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# Space Weather Follow On (SWFO) Program Calibration and Validation Plan

**U.S. Department of Commerce (DOC)**
**National Oceanic and Atmospheric Administration (NOAA)**
**National Environmental Satellite, Data, and Information Service (NESDIS)**
**National Aeronautics and Space Administration (NASA)**

# Space Weather Follow On (SWFO) Program

# Calibration and Validation Plan

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# Preface

This document is under SWFO configuration control. Once this document is approved, SWFO approved changes are handled in accordance with Class I and Class II change control requirements as described in the SWFO Configuration Management Procedures, and changes to this document shall be made by complete revision.

Any questions should be addressed to:

SWFO Configuration Management Office
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# Change History Log

| **Revision** | **Effective Date** | **Description of Changes**<br>(Reference the CCR & CCB/ERB Approval Date) |
|---|---|---|
| Original | 01/06/2023 | Initial baseline reviewed and released via SWFOGS-CCR-0002. |
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# CALIBRATION AND VALIDATION OVERVIEW

# 1. INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite Data and Information Service (NESDIS) has created the Space Weather Follow On (SWFO) program with the goal of supplying the National Weather Service (NWS) Space Weather Prediction Center (SWPC) and other stakeholders with critical measurements of Earth's space environment. The measurements are necessary for situational awareness of the current activity levels and accurate forecasting of future disturbances. Acquisition assistance for the program is provided by the National Aeronautics and Space Administration (NASA). The SWFO program is a continuation and expansion of earlier NOAA observational capabilities.

## 1.1 Scope

This document describes the calibration and validation (cal/val) procedures for the SWFO Program, which are applied to instruments operating in space and collecting data, and to software used on the ground to process such data and develop space weather data products. Instrument cal/val as well as product validation are essential to SWFO mission success. Pre-launch verification determines that an instrument system, subsystem, or component is functioning within requirements. Calibration and characterization continue after launch as a means to maintain quality of the SWFO data products. Validation is defined as the process of determining that the deliverable item satisfies its intended use in its intended environment.
The document is complementary to the SWFO Verification and Validation Plan and consistent with the SWFO validation objectives.

### 1.1.1 Additional Information

The document describes the methods used to improve the accuracy of the instruments and data products. Cal/val procedures are essential in ensuring data product quality.

SWFO is a major project in NOAA's satellite acquisition program, and a comprehensive and integrated cal/val plan is:

- A description of cal/val activities and processes implemented to ensure observations from the SWFO program meet NOAA's operational mission requirements;
- A link between SWFO data product performance and instrument calibration and the application of ground processing algorithms and monitoring tools in the ground segment data processing system;
- A tool for planning, budgeting, implementation and execution of calibration-related activities within the Program to address the increased complexity and demanding accuracy and stability requirements of SWFO instruments;
- A program-wide perspective of SWFO cal/val; and

- A structure that facilitates long-term data integrity and user confidence, and institutional technical memory.

## 1.2 Purpose

Cal/val procedures are essential in maintaining data product accuracy and quality. Calibration is applied to the instruments as well as to the ground processing algorithms (GPAs). It is an important function before launch and during the operational life of the mission. Validation of GPAs and data products is useful in ensuring product quality.

The SWFO instruments are expected to have stringent calibration standards. Space weather forecasters and real-time numerical weather prediction (NWP) models depend on images and data with as-few-as-possible artifacts and other errors. In NWP work, calibration biases must be resolved before assimilation. This translates to diligent calibration, and vigorous post-launch Level-1b (L1b) product validation, efforts to ensure data usability accompanies data accessibility.

Given the importance of cal/val to mission success, the SWFO Program has made a long-term commitment and synergistic effort towards implementing these functions. This not only enhances our knowledge of whether or not mission requirements and instrument specifications are being met, but encourages long-term data quality and user confidence. Given the broad scope of the mission cal/val activities associated with these priorities, it is important that a comprehensive cal/val plan be created and maintained.

## 1.3 Organization

This Calibration and Validation Plan (CVP) is organized in three parts.

Part 1 (Sections 1-5) contains the general approach for cal/val in the SWFO Program.

Section 1 (this section) provides information regarding the scope, purpose, and organization of this document.

Section 2 lists parent documents and related documents that were used as sources of information for this document or that provide additional background information to aid understanding of the interface implementations.

Section 3 presents the SWFO program and introduces its segments and their elements. It describes the data processing and dissemination of products to space weather information users. It also provides a summary view of the data products for each instrument and defines levels for all products.

Section 4 describes the calibration approach used in the Program. It discusses the main activities for each relevant phase of the mission, describes roles and responsibilities, and lists deliverables.

This section contains plans associated with:

- Instrument characterization and calibration through all mission phases;
- Level-0b – L3 product processing algorithms through all mission phases; and
- Post-launch activities:
    - Near- and long-term instrument performance monitoring; and
    - Spatial and L2 measurement validation, assessment, and anomaly resolution.

In the first part of the document, special focus is given to on-orbit data integrity activities — *e.g.*, measurement performance analyses; sensor parameter trending; in-flight calibration system analysis; intersatellite/inter-sensor calibration; vicarious calibration; and spatial calibration — of the instruments. In addition to sourcing NOAA and NASA earlier programs, a great deal of information has also been extracted from instrument and ground segment vendor delivered documents to create the plan. It is developed based on the experience and lessons-learned from the heritage NOAA systems, as well as other programs. The methodologies described in the first part encompass both traditional approaches and the current state-of-the-art in cal/val.

Section 5 describes the overall product validation approach. It presents several correlative data sources and discusses major challenges and their resolution.

Part 2 (Sections 6-7) focuses on remote sensing of the Sun in the visible part of the electromagnetic spectrum.

Section 6 describes cal/val activities for the Compact Coronagraph 1 (CCOR-1) at geostationary orbit and CCOR-2 at Lagrange point 1 (L1) observing the faint solar corona in visible light. The activities relevant to data products at Levels 1a, 1b, and 2 are described first, followed by activities relevant to Level 3. In each subsection, a review of the relevant requirements is presented, and is followed by a description of instrument and algorithm development. Activities are divided in before- and after-launch phases including the operational phase.

The structure of Section 6 is repeated for all other instruments.

Part 3 (Sections 7-9) focuses on in situ (local to the spacecraft) measurements of the solar wind, which flows out from the surface of the Sun and fills the solar system.

Section 7 describes cal/val activities for the Solar Wind Plasma Sensor (SWiPS) at L1 measuring the low-energy (“thermal”) plasma which defines most of the solar wind.

Section 8 describes calibration and validation activities for the SupraThermal Ion Sensor (STIS) measuring the flux of particles with energies higher than the solar wind plasma.

Section 9 describes calibration and validation activities for the Magnetometer (MAG) measuring the magnetic field carried by the solar wind.

Appendix A contains references.

Appendix B contains abbreviations and acronyms.

# 2. RELATED DOCUMENTATION

The latest versions of all documents listed below should be used. The latest SWFO documents can be obtained from https://ipdtdms.gsfc.nasa.gov/frontmenu_dsp.csm. SWFO Project documents have a document number starting with 411, 411.1 or 411.2 indicating the governing Configuration Control Board (CCB) (Program, Flight or Ground) that has the control authority of the document.

