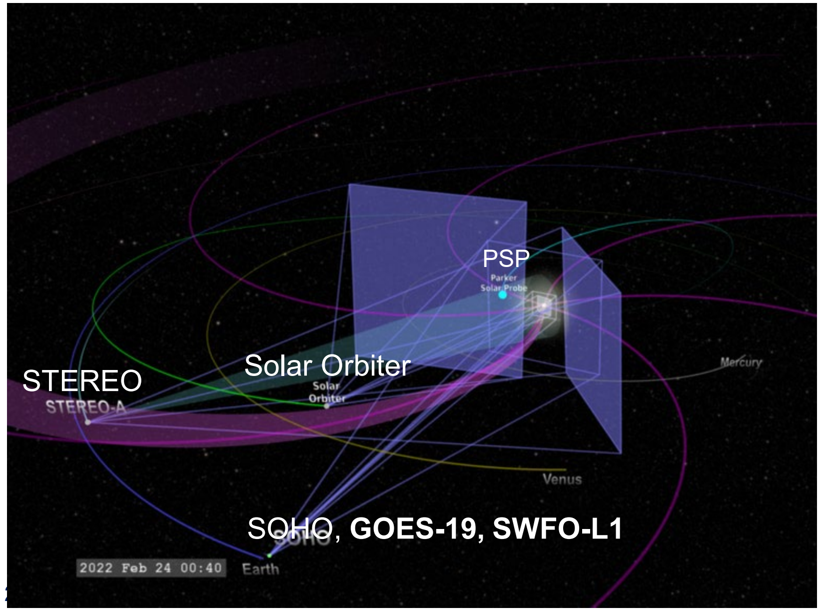
CCOR-1



CCOR-2

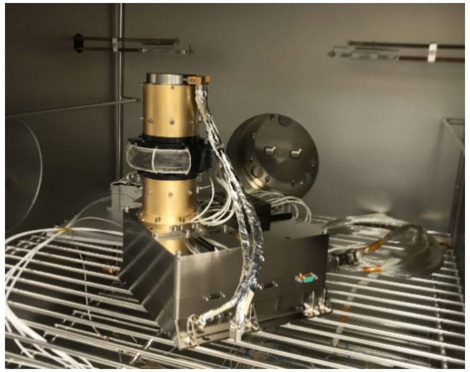
- CCOR-1 is hosted on the GOES-19 satellite at GEO (L. 6/2024).
- CCOR-2 is carried on SWFO-L1 (L. 9/2025) to be placed at L1.
- The image streams from both instruments will be replacing the operational function of SOHO/LASCO's observations.
- These can be combined with observations from other coronagraphs and heliospheric imagers (PUNCH, STEREO, PSP, Solar Orbiter, CODEX, VIGIL (2031)) contributing to the Heliospheric Observatory (HSO).
- SWFO will provide reference measurements due to its location on the Sun-Earth line and continuous observation/high availability.

Coronal White Light Intensity	Threshold
Image Center and Orientation	Sun-centered, Solar North-aligned
Field of View (FOV)	3-22 R_{Sun} for SWFO-L1 3.7-17 R_{Sun} for SWFO GOES-U
Minimum Intensity	1×10^{-11} B_{Sun}
Maximum Intensity	1×10^{-8} B_{Sun}
Spatial Resolution	<70 arcsec for SWFO-L1 <50 arcsec for SWFO GOES-U
Maximum Acquisition Time	30 sec
Measurement Accuracy	± 10%
Measurement Location	Lagrange Point 1 for SWFO-L1 GEO for GOES-U
Refresh Rate	15 min

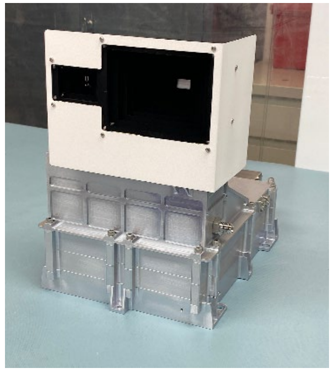


SWFO-L1 Instrumentation: Solar Wind Measurements

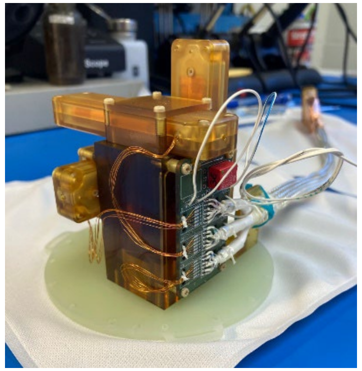
Solar Wind Plasma Sensor (SWiPS): Based on NASA's IES for Rosetta and built by SwRI (PI: Rob Ebert), it measures solar wind plasma moments.



SupraThermal Ion Sensor (STIS): Based on MAVEN/SEP and built by University of California, Berkeley (PI: Davin Larson), it collects suprathermal ion and electron fluxes.



Magnetometer (MAG): A set of two fluxgate sensors, built by Univ. of New Hampshire and SwRI (PI: Roy Torbert), measures the IMF.



Thermal Plasma Ion Velocity	Threshold
Minimum Velocity	200 km/sec
Maximum Velocity	2500 km/sec
Measurement Accuracy	± 10%
Measurement Location	Lagrange Point 1
Refresh Rate	60 sec

Thermal Plasma Ion Density	Threshold
Minimum Density	0.1 particles/cm^3
Maximum Density	150 particles/cm^3
Measurement Accuracy	±10%
Measurement Location	Lagrange Point 1
Refresh Rate	60 Sec

Suprathermal Ion Differential Flux	Threshold
Minimum Energy	50 keV
Maximum Energy	2,000 keV
Minimum Flux, $j_{i,min}$	$2.48x10^2$ * E(KeV)$^{-1.6}$
Maximum Flux, $j_{i,max}$	$1.01x10^7$ * E(KeV)$^{-1.6}$
Flux Accuracy	For energy E=2 MeV: a) ±100% at $j_{i,min}$ and ±20% at $j_{i,mid}$=0.001 #/cm^2/s/sr/keV with linearly interpolated accuracies in the intermediate range: $j_{i,min} < j_i < j_{i,mid}$ b) ±20% for fluxes above $j_{i,mid}$
Measurement Location	Lagrange Point 1
Refresh Rate	300 sec Perf: 2 sec

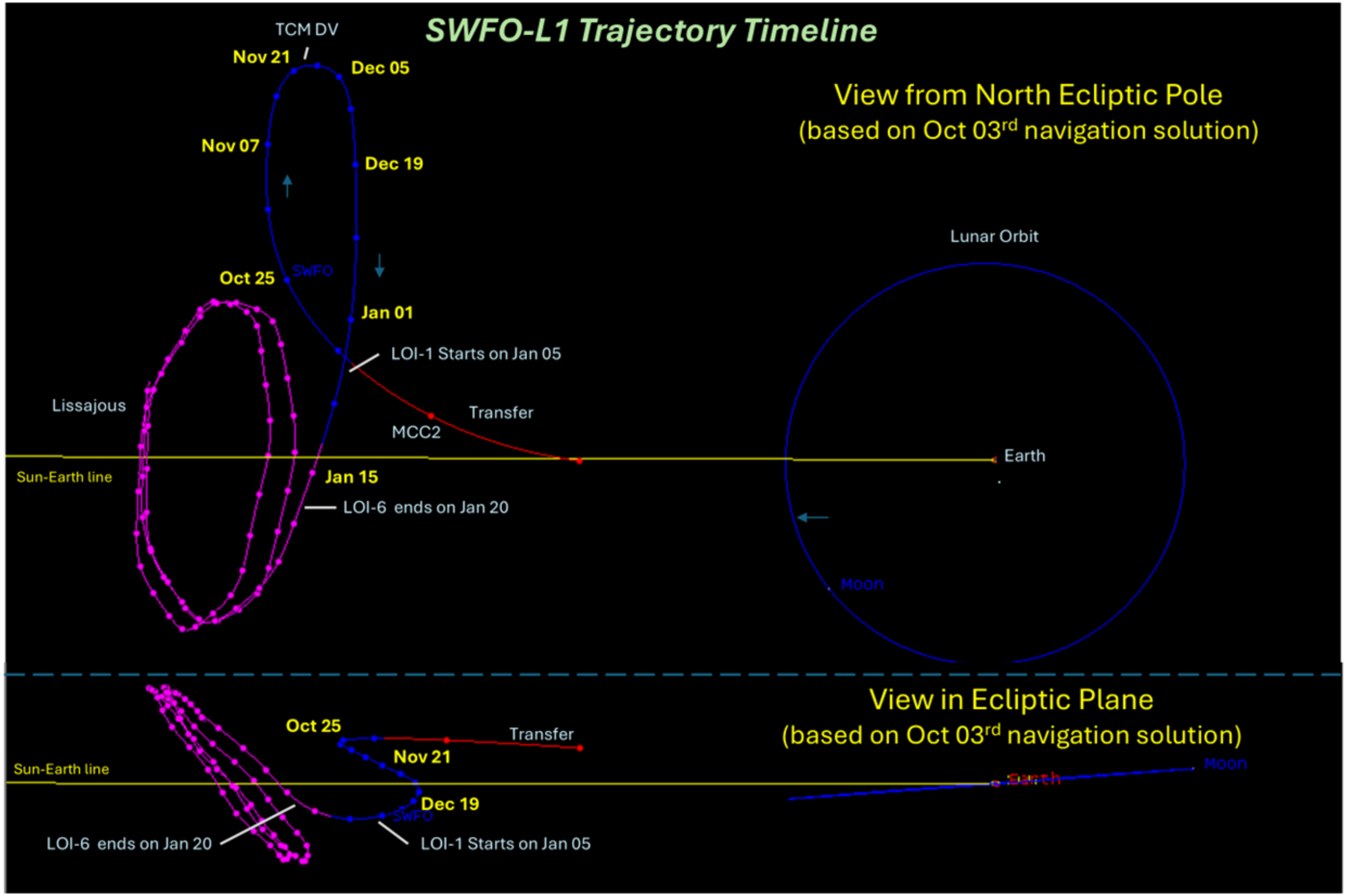
Vector Magnetic Field	Threshold
Range (each component: x, y, z)	±200 nT
Measurement Accuracy (each component: x, y, z)	±1 nT, 0–25 nT ±4%, > 25 nT
Measurement Location	Lagrange Point 1
Refresh Rate	60 sec Perf: 64 Hz

- The SWFO in situ instruments have high heritage from research missions funded by NASA and other agencies
- Instrument performance is expected to exceed requirements based on ground testing and, in one case (CCOR-1 coronagraph), on in-flight record.
- The time resolution of the measurements enables both operational (space-weather) and science usage.
- These are expected to be reference measurements based on the location (L1 point), continuous operation/high availability, and low-latency (reqt: 5 min, actual much lower)

Spacecraft Launch

- SWFO-L1 (now SOLAR-1) and its rideshares, NASA's IMAP and CGO, were launched on September 24, 2025 at 07:30 ET.