## 2.1 Parent Documents

The following document(s) is (are) the Parent Document(s) from which this document has been derived. Any modification to a Parent Document will be reviewed to identify the impact upon this document. In the event of a conflict between a Parent Document and the content of this document, the SWFO Program CCB has the final authority for conflict resolution.

**Table 1: Parent Documents**

| Document Number | Title |
|---|---|
| 411.0-00005 Revision - | Space Weather Follow On (SWFO) Program Preliminary Level 1 Requirements Document (L1RD) |
| | Space Weather Follow On (SWFO) Program System Engineering Management Plan (SEMP) |

## 2.2 Applicable Documents

The following document(s) is (are) the Applicable Document(s) from which this document has been derived. Any modification to an Applicable Document will be reviewed to identify the impact upon this document. In the event of conflict between an Applicable Document and the content of this document, the SWFO Program Control Board has the final authority for conflict resolution.

**Table 2: Applicable Documents**

| Document Number | Title |
|---|---|
| 411.0-00016, Rev A | Space Weather Follow On – Lagrange 1 (SWFO-L1) Project Level 2 Requirements Document (L2RD) |
| 411.0-00013, Rev C | Space Weather Follow On (SWFO) Ground L2RD |
| 411.0-00012, Rev A | Space Weather Follow On Geostationary Operational Environmental Satellite - U (SWFO GOES-U) L2RD |

## 2.3 Information Documents

The following documents are referenced herein and amplify or clarify the information presented in this document. These documents are not binding on the content of this document.

**Table 3: Information documents.**

| Document Number | Title |
|---|---|
| 411.1-00014 | National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC), SWFO-L1 Satellite Requirements Document, August 2019 |
| SSD-RQT-CC001 | Naval Research Laboratory (NRL), Operational Requirements Document (ORD) for the Compact Coronagraph (CCOR), SSD-RQT-CC001, August 2018 |
| SSD-PLN-CCOR-018 | NRL, Instrument Operations Plan for the Compact Coronagraph (CCOR), SSD-PLN-CCOR-018, August 2018 |
| 411.1-00012 | NASA GSFC, SWFO-L1 Solar Wind Plasma Sensor (SWiPS) Requirements Specification (SPEC), September 2019 |
| 411.1-00003 | NASA GSFC, SWFO-L1 SupraThermal Ion Sensor (STIS) Requirements Specification (SPEC), September 2019 |
| 411.1-00009 | NASA GSFC, SWFO-L1 Magnetometer (MAG) Requirements Specification (SPEC), September 2019 |
| 410-R-CONOPS-0008, V2.9 | NOAA/NESDIS/GOES, GOES-R Series Concept of Operations (CONOPS), July 8, 2016 |
|  | NOAA/NESDIS/OPPA, Space Weather Follow On (SWFO) Management Control Plan (MCP), June 2019 |
| SWFO-SYS-PLAN | NOAA/NESDIS/OPPA, Space Weather Follow On – Lagrange 1 (SWFO-L1) Verification and Validation (V&V) Plan (in development, February 2021) |
|  | NOAA/NESDIS/OPPA, Space Weather Follow On (SWFO) Algorithm Development Management Plan for Ground Segment Product Generation (in development) |
| 411.0-00001 | NOAA/NESDIS/OPPA, Space Weather Follow On – Lagrange 1 (SWFO-L1) Configuration Management Plan (in development) |
| 411.0-00009 | NOAA/NESDIS/OPPA, SWFO Program Resource Allocation Document (RAD) |
| 411.0-00029 | NOAA/NESDIS/OPPA, SWFO Verification and Validation Plan |
| 411.2-00008 | NOAA/NESDIS/OPPA, SWFO Ground Segment Command and Control (C2) Requirements Document (C2RD) |

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|---|---|
| 411.2-00009 | NOAA/NESDIS/OPPA, SWFO Ground Segment SWFO Antenna Network (SAN) Requirements Document (SAN RD) |
| 411.2-00010 | NOAA/NESDIS/OPPA, SWFO Ground Segment Product Generation – Product Distribution (PGD) Requirements Document (PGD RD) |
| 411.2-00024 | NOAA/NESDIS/OPPA, Space Weather Follow On – Lagrange 1 (SWFO-L1) Observatory to SWFO Antenna Network (SAN) Interface Requirements Document (IRD) |
| SWRI 26093-CPP-01, Preliminary | Calibration Program Plan for the Space Weather Follow On at Lagrange 1 (SWFO-L1) Solar Wind Plasma Sensor (SWiPS) Instrument |
| UCB BST-SYS-006 | SWFO STIS Calibration Program Plan |

# 3. SWFO PROGRAM SUMMARY

The SWFO Program represents a continuity capability with comparable spatial and temporal resolution over the capabilities of earlier missions, which have been operating past their nominal lifetime. These legacy missions are the Solar and Heliospheric Observatory (SOHO), a joint NASA and European Space Agency mission, and NOAA's Deep Space Climate Observatory (DSCOVR). The Geostationary Operational Environmental Satellites- Series U (GOES-U) and SWFO-L1 spacecraft are expected to be available for operations in 2025 and operate for at least 5 years. Depending on the needs of the GOES-R and SWFO programs, GOES-U may go into storage until 2032.

The SWFO Program comprises two segments, the Flight Segment and the Ground Segment (GS). The Flight Segment provides the space weather measurements that are processed into data products of different levels at the GS.

The Program instruments include those carried on the SWFO-L1 observatory namely CCOR-2, SWiPS, STIS, and MAG; and the CCOR-1 coronagraph hosted on the GOES-U satellite of the GOES-R Program. Using these instruments, the SWFO program will acquire solar images and solar wind measurements to monitor space weather drivers.

Instrument calibration, characterization, and validation, as well as L2 product validation, are essential to SWFO mission success. The SWFO definition of calibration is "the process of determining factors for converting and correcting raw detector measurements into science data units (e.g., radiance) with the specified level of accuracy". Additionally, instrument characterization describes quantitatively how the behavior of a given system, subsystem, or component – e.g., interference filter spectral response, optical distortion, charged-couple device quantum efficiency, electronic cross-talk, etc. - responds under the expected range of operational conditions. Together, the tests, demonstrations, analysis, and inspections associated with calibration and characterization form the backbone of a verification process. Verification nominally occurs prior to delivery and launch, and its purpose is to determine that an applicable instrument system, subsystem or component is functioning within requirements. Calibration and characterization continue after launch as a means to maintain quality of the SWFO L2 data products. Validation is the process of determining that the deliverable item satisfies its intended use in its intended environment, and the validation of SWFO instruments and L1a-L3 products is most fully realized after launch with observations and in situ measurements.

## 3.1 Flight Segment

The Flight Segment contains the SWFO-L1 observatory and several instruments used for recording imagery and other measurements and carried on SWFO-L1 and the GOES-U satellite.

### 3.1.1 The SWFO-L1 Observatory

The Space Weather Follow On – Lagrange 1 (SWFO-L1) observatory will orbit the L1 point. It is a three-axis stabilized spacecraft providing attitude control, thermal control, and communications capabilities; and carrying several space weather instruments.