Mission Trajectory

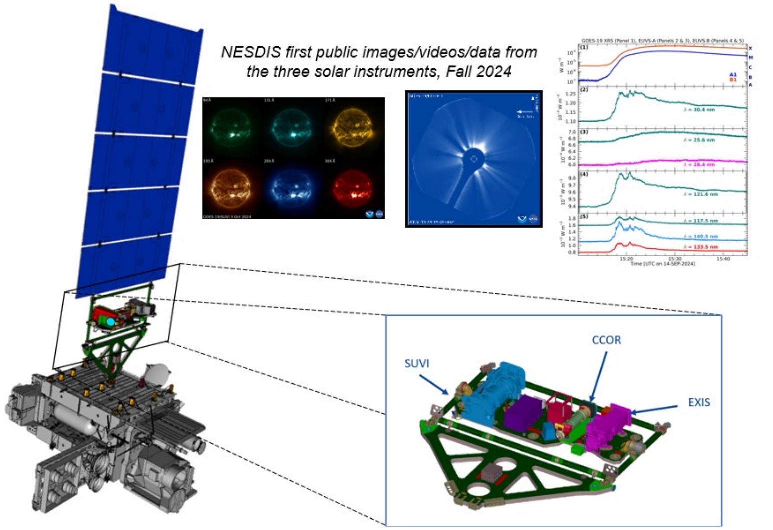


SOLAR-1 Mission Status: Summary

- SWFO-L1 was launched on September 24, 2025.
- All instruments have been powered on, and deployments (MAG boom, High Gain Antenna [HGA]) were completed successfully.
- SWFO-L1 arrival at its orbit around L1 took place on January 23, 2026. The spacecraft was then renamed SOLAR-1 as the first of a new sequence of L1 missions.
- For CCOR-2, first light (door opening) took place on January 23 following the Lagrange Orbit Insertion (LOI).
- On a 24/7 basis, real-time science and HK data are collected by NOAA's worldwide network of ground stations, processed by the Space Weather Prediction Center (SWPC) and National Centers for Environmental Information (NCEI) at minimal latency, and archived.
- SWFO-L1 is currently in the Post-Launch Commissioning (PLC) stage. The Initial Operational Capability (IOC=provision of all Key Performance Parameters, KPPs, to users) is planned NET April 22, 2026.
  - Handover from NASA to NOAA will take place on April 21, 2026.
  - Product validation includes eight reviews (4 completed). They are accompanied by four first-public-data announcements (3 completed).
- Comparisons of the MAG data with ACE show very good agreement.
  - Similarly, comparisons with IMAP (during the transfer orbit to L1, at a distance of ~0.5 R_E) during several intervals shows a high correlation and agreement down to small structures (<1 nT, <60 s).
  - Analysis of plasma and particle-flux datasets has also started and given very good results so far.

SWFO's Relation to the GOES-R (now: GEO) Program

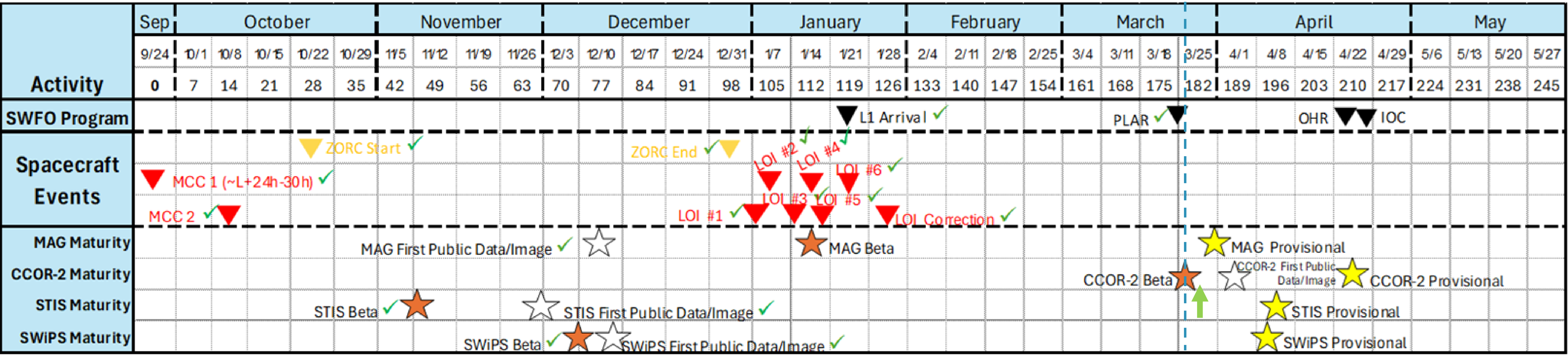
- In order to understand the SWFO product validation, it is useful to recall the corresponding process for GOES-R.
- In fact, since inception, SWFO and its SOLAR-1 observatory have been closely linked to the GOES-R program. They have frequently relied on its infrastructure and adopted best practices.
- Major synergies include:
  - Hosting of the CCOR-1 instrument on the GOES-19 satellite
  - Developing the SWFO Command and Control Center within the GOES-R system
  - Emulating programmatic elements: mission design, main programmatic functions (MM, EM, PG, PD), CONOPS, etc.
  - Emulating systems engineering and technical approaches: requirement development and verification, testing, calibration and validation process, etc.
- However, clearly there are also differences in the observations and products, program scope and size, system and instrument vendors, and other implementation parameters.
- For the discussion here, the SWFO product validation approach has been significantly influenced by GOES-R practices.



SWFO Product Validation Process

The GOES-R heritage extends to SWFO's product validation process. Key components of the SWFO approach include:

- Post-Launch Commissioning (PLC similar to GOES-R PLT) events focus on instrument performance: implementation and data analysis is primarily carried out by the instrument developer with further analysis by NOAA/NCEI
- Post-Launch Product Testing (PLPT) events focus on data quality: implementation and data analysis is carried out by NOAA/NCEI
- Product Validation Reviews (PVRs, similar to GOES-R PS-PVRs)
- Data sharing policy: NOAA/SWPC releases real-time data freely after the provisional (second in order) review for the instrument; similarly, NCEI makes archived operational/retrospective data available.
- First public image/data announcement: between the first two reviews, an image or graph is shared publicly as a first indication of instrument health and data quality.
- Initial Operational Capability: event at which all Key Performance Parameters (KPP) start to be released to the public.



SWFO Product Validation Schedule

Each product undergoes three Product Validation Reviews (PVRs):

1. Beta: internal release to NOAA users
2. Provisional: public release to all operational and science users
3. Full: final release.

Mission	Instrument	Products	1. Beta PVR	2. Prov. PVR	3. Full PVR	First public data announcement
GOES-19, L. Jun 2024	**CCOR-1**	Coronal imagery	Jan 30, 2025	Feb 24, 2025	May 28, 2026	Oct 22, 2024
SOLAR-1 L. Sep 2025	**SWiPS**	(n, V, T): protons (n, V): alpha particles	Dec 8, 2025	Apr 7, 2026	Feb 18, 2027	Dec 12, 2025
	STIS	Particle flux: suprathermal ions, electrons	Nov 12, 2025	Apr 8, 2026	Feb 25, 2027	Nov 26, 2025
	MAG	Interplanetary magnetic field	Jan 14, 2026	Mar 31, 2026	Mar 2, 2027	Dec 11, 2025
	CCOR-2	Coronal imagery	March 24, 2026	Apr 22, 2026	Apr 22, 2027	Feb 12, 2026

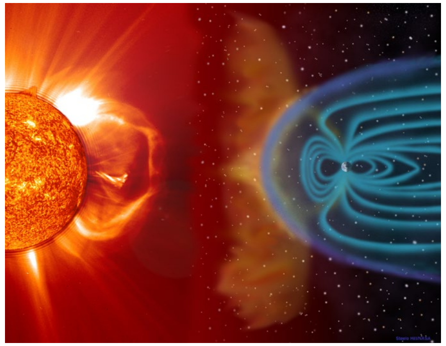
Completed
In Progress
Not Started

At the end of all provisional PVRs, the program reaches its Initial Operational Capability (IOC):

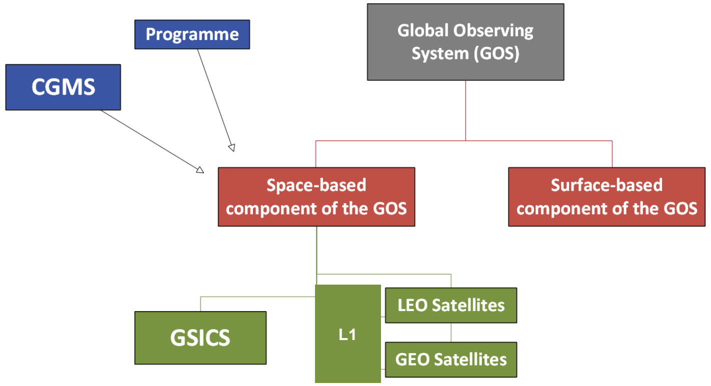
All data are released to users through SWPC (real-time streams) and NCEI (archived products)

Relevance to GSICS

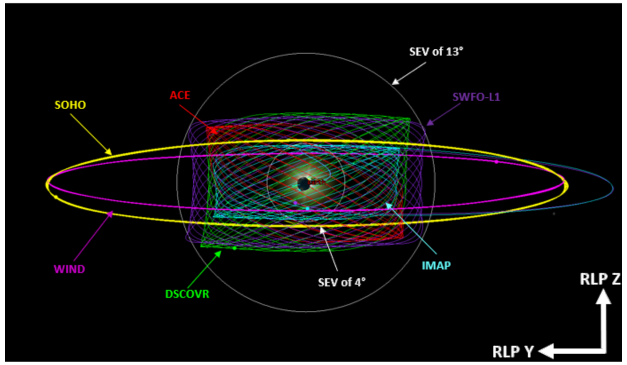
- <u>Background</u>: Space weather is driven by multi-scale phenomena, characterized by long spatial and temporal correlations. Because Earth's space environment is primarily modulated by external solar/heliospheric activity, monitoring the state of the solar atmosphere and the solar wind is critical not only for forecasting, but also for understanding real-time conditions
  - SWFO (and SOLAR-1) provide key components of this information.



1. <u>The upstream boundary</u>: The solar wind upstream of the Earth is an important boundary condition for space weather in geospace environments (magnetosphere, ionosphere, thermosphere).
   - Therefore, it is essential to <u>continually monitor the solar and solar-wind states</u> and utilize them as drivers of space weather conditions at geospace environments.
   - SOLAR-1/SWiPS, MAG: SW/IMF measurements are regularly used for <u>situational awareness</u> of the GEO and LEO environments and used in <u>driving numerical weather models</u>
   - SOLAR-1/STIS: suprathermal particle data can be used as a precursor for SEP events at GEO and lower altitudes.



2. <u>Intercalibration of satellite measurements at L1</u>: the advent of multiple platforms at L1 ("L1 swarm") enables the development of methods of quantitative comparisons of corresponding datasets.
   - There are now six solar wind monitoring spacecraft orbiting the Sun-Earth L1 point: recently launched SOLAR-1, IMAP, Aditya-L1, and the earlier ACE, DSCOVR, and Wind. There is <u>a significant need for intercalibration of plasma/IMF/particle-flux data</u> for operational as well as science objectives.