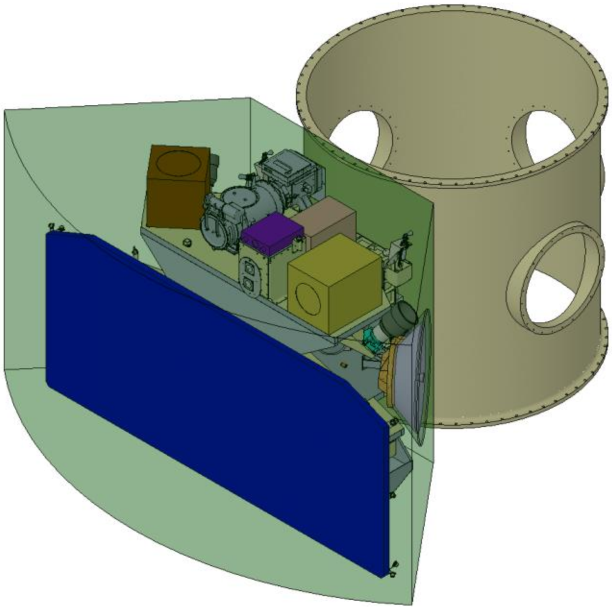

**Figure 1. SWFO-L1 Observatory with instruments on the ESPA ring.**

The spacecraft will carry the CCOR-2, similar in objectives and operation to CCOR-1. The CCOR will be an improvement in size and mass over the Large Angle and Spectrometric Coronagraph (LASCO) carried on SOHO.

SWFO-L1 will also carry the Space Weather Instrument Suite (SWIS) to make in situ measurements of the solar wind flowing past the SWFO-L1.

- The SWiPS will measure properties of the solar wind plasma, which is at low energies (“thermal”). It will provide comparable measurements to the Faraday Cup (FC) instrument carried on DSCOVR, but at a lower time resolution.
- The STIS will measure the flux of particles at higher energies than the plasma. It is a new capability compared to DSCOVR and comparable to NASA’s Advanced Composition Explorer’s (ACE) Electron, Proton, and Alpha-Particle Monitor (EPAM) instrument.
- The MAG will measure the interplanetary magnetic field carried by the solar wind.

### 3.1.2 GOES-U and the Compact Coronagraph-1

The GOES-U, shown in Figure 2a, is the fourth satellite in the GOES-R series with Earth observation and space weather measurement capabilities. This satellite will carry the CCOR-1 for the SWFO Program. The satellite contains a Solar Pointing Platform (SPP) which will carry CCOR-1 together with other solar imaging and irradiance instruments (Fig. 2b). The SPP provides stabilization control while instruments maintain their own thermal control.

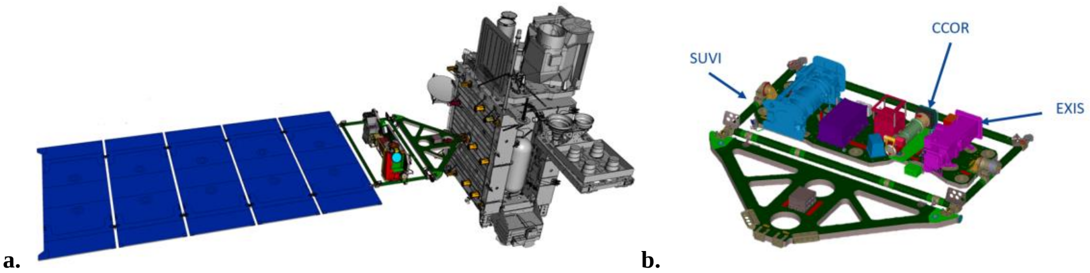

**Figure 2. a. The GOES-U satellite. b. The Solar Pointing Platform (SPP) carrying the CCOR-1 and other instruments.**

CCOR-1 is an important part of the SWFO Program. It is a telescope designed to take images of the faint solar corona while blocking the light of the solar disk. It is similar to CCOR-2 operating onboard the SWFO-L1 observatory.

## 3.2 Data Products and Levels

Images or measurements recorded by SWFO instruments will be used to create the environmental data products shown in Table 4. The plasma properties refer to the solar wind while the magnetic field is the IMF carried by the wind. The plasma velocity and the magnetic field are vectors, and the suprathermal ion flux is evaluated over several energy channels.

The most important data products are defined as the Key Performance Parameters (KPPs). The SWFO Program reaches its Initial Operational Capability (IOC) for each of its two flight projects (the SWFO-L1 observatory and the CCOR-1 instrument on GOES-U) when it has generated all KPPs from that project and has made them available to space weather users. Note that the CCOR-1 instrument on GOES-U is not considered a KPP.

**Table 4. SWFO Program high-level data products with Key Performance Paramters indicated.**

| Instrument | Data Product | KPP |
|---|---|---|
| CCOR-2 | Coronal White-light Intensity | Y |
| SWiPS | Solar wind plasma density | N |
| SWiPS | Solar wind plasma velocity (vector) | Y |
| SWiPS | Solar wind plasma temperature | N |
| SWiPS | Solar wind plasma pressure | N |
| STIS | Suprathermal ion differential flux | N |

| | | |
|---|---|---|
| MAG | Magnetic field (vector) | Y |

Similarly, the Program reaches its Full Operational Capability (FOC) independently for each project when it has made all data products, including KPPs, from that project available to users.

The data levels are defined in general terms as follows:

- **Level 1a:** Derived from Level 0b products at full resolution, time-referenced with physical units, and typically referenced to the sensor and/or spacecraft coordinate frames. Data may be calibrated and shall be annotated with ancillary information including data quality indicators, calibration coefficients and parameters for referencing the spacecraft and field of view to a defined coordinate system.
- **Level 1b:** Derived from Level 1a at full resolution, time-referenced with physical units, and referenced to a standard coordinate system (e.g. Earth Centered Inertial). Data are typically calibrated and annotated with ancillary information including data quality indicators, calibration coefficients and parameters for referencing the spacecraft and field of view to a defined coordinate system.
- **Level 2:** Derived environmental variables at a comparable temporal and spatial resolution to the Level 1 source.
- **Level 3:** Data or retrieved environmental variables that have been spatially and/or temporally resampled (i.e. derived from Level 1 or 2). Such resampling may include averaging and compositing.

The general definitions given above are further refined for individual instruments in their respective sections (6-10).

Data products are created in increasing order of levels, so for example Level 2 products are created from Level 1b products. However, there are some exceptions as detailed for CCOR in Section 6 and for SWiPS in Section 7. Also, for most instruments the lowest level of fully calibrated data is Level 1b, but for CCOR and SWiPS it is Level 2.

In addition to the above data levels defined for the SWFO Program, SWPC and National Centers for Environmental Information (NCEI) of NESDIS will develop Level 4 data products for their own use. However, those products are outside the scope of this document.

## 3.3 Ground Segment

The Ground Segment comprises three elements (Fig. 3a) which are discussed below:

- SWFO Antenna Network (SAN)
- Command and Control (C2)
- Product Generation and Distribution (PGD)

The main facilities where the service functions will be implemented will be the NOAA Satellite Operations Facility (NSOF) in Suitland, MD; and SWPC of NWS and NCEI. NCEI has two facilities, in Boulder, CO (NCEI-CO) and Asheville, NC (NCEI-NC), that are part of PGD.

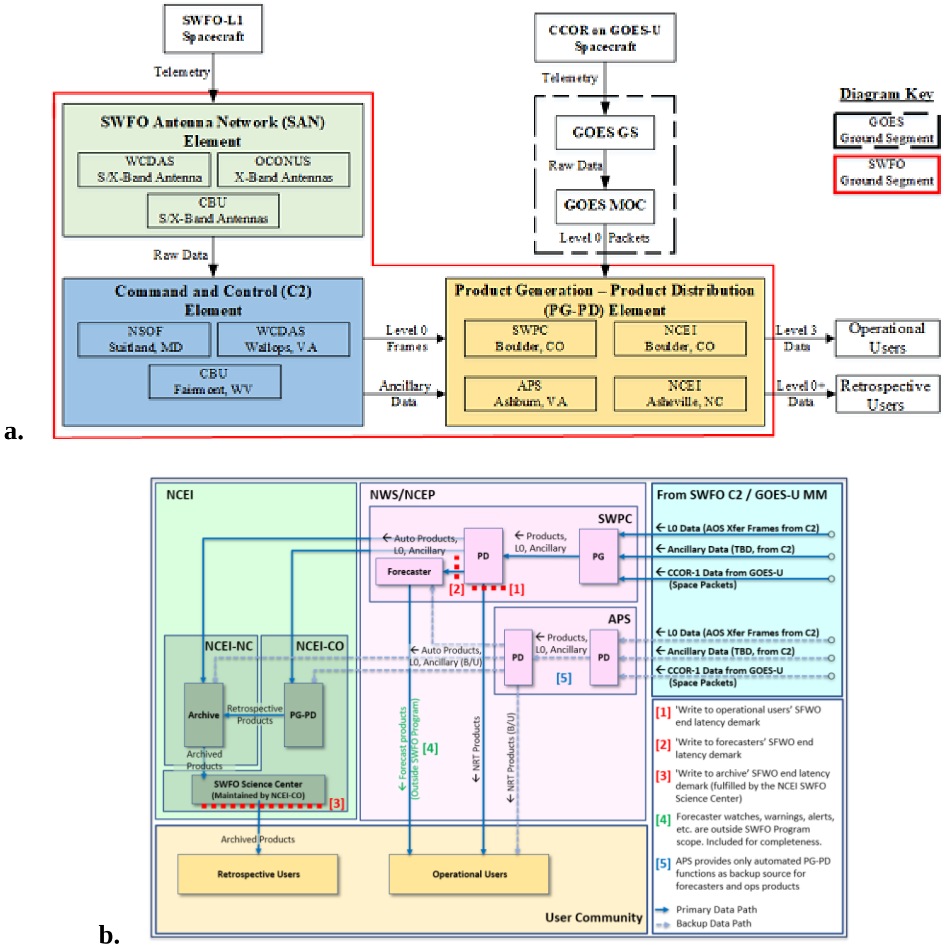

**Figure 3. a. SWFO Ground Segment. b. Product Generation and Distribution element.**

### 3.3.1 The SWFO Antenna Network and the Command and Control Element

The SAN provides raw mission and housekeeping data downlinked from the SWFO-L1 observatory to the C2 element. The SAN consists of several antenna stations around the globe.

The C2 element of the SWFO GS operates out of three physical locations: the NSOF, Wallops Command and Data Acquisition Station (WCDAS), and Consolidated Backup Unit (CBU). It processes the raw data provided by the SAN and by NOAA partner organizations. C2 creates Level 0 (L0) data and provides them to PGD.

### 3.3.2 The Product Generation and Distribution Element

The PGD element implements the following functions:

- Development of algorithms, Algorithm Theoretical Basis Documents (ATBDs), and production code.

- Product generation (PG) implemented in SWPC for operational (real-time) products and NCEI Solar and Terrestrial Physics Section (NCEI-STP) for retrospective (non-real-time) products. Each one will generate Level 1a, 1b, 2 and 3 products.
- Product distribution (PD) with SWPC distributing products to operational users and NCEI distributing products to retrospective users.
- Cal/val. NCEI and SWPC will work with several other groups to implement these functions. Additional information is provided in Section 4.2 below.
- Data stewardship, including data archiving. NCEI is responsible for maintaining all data products as well as L0 mission and housekeeping data, and ancillary data. The long-term archiving happens within in the NCEI-Data Stewardship Division (NCEI-DSD) while short-term access is available from services coordinated between NCEI-DSD and NCEI-STP. NCEI-STP will lead the development of the SWFO Science Center, a portal aimed at facilitating user access to the products.

### 3.3.3 The Interface to the GOES-R Ground Segment

As mentioned in Section 3.1.2 above, CCOR-1 will operate on the GOES-U spacecraft. The GOES-R Ground Segment is responsible for delivering CCOR-1 L0 data to PGD and specifically to SWPC.

# 4. CALIBRATION ACTIVITIES

## 4.1 Major Calibration Activities

This section discusses the most significant activities needed to develop fully calibrated products and their higher-level successors. As mentioned in Section 3.2, fully calibrated products are at Level 1b for STIS and MAG, but Level 2 for CCOR images and SWiPS plasma density, velocity, and temperature.

SWFO instrument spatial and/or L2 measurement calibration activities span the Flight Project and Ground Segment, as well as related NESDIS and NWS centers. Although the methods used to perform the calibration activities may change depending on instrument lifecycle phase, they are carried out throughout the SWFO Program. Critical to the success of these activities is a supporting workforce with diverse technical and management skills, and a reliance on proven pre- and post-launch calibration methods that are carefully planned and implemented.

A high-level overview of the SWFO L2 cal/val efforts is given in Table 5. The table describes the changing roles and responsibilities of each group through all phases of mission life. It is noted here that following launch, the product validation is separated into two distinct phases: A Post-Launch Commissioning (PLC) Phase and an Operational Phase. The PLC Phase is a six-month period that includes an approximately one-month period of Post-Launch Product Testing (PLPT) at its end. In Sections 4.2 and 4.3, summaries of the supporting teams and mission lifecycle phases are given, respectively.

Going into more detail, cal/val is divided into three phases: (1) ground calibrations performed by the instrument vendor, (2) initial in-flight instrument commissioning and PLC activities to ready and verify the basic functioning of the instrument for operational use, and (3) PLPT activities for identifying anomalies and verifying that science data meets the needs of NWS.

In general, the three phases of cal/val are subdivided into the following activities.

**Ground Calibration.** This activity is mainly focused on obtaining instrument specification parameters, for instance, channel geometric factors, energy bounds, and their uncertainties. Complete energy and angular response functions of the sensor are also obtained. More specifically, particle instrument ground calibrations may also include characterizing sources of and quantifying out-of-band contamination, temperature dependence, etc. In addition to ground calibrations, instrument and GPA design modeling may be performed to improve the accuracy of the science data and ensure the instrument will meet requirements (i.e., Ground Verification & Validation (V&V)).