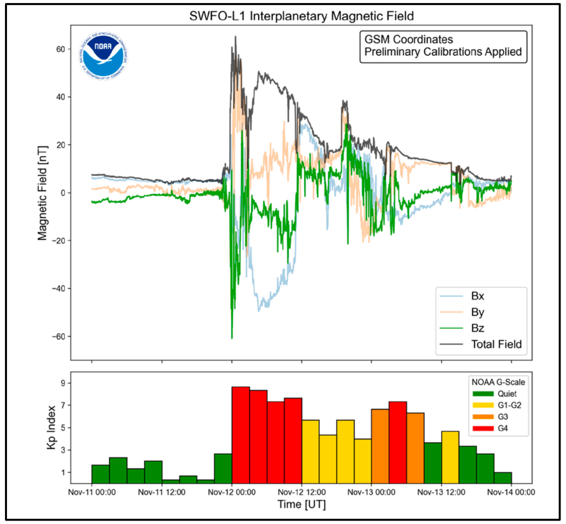
[Webster and Folta, Feb 2025]

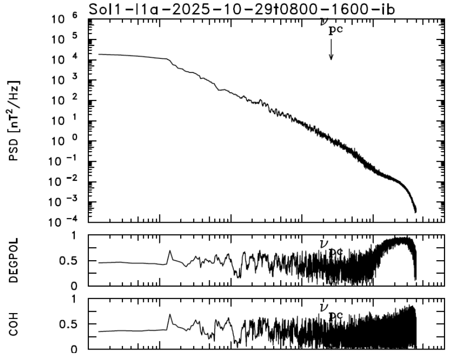
*SEV = Sun-Earth Vehicle Angle
*RLP = Rotating Libration Point

Neighbors at Sun-Earth L1

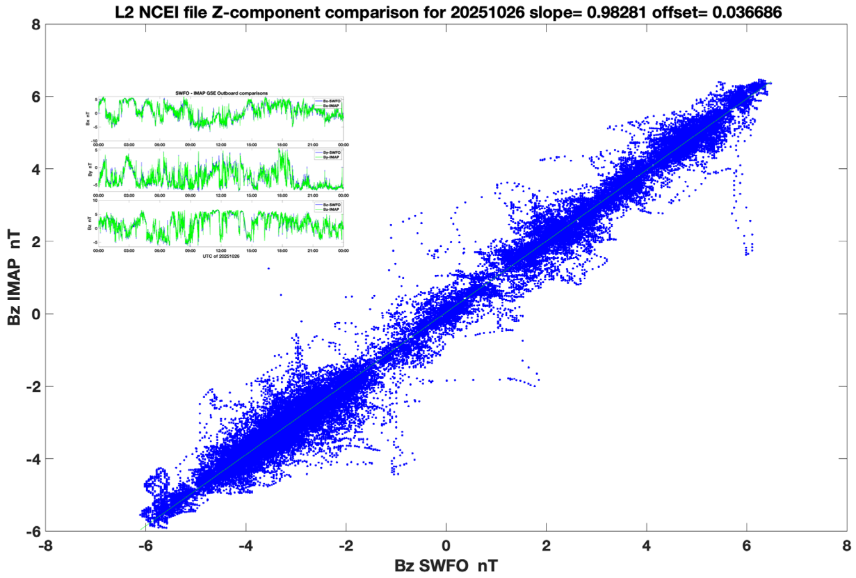
SOLAR-1/MAG Data Products

- Product types: magnetic field (vector) in GSE, GSM, and ECI coordinate systems
  - Planned operational use: driving SWPC/Geospace, OVATION-Prime, WAM-IPE, and other models, situational awareness
- Examples: measurements of CMEs, shocks, waves, turbulence at high resolution (<0.3 nT) and cadence (64 vectors/s); several events shown on right.
- Product status and quality: excellent quality supported by PLC reports and NCEI/SWPC analysis. Instrument meets/exceeds all requirements and products have been generated without limitations.
- Cal/Val: comparison between OB/IB sensors and intercalibration with IMAP, ACE, etc. has given very satisfactory results (example on right)
  - Instrument parameters have been adjusted using measurements and tests. Offsets calculated from Alfvenic intervals. Additional measurements taken during X- and Y-calibration rolls.
- Outlook: After the provisional-maturity PVR planned for March 31, 2026, MAG products will be ready for operations.