**PLC.** Initial in-flight instrument commissioning and tests needed to ready the instrument for operational use and verify it is functioning properly

- Instrument turn-on and initial checkout, e.g., nominal engineering and science data.
- Initial In Flight Calibrations (IFCs), including analysis of results

- Optimizations, e.g., setting detector bias voltages, pulse height detection thresholds, microchannel plate gain, etc.
- Any needed on-orbit instrument calibration that augments ground calibrations

**PLPT.** Validation of science quality of data and comparisons with legacy measurements used by NWS SWPC, critical for ensuring continuity of SWPC alerts

- Backgrounds Trending
    - Quantify background levels and variations in background levels
    - Perform correlations between backgrounds and measurements or models of known or likely sources (e.g., galactic cosmic rays)
    - Determine correct values for background removal coefficients
- Evaluation of Out-of-band Contamination (Out-of-band contamination refers to counts from particles not in the intended species, field-of-view or channel energy band.)
    - Look for evidence of out-of-band contamination in measurements and compare with known or likely sources
    - Quantify susceptibility to out-of-band contamination and magnitude with respect to measurements
- Cross Comparisons/Calibrations with Similar Measurements
    - Goal is to quantify differences with similar measurements from other spacecraft (e.g. DSCOVR, ACE, or LASCO)
    - Important for establishing continuity with legacy NOAA instruments/measurements
    - May indicate violation of accuracy requirements, but does not necessarily verify accuracy requirements are met
    - Complicated by differing energy-angle coverage and spacecraft locations – Will perform apples-to-apples comparisons where possible

PLC activities are typically planned by the instrument vendor in coordination with the Mission Operations Support Team (MOST). PLC commanding is overseen by the MOST team and executed by Office of Satellite Products and Operations (OSPO). PLPT activities are typically planned by NCEI. Because the data from a single PLC or PLPT test may be used by both NCEI and the vendor, in the commissioning phase the vendor may perform a test that is also labeled as a PLPT. Some PLPT work may be done after the instrument is operational. Cal/val activities specific to individual instruments are listed in Sections 6 through 9.

## Table 5. A high-level overview of SWFO instrument calibration activities.

| SWFO Teams | Instrument and L2 Algorithm Development | Satellite and L2 Integration and Testing | Post-Launch Commissioning (PLC) Post-Launch Product Testing (PLPT) | | Operational Phase |
|---|---|---|---|---|---|
| | | | **PLC** | **PLPT** | |
| 1. Flight Project (FP)<br>2. Instrument Vendors<br>3. Spacecraft Vendor | • Design, document, and implement instrument and associated L2 algorithms (2,3)<br>• Characterize and calibrate instrument at system, sub-system and/or component levels (2,3)<br>• Verify instrument performance meets specifications, and where applicable is traceable to NIST standards (1,2,3)<br>• Define, document, and deliver specs for a comprehensive operational calibration monitoring and maintenance process (2,3)<br>• Oversee and manage instrument vendor design, assembly, integration and test/analysis related to instrument calibration and L1b algorithms (1)<br>• Analyze instrument vendor pre-launch test data (1)<br>• Resolve calibration-related sensor and L2 algorithm anomalies through mitigation or the requirements waiver/deviation process (1,2,3) | • Integrate instrument with spacecraft (3)<br>• Verify instrument operability on spacecraft platform (2,3)<br>• Support data collection for Government system-level spacecraft-GS processing compatibility validation efforts (2,3)<br>• Plan on-orbit PLC (1,2)<br>• Oversee and manage instrument and spacecraft vendor I&T (1)<br>• Resolve satellite anomalies related to calibration through mitigation or the requirements waiver/ deviation process (1,2,3) | • Assist MOST in instrument PLC cal/val testing and validation activities (1,2,3)<br>• Support satellite, calibration, and L2 algorithm anomaly resolution (1,2,3) | • Assist MOST in instrument PLPT cal/val trending activities (1)<br>• Support satellite, calibration, and L2 algorithm anomaly resolution (1,2,3) | • Support satellite, calibration, and L2 algorithm anomaly resolution (1,2,3)<br>• Update L2 data processing algorithm as requested (2,3) |
| 1. Ground Segment (GS) Project (GSP)<br>2. GS Vendor | • Validate instrument vendor L2 algorithms, databases, and instrument Constants (2)<br>• Implement and test L2 algorithms (2)<br>• Vendors to deliver L0b-L2 code<br>• AWG to develop, optimize, I&T, and develop operational codes (2)<br>• Develop instrument calibration data sets and cal/val monitoring tools (2)<br>• Design Development Environment analysis capabilities for instrument calibration, L2 algorithm and calibration database anomaly resolution and updates (2)<br>• Oversee and manage GS vendor design, implementation and testing related to L2 algorithms and calibration-related GS Core capabilities (1) | • Verify integrated L2 processing, instrument monitoring and development environment capabilities (1,2)<br>• Verify contents and flow of instrument calibration Data (1,2)<br>• Resolve GS-related incompatibilities between the instrument data streams and L2 product processing (1,2)<br>• Oversee and manage GS vendor I&T (1)<br>• Participate in planning of on-orbit PLC and PLPT (1)<br>• Train users of cal/val-related GS data storage, monitoring and analysis resources (1,2) | • Support on-orbit instrument performance tests and data processing (1,2)<br>• Participate in L2 processing anomaly resolution efforts (1,2)<br>• Implement changes in L2 processing calibration tables (1,2)<br>• | • Support on-orbit instrument performance tests and data processing (1,2)<br>• Participate in L2 processing anomaly resolution efforts (1,2)<br>• | • Support updates of GS instrument calibration and L2 product processing, monitoring, and analysis capabilities as requested (2) |
| Algorithm and Calibration Working Groups (AWG, CWG) | • Support requirements waiver process and cal/val activities | • L1+ cal/val activities | • L1+ cal/val activities | • L1+ cal/val activities | • L1+ cal/val activities |

## 4.2 Teams Supporting SWFO Calibration

SWFO requires Flight and Ground vendor technical experts to design, document, fabricate, integrate and test instruments and L2 ground processing algorithms, and to ensure the instruments and algorithms meet Government-defined specifications. It also requires government teams from the SWFO program and projects to oversee this process, and to formally verify vendor test results. Immediately after launch, government and vendor personnel with a wide range of experience are responsible for validating on-orbit instrument performance to ensure they meet user expectations, as defined by pre-launch analytical predictions based on actual instrument laboratory performance measures, and can be maintained in nominal operations. During that time, these personnel also establishes a post-launch calibration baseline for each instrument.

During routine operations, long-term instrument and L3 product performance monitoring and anomaly resolution are performed by NOAA engineers and scientists, with as-requested support from the SWFO vendors during anomaly periods (TBD). Since spatial and L2 measurement calibration are integral to mission success, calibration work continues throughout the SWFO projects and is supported by appropriately trained staff. The teams supporting SWFO calibration and their roles and responsibilities are described briefly in this section and in Table 5.

### 4.2.1 Flight Project

The SWFO Flight Project is composed of systems engineers, aerospace engineers, and other satellite operations experts. These subject matter experts assist with spacecraft and instrument procurement, as well as acquisition of testing and calibration systems, and maintain flight segment requirements and operational concepts. Flight Project personnel oversee the process of satellite and spacecraft design, development, and implementation, and have the responsibility of ensuring that these assets are proven to perform to requirements as outlined in Performance and Operational Requirements Document (PORD) for each instrument and the SWFO-L1 Spacecraft Requirements Document.