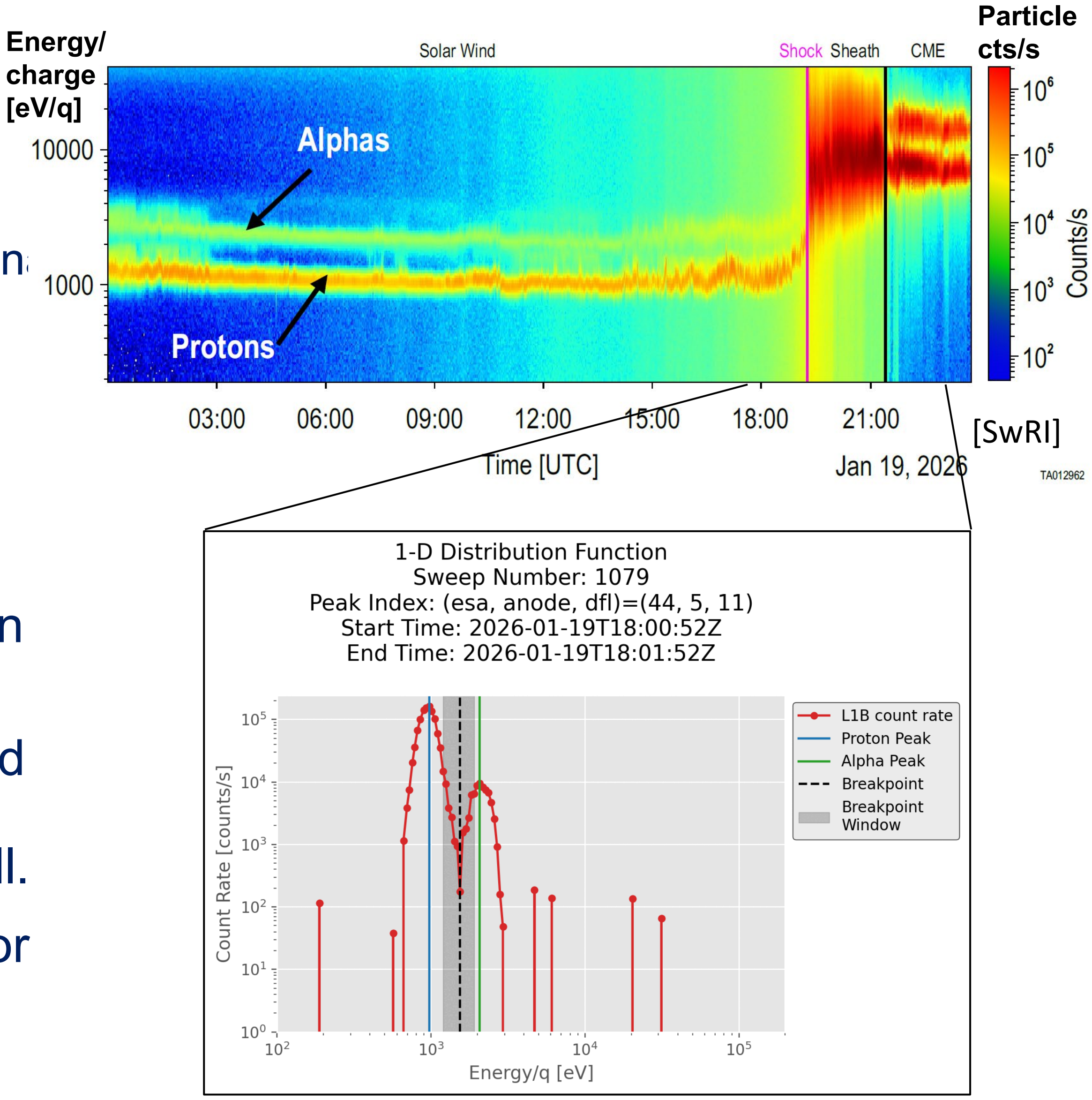
Magnetic-field spectral analysis [UNH]



IMAP MAG data are used by permission and for Cal/Val purposes [UNH]