Before launch, the Flight Project vendors for spacecraft and for instruments provide aerospace managers and engineers that design, fabricate, assemble, and integrate these flight components. Instrument vendors must document and execute tests that will verify instrument performance. Since they are also responsible for development of the L2 GPAs, the vendor personnel will support ground segment implementation of the algorithms. As members of the Calibration Working Group (CWG, see Section 4.2.4), they may also be consulted for pre-launch testing of the ground segment data processing capabilities. After launch, the Flight Project and spacecraft and instrument vendors work with the MOST to perform and analyze the results of tests that will validate that instrument performance meets user needs. Vendors are responsible for instrument anomaly resolution efforts after launch, including L2 GPA updates. Vendors are also responsible for monitoring instrument trending on-orbit after IOC and providing flight table updates in conjunction with Algorithm and Calibration Working Groups.

### 4.2.2 Ground Segment Staff

The SWFO GS is composed of Government managers; systems engineers; satellite communications, operations, and data processing and distribution engineers; product scientists; and information technology experts. The GS personnel procure the ground system, including the hardware and software for processing, monitoring, and resolving anomalies related to L2 and 3 product generation. They are responsible for implementing the GS Level 2 and lower Requirements, and they oversee the process of GS design, development, and implementation by the GS vendor. They are also responsible for ensuring that GS Level 4 requirements verification has been demonstrated by the GS vendors before launch, and for supporting validation of GS functions before and after launch.

The GS vendors and supporting Government entities (SWPC and NCEI) supply personnel with similar credentials as the SWFO GS. PGD's units, SWPC and NCEI, have the responsibility of designing, developing, integrating, and testing the ground segment that can perform data processing, monitoring, anomaly resolution and distribution in accordance with GS Level 4 specifications. PGD will also implement L2 instrument vendor GPAs into GS algorithms. Before launch, PGD will work with the MOST and other SWFO working groups to perform tests that will validate the GS, while after launch they will offer operational support for PLC and Mission Operations.

### 4.2.3 Algorithm Working Group

The Algorithm Working Group (AWG) includes the SWPC (lead), NCEI instrument vendors, C2, and the Flight Project and is chaired by the SWFO Scientist. This group is responsible for developing, verifying and supporting implementation of L1+ product algorithms into the SWFO GS. In collaboration with the CWG, the AWG is also responsible for identifying and understanding sources of product discrepancies that may be found during the course of these comparisons. In turn, these findings are to be reported by AWG members to product stakeholders. Finally, SWPC and NCEI develop Level 4 data products for their own use, but these are outside the scope of this document.

### 4.2.4 Calibration Working Group

The CWG members are primarily working-level engineers and scientists at NCEI (lead) and SWPC, SWFO Scientist, instrument vendors, C2, spacecraft vendor, the Flight Project, and GOES-R GS. Other participants include staff from the spacecraft vendor, the GOES-R GS, and OSPO. The CWG provides technical capabilities to the SWFO Programs Systems Engineer (PSE) and Ground Segment Engineer (GSE) in support of the development and implementation of SWFO series instrument calibration systems and L2 product algorithms. The CWG oversees the development and implementation of the calibration of the SWFO instruments to ensure that each instrument's calibration complies with the requirements set forth, and conforms to recognized international standards and "best" calibration practices. As part of its work, CWG will identify product quality issues and anomalies that impact usage of the instruments' data, and help to mitigate those issues where possible. They also lead the post-launch L1+ product validation effort, which includes comparing each L1+ product retrieved from the CCOR telescopes and in situ data against those derived from in-situ and remotely-sensing measurements from other satellites and ground observatories. These efforts for Levels 1a through 3 are described in more detail in corresponding sections for each instrument in Parts 2 and 3 of this document.

### 4.2.5 Mission Operations Support Team

The MOST is formed by the Flight Project to focus on mission operations, from pre-launch planning and development, through launch and orbit raising, PLC, and transition to sustaining operations. The MOST includes personnel from SWFO PSE, and Flight Project and GS. It includes discipline engineers (spacecraft bus and instruments), systems engineers, flight and ground controllers, mission planners and schedulers, ground systems engineers, software maintenance, and associated support personnel. Extended MOST membership will include OSPO, Flight and GS contractor personnel, and NCEI and SWPC personnel depending on mission phase. A key feature of the MOST will be early involvement of several NOAA operations staff dedicated to SWFO mission operations in the early stages of pre-launch development. The MOST will be led by the SWFO Mission Operations Manager.

### 4.2.6 NESDIS Office of Satellite and Product Operations

As is done in earlier systems such as DSCOVR, the NSOF will be the home of the OSPO satellite operators. They will participate in the CWG calibration and validation activities for the post-launch life of the mission.

## 4.3 Calibration Activities for SWFO Lifecycle Phases

There are four life-cycle phases associated with SWFO-L1 and the GOES-U/CCOR-1 projects that are relevant to calibration: Instrument and Level 2 Algorithm Development; Satellite and Algorithm Level 2 Integration and Test (I&T); PLC, including PLPT; and Mission Operational Life (Table 5). These four phases, and their detailed relation to cal/val activities, are described further below.

### 4.3.1 Development Phase

This phase includes:

- The Instrument and Level 2 Algorithm Development Phase
- and the Satellite and L2 Algorithm Integration and Testing, Phases

The first two phases of the SWFO lifecycle are presented together in this document, because calibration responsibilities are structured similarly throughout the two phases. During these pre-launch phases, instrument vendors carry out many design, implementation and test responsibilities related to calibration. The SWFO CWG, PSE, and Flight engineering teams participate in vendor instrument and L2 algorithm requirements and design reviews, test readiness reviews, and technical interchange meetings. These teams also provide oversight to ensure that pre-launch instrument measurements are traceable to NIST standards (where applicable) and fulfill the requirements set forth in the instrument PORD. The CWG works closely with the Flight Project instrument managers and engineers during pre-launch testing and characterization to review test results and assure that instrument performance meets requirements in a manner which reflects user intent.

As launch approaches, and the instruments are being integrated onto the satellite and L1a+ algorithms are being integrated into the ground segment, the MOST schedules and implements end-to-end segment and system validation tests. During this time, the CWG plans to work with the MOST to ensure that calibration-related data processing, availability, monitoring and analysis will meet the needs of calibration engineers and scientists. For SWFO-L1, the CWG will coordinate calibration and L2 product-related tests. Due to their relatively large cost, the SWFO Program plans to leverage, to the greatest possible extent, the field campaigns executed by other missions (Interstellar Mapping and Acceleration Probe (IMAP), Polarimeter to Unify the Corona and Heliosphere (PUNCH), Solar Terrestrial Relations Observatory (STEREO), etc.) during the SWFO-L1 and GOES-U post-launch periods.

Coordination and management of cal/val activities during these phases is carried out by the CWG. PGD serves as a communications conduit between technical subject matter experts and the PSE Lead Engineer and SWFO Scientist regarding SWFO product-related requirements risks and waivers/deviations. The CWG during this time also focuses on preparation for cal/val activities that will take place during the PLC period.

### 4.3.2 Post-Launch Commissioning

The PLC phase for a given satellite begins with the validation of spacecraft bus performance, including that of key subsystems such as the Attitude Control Systems (essential for imaging performance of the coronagraphs), is validated. Another part of PLC entails most calibration and L1b product related activities occur. These two activities within the PLC phase conclude when sufficient product validation tests have been performed to provide an initial assessment that the SWFO Program meets users' needs.