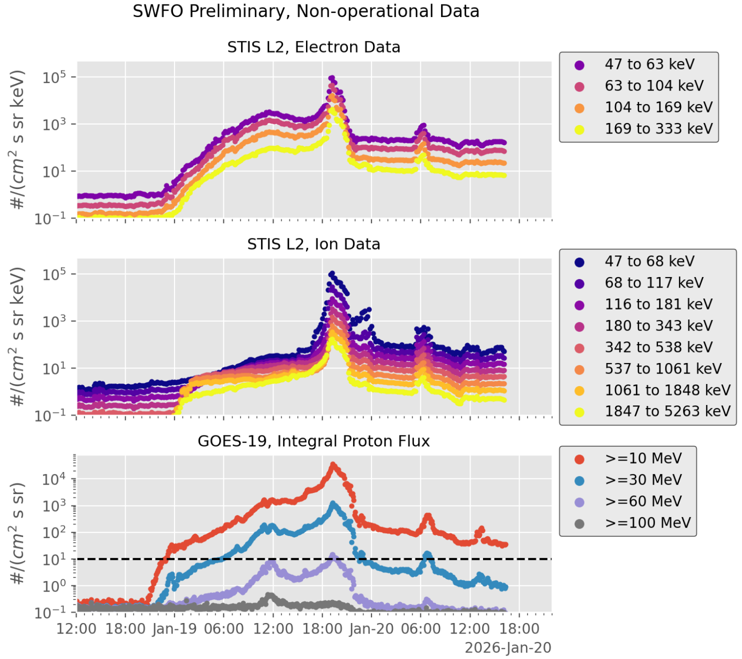
SOLAR-1/SWiPS Data Products

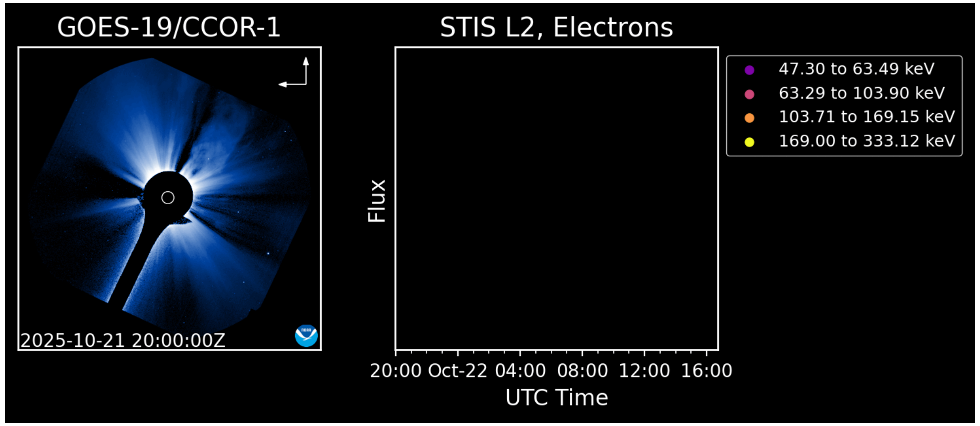
- Product types: Level 2 solar wind density, velocity (vector), temperature.
  - Planned operational use: driving SWPC/Geospace, OVATION-Prime, WAM-IPE, and other models, situational awareness
- Examples: measurements of CMEs, shocks, waves, turbulence at high resolution; the January 19 CME is shown on the right.
- Product status and quality: Excellent quality of measurements providing resolution of small features in spectrograms, high dynamic range in (n, V, T).
- Cal/Val: ongoing comparison with ACE, DSCOVR, and Wind plasma measurements has shown very good results. IMAP/SWAPI data have been obtained as well.
- Outlook: After the provisional-maturity PVR planned for NET April 7, 2026, SWiPS products will be ready for operations.



SOLAR-1/STIS Data Products

- Product types: suprathermal ion and electron fluxes at higher resolution than ACE/EPAM.
  - Planned operational use: long-lead-time forecasts of solar radiation storms relevant to astronaut health and civil aviation; forecasts of geomagnetic storm activity expressed in terms of Kp index
- Examples: Events on Nov 11-13, Jan 10 and 19, etc. (right)
- Product status and quality: Excellent quality of high-resolution ion/electron energy spectra meeting accuracy requirements. While validation is continuing, all indications are that the data are useful in improving forecasts.
- Outlook: After the provisional-maturity PVR planned for NET April 8, 2026, STIS products will be ready for operations.





[SWPC]

Access to SWFO Data and Information

1. Operational data: access via the Space Weather Prediction Center (SWPC).
2. Cloud-based archive of operational and retroprocessed data: available from NOAA/NCEI's Space Weather Portal (SPOT)
3. Information on the Program, spacecraft, and instruments: Space Weather Observations (SWO) webpage.

2. NCEI

https://www.ncei.noaa.gov/products/space-weather/swfo

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Space Weather Follow-On (SWFO)

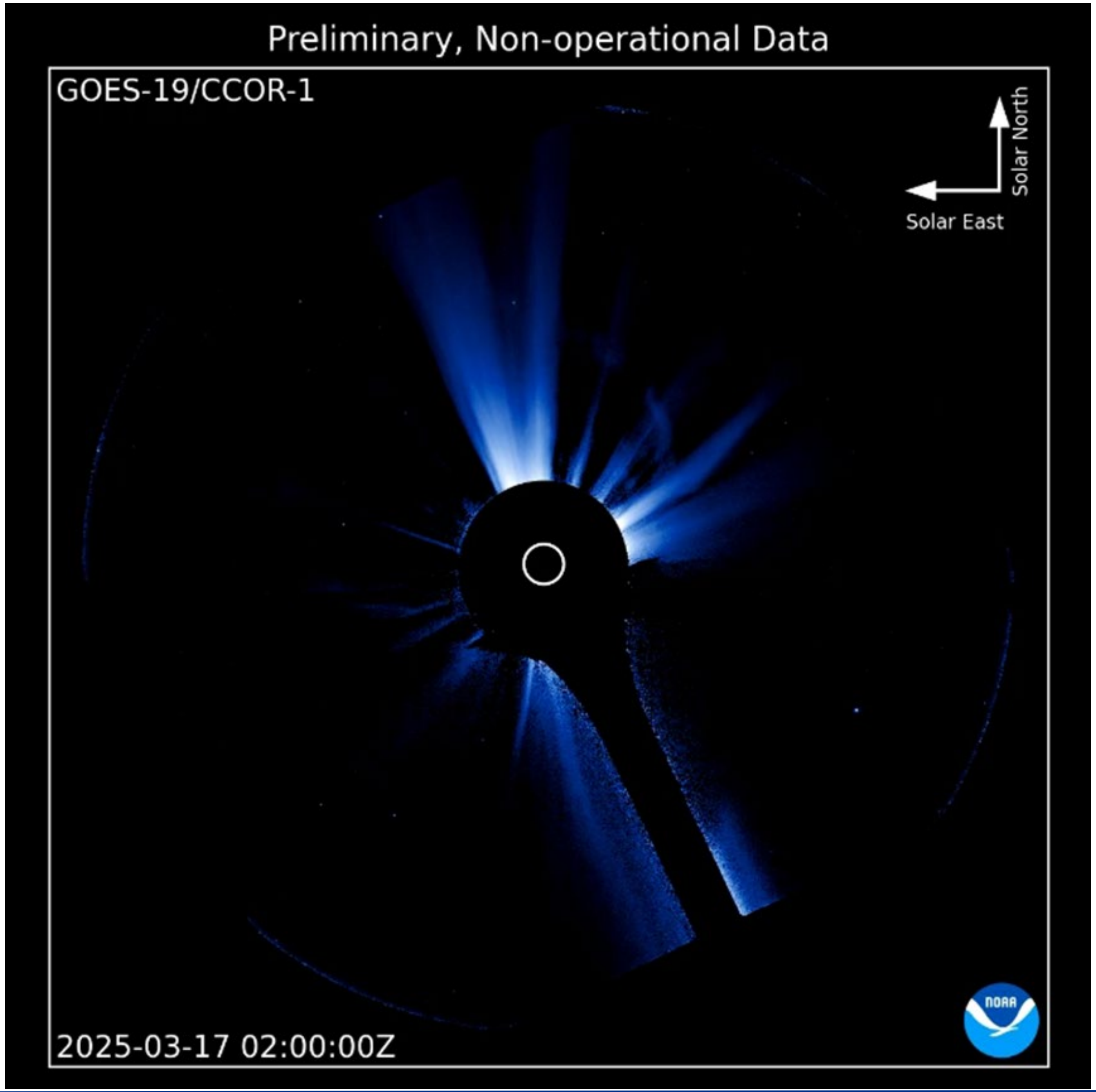
The Space Weather Follow-On (SWFO) program was designed to ensure continuity of critical space-based measurements of the solar corona and interplanetary medium. It supports NOAA's mission to monitor Space Weather and to provide timely and accurate warnings to help our nation prepare for and minimize potential impacts to the economy and human health.