At this point, it is critical to have adequate monitoring and analysis tools, and support computing infrastructure, to determine the performance of SWFO instruments and their products once they are on orbit. In the PGD element, there will be tools and supporting internally networked computing resources needed to monitor essential instrument calibration-related parameters that impact L2 product performance. Tools needed to perform in-depth analysis of these parameters are being developed before launch by the various CWG members for use by organizations external to the GS that support PLC and operations. More information about this can be found within the Concept of Operations (CONOPS).

### Science-Focused Activities during Post-Launch Commissioning

Following the launch of each one of the GOES-U and SWFO-L1 spacecraft, the spacecraft contractor and the instrument vendors are responsible for analyzing performance of the instruments and their host spacecraft on orbit. For this purpose, the Flight Project and MOST develops and implements detailed PLC plans and the CWG will work within these plans. The scope of these plans demonstrate that instrument and spacecraft performance related to key Level 3 requirements has not degraded due to launch and the on-orbit environment. They also demonstrate key functionalities not demonstrated in activation or normal operations. On-orbit instrument calibration and L2 product performance validation begins during these science PLCs. “Science PLCs” or “PLC for calibration” are those PLC activities that lead to calibration artifacts (flight LookUp Tables or flight-LUTs, ground calibration tables, detector characterization, calibration parameters, etc.) that will be utilized in the instrument calibration beyond the PLC phase. Some of the science PLCs are the first execution of calibration tests that are planned to be performed through PLC or even through the lifetime of the mission.

During PLC, the CWG members will conduct calibration, sensor monitoring and analysis functions associated with generation of the SWFO L2 data stream, which includes the calibration of the instruments and the application of the calibration equations to the L0 data, with support from MOST. This includes real-time trending and monitoring of selected data from L2 and L3 processing, validation of using ground segment tools, inference of initial performance measures, support of anomaly investigations, and support of payload/instrument operations.

CWG will be using the ground calibration tables and performing ground-processing calibrations. Flight Project and MOST will use instrument LUTs which relate to L0 raw data to assist CWG in the flight calibration.

The CWG has many important roles during PLC. Besides helping the Flight Project and MOST develop, execute, and analyze the results of the science PLCs in the instrument L2 data area, the CWG supports these tests in other ways. This support includes guidance and selected independent analysis of instrument checkout, calibration, and performance; and independent analyses of science PLC measurements to generate calibration database parameters derived from on-orbit measurements. These efforts are coordinated and managed within the CWG. Meanwhile, the AWG is the forum for initiation of cal/val-related anomaly resolution, which is described in the CONOPS.

### 4.3.3 Post-Launch Product Testing

PLPT of SWFO L2 and L3 products is an important data integrity exercise designed to provide Stakeholders with a snapshot of product science performance before observatory Handover. As opposed to science PLCs, PLPT analyses primarily utilize nominal operational instrument calibration and science data modes.

In addition, success criteria are based first on analytical pre-launch product performance predictions from pre-launch vendor testing results; and second on the actual performance during flight. Ultimately, PLPT is a key activity in the long-term process of L2 product validation, as it establishes a post-launch baseline for long-term spatial, spectral and L2 measurement calibration. To meet these demands of SWFO instrument PLPT, the CWG plans to implement, in coordination with the Flight Project and MOST, an integrated approach to satellite instrument calibration and L2 product validation. The components of this integrated cal/val system rely heavily on tested and peer-reviewed on-orbit calibration methodologies. These efforts are coordinated and managed within the CWG.

### 4.3.4 Ground Processing System and Operational Life Phase

To ensure continued SWFO data quality, long-term instrument performance monitoring and analysis is also an essential task to take place during this SWFO lifecycle phase. Similar to PLPT described in the previous section, the SWFO mission operational life activities planned by NCEI and SWPC harness an integrated calibration and L2 product validation system that relies heavily on tested and peer-reviewed on-orbit calibration methodologies. Many of the long-term product performance monitoring analyses are simply PLPT tests that are continually performed throughout instrument life. If new methods and capabilities are developed within the discipline of cal/val that can be leveraged within SWFO, changes to SWFO series long-term instrument performance activities may occur.

During this phase of instrument life, calibration engineers from CWG (in this case: NCEI, SWPC, and instrument vendors) and GS engineers will be enlisted for the purpose of resolving anomalies regarding the SWFO instruments and their L2 data performance. Calibration anomaly resolution is discussed further in Section 9 of this document and in the CONOPS.

The operational calibration, GPAs and associated calibration data-bases needed to process SWFO instrument L0 data into L2 products are developed by each instrument vendor for CCOR, SWiPS, STIS, and MAG. For the in situ instruments, algorithms are delivered by the instrument vendors to the Flight Project in a Contract Data Requirements List (CDRL-80). The databases are delivered in a similar manner in a calibration data book (CDRL-79). For CCOR, the Naval Research Laboratory (NRL) will deliver GPAs and calibration data books. After a handover of these documents to the GS, these L2 GPAs and database documents are used by SWPC and NCEI to develop production code for operational implementation at SWPC and for retrospective and reprocessing activities at NCEI. Operational image processing including calibration for the CCOR instruments also follows the same process though the CCOR vendor does not have CDRLs. These GPAs can be found in the CDRL documents (CDRL-46) delivered to the Flight Project by the instrument vendors. The CWG works with the instrument and spacecraft contractors, with the help of the Flight Project instrument managers, to ensure that these deliverables are adequate to meet NOAA’s needs, and potential improvements may be suggested if the GPAs do not meet requirements.

Pre-launch operational implementation of the L2 ground processing algorithms by PGD is a process that bridges the Space and GSs, and thus requires a great deal of communication between them. For this reason, GS contractor questions and comments regarding the algorithms and databases are arbitrated with the help of the Flight Project and GSP with technical support from

CWG. In order to ensure proper implementation of each L2 processing algorithm, the inputs used and outputs generated during L2 algorithm testing by each instrument vendor will be delivered along with the algorithm package. These test case data can be found in an algorithm testing package from each instrument vendor. In the final step of the L2 ground processing algorithm implementation process, PGD will need to acknowledge successful execution of L2 test cases provided by the instrument developers.

Another important pre-launch activity – performed by the MOST and CWG – will be the end-to-end test of compatibility between the downlinked data streams from the instruments and the GS L2 processing. This test simulates the on-orbit performance of the satellite and GS. For CCOR this test consists of playing instrument output data - obtained during spacecraft-level thermal-vacuum testing with the instrument viewing a rudimentary laboratory target - into the front end of the GS processing chain. The processing and database of the GS, both hardware and software, will be in their final on-orbit configuration. The outputs of the L2 processing are then validated. Results at intermediate processing stages may also be inspected. Such a test is to be carried out TBD months before launch during the MOST End-to-End Test 3 (TBR), allowing time for corrections to be made (and tested) to the processing software and/or the databases, if needed.