NCEI archives and disseminates SWFO operational and science-quality data products, preserves and improves content, and ensures that data and metadata are accessible and easy to use. This page provides access to data and documentation from SWFO instruments.

*The upcoming **NCEI Space weather POrTal (SPOT)** will be the one-stop cloud-based NOAA web poi data. The first data served via SPOT will come from the SWFO program. While the SPOT portal is rec data links via NODD (NOAA Open Data Dissemination). This is a cloud-based initiative that provides environmental datasets through cloud service providers.*

Check this page for an announcement on SPOT's future release date.

For questions about the data, use the contact info in the relevant readme files, or email ncei.info(

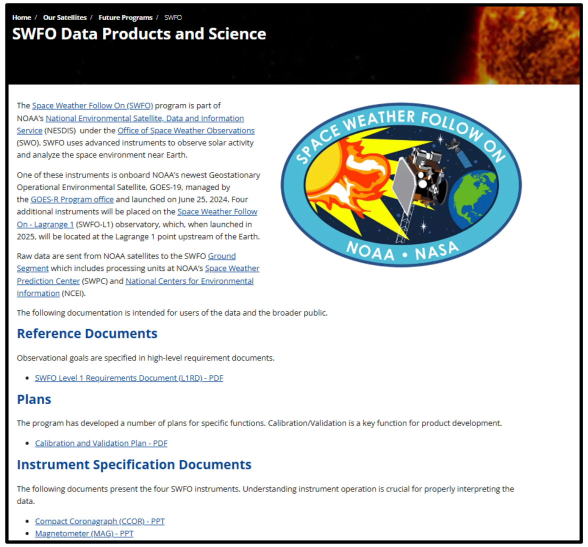


1. SWPC

https://www.swpc.noaa.gov/observations

3. SWO

https://www.nesdis.noaa.gov/our-satellites/future-programs/swfo/swfo-data-products-and-science



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SWFO Data Products and Science

The Space Weather Follow On (SWFO) program is part of NOAA's National Environmental Satellite, Data and Information Service (NESDIS) under the Office of Space Weather Observations (SWO). SWFO uses advanced instruments to observe solar activity and analyze the space environment near Earth.

One of these instruments is onboard NOAA's newest Geostationary Operational Environmental Satellite, GOES-19, managed by the GOES-R Program office and launched on June 25, 2024. Four additional instruments will be placed on the Space Weather Follow On - Lagrange 1 (SWFO-L1) observatory, which, when launched in 2025, will be located at the Lagrange 1 point upstream of the Earth.

Raw data are sent from NOAA satellites to the SWFO Ground Segment which includes processing units at NOAA's Space Weather Prediction Center (SWPC) and National Centers for Environmental Information (NCEI).

The following documentation is intended for users of the data and the broader public.

Reference Documents

Observational goals are specified in high-level requirement documents.

- SWFO Level 1 Requirements Document (L1RD) - PDF

Plans

The program has developed a number of plans for specific functions. Calibration/Validation is a key function for product development.

- Calibration and Validation Plan - PDF

Instrument Specification Documents

The following documents present the four SWFO instruments. Understanding instrument operation is crucial for properly interpreting the data.

- Compact Coronagraph (CCOR) - PPT
- Magnetometer (MAG) - PPT

Summary

- The SWFO Program (CCOR-1 and SWFO-L1) provides the critical continuity of coronal imagery and solar wind measurements to the Space Weather Prediction Center. Its data products have dual use in supporting situational awareness and furthering solar and heliospheric research.

- The SWFO-L1 observatory was launched from Kennedy Space Center on September 24, 2025 as a rideshare with IMAP and CGO, and has been in nominal condition. After completing the Lagrange Orbit Insertion (LOI) maneuvers on January 23, it was renamed SOLAR-1. All instruments have been collecting high-quality data. NOAA recently shared the first public images for the plasma, IMF, and suprathermal-particle sensors.

- SWFO provides situational awareness for GSICS-related data products at GEO and LEO and drives relevant numerical weather prediction models. The SWFO science teams apply intercalibration and reprocessing methods to data at L1 similar to those applied to particle and field measurements at Earth-centered orbits.

- Based on the SOLAR-1 operation from Lagrange 1, the in situ data and coronal images are expected to be used in a wide range of geospace applications including the driving of real-time models of the space environment and supporting model development and analysis. A growing number of papers and presentations are documenting this progress, including a collection planned for publication in Space Science Reviews (SSR).

- SOLAR-1 data will be accessible at the NCEI Space Weather Portal (SPOT). More information is available at SWO's SWFO webpages including the Data Products and Science webpage which includes papers, presentations, and spacecraft- and instrument-related technical documentation. In addition, an article on SOLAR-1 will appear in the April issue of the quarterly GSICS Newsletter.