Data format and quality flags will be largely developed and implemented pre-launch for the SWFO instrument L2 and calibration data sets with input from the instrument and spacecraft vendors and support from the CWG. The data formats are defined in the vendor CDRLs and similar NRL documents. For more information regarding pre-launch cal/val activities, organizations and working groups, roles and responsibilities, resources, and schedules associated with the ground processing system and operational calibration refer to the CONOPS.

After launch, the MOST - with support of instrument, spacecraft and GS, CWG, and OSPO - are responsible for carrying out PLC activities related to instrument calibration and L2 and L3 product performance. This includes monitoring of calibration-relevant sensor parameters and data taken during on orbit instrument calibration events. It also includes interrogating parameters generated during L2 data processing, and performing simple diagnostics on all calibration data. Furthermore, these members work together to diagnose and mitigate instrument calibration and L2 and L3 product anomalies. During Mission Operational Life, the CWG assumes these responsibilities with participation from NCEI, SWPC, SWFO Scientist, and instrument, spacecraft and GS contractors.
Day-to-day operational monitoring of CCOR L2 radiometric quality – carried out by the CWG – is to include near real-time monitoring of calibration-related instrument parameters and data, as well as the examination of the parameters generated from L2 and L3 processing. NCEI and SWPC are responsible for supporting these activities through the CWG and AWG.

As inferred above, PLC and navigation processing for all SWFO instrument data needs to be carefully tracked and any anomalies mitigated. In order to perform cal/val monitoring, maintenance and anomaly resolution for the SWFO program, the GS, Flight Project, and external support organizations have accounted for appropriate functionalities, resources, and interfaces. A Program-level description of these functionalities, resources, and interfaces, as well as a summary of the paradigm of their use and the working relationship of its users, can be found in the CONOPS.

### 4.3.5 Anomaly Resolution

After launch of GOES-U and SWFO-L1, L2 product performance anomalies due to issues such as calibration bias and instability may arise that need to be investigated and mitigated. A generic process including necessary elements of L2 product/algorithm anomaly resolution is shown in Figure 4. The process typically starts with analysis of instrument calibration and L2 product data gathered in a time and/or space region associated with the anomaly. If any L2 algorithm revisions are to be made, which includes calibration table changes, then L0 or L0b data associated with the same time and/or space period would be needed to execute the algorithm during the revision process. If a resolution to the deficiency is found, and L2 algorithm update package will have to be created, so the algorithm change can be implemented into operations. After implementation, validation of the algorithm implementation, and of the product output from the updated algorithm using validation reference data, would be necessary.

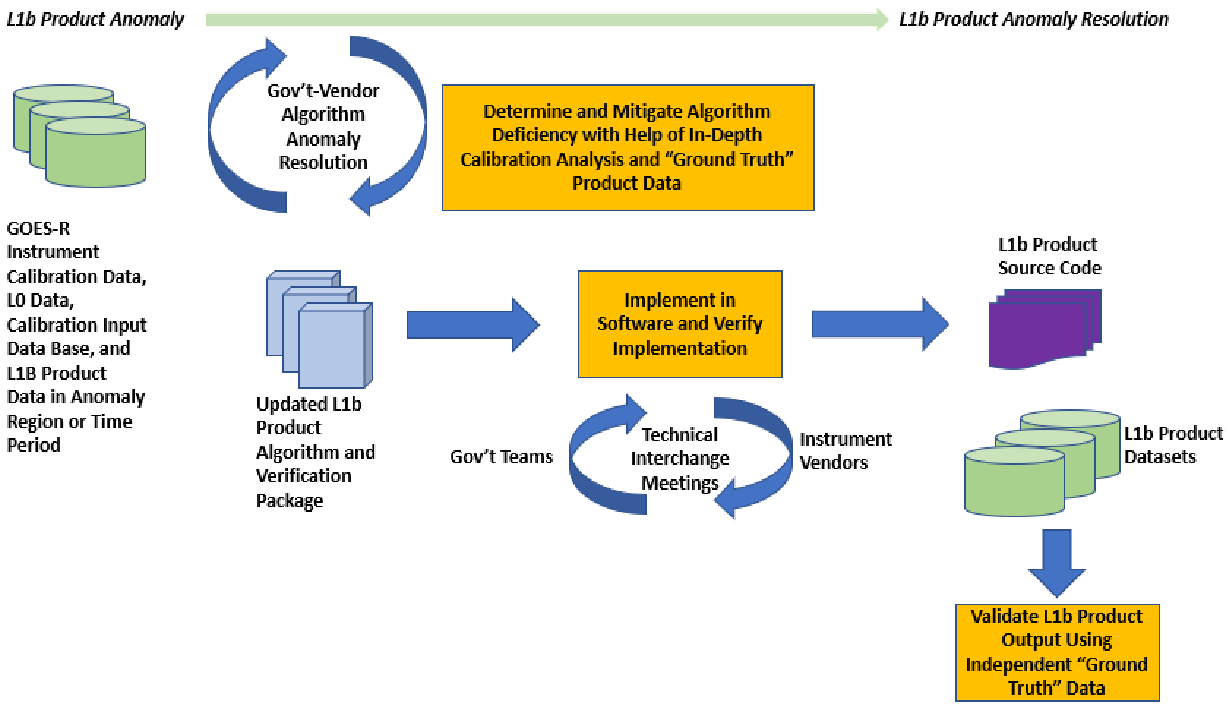

**Figure 4. Schematic for L1b product anomaly resolution.**

The main resources and processes associated with L2 product anomaly resolution consist of the following:

- Operational monitoring of calibration-relevant SWFO spacecraft and sensor parameters, as well as real-time SWFO L2 product processing output;
- A computing development environment to

  - Perform analysis of operational monitor data to find correlations between calibration anomalies and changes in spacecraft and instrument state and function
  - Examine, develop, and test anomaly mitigation strategies in operational L2 algorithms
  - Receive and test updated instrument calibration databases for L2 algorithms;
- A mechanism to implement any L2 algorithm changes or calibration table updates in the integration and test environment, and then in operational L2 product generation.

On-orbit instrument/algorithm anomaly resolution efforts often require governmental agencies, vendors, and data users to work together. Each organization has a task that represents a segment of the overall process of anomaly resolution. Thus, communication and coordination between these entities is essential. The organizations that participate in post-launch cal/val anomaly resolution change during the course of the SWFO projects. During PLC, these anomalies are to be handled by the Flight and GS Projects, and MOST, as well as calibration engineers and scientists from the CWG, the SWFO Scientist, OSPO, and the instrument, spacecraft and ground segment vendors. During Mission Operational Life, OSPO assumes these responsibilities with support as needed from NCEI, SWPC, SWFO Scientist, and instrument, spacecraft and GS contractors. More details regarding the instrument calibration and L2 product anomaly resolution process can be found in the CONOPS.

# 5. PRODUCT VALIDATION OVERVIEW

The intent of post-launch SWFO product validation is to provide product performance information and data that allows an assessment of the degree to which actual products meet expectations in the intended operational environment, as referenced to the Level 2 requirements and pre-launch performance. Post-launch product validation differs from pre-launch requirements verification in that L2 requirements are used only as a framework to define validation activities, since contractual GPA "sell-off" occurs before launch as part of requirements verification. On the other hand, the validation process is expected to trigger algorithm updates as deemed necessary if significant product deficiencies are found on orbit.

This section discusses the general approach for post-launch product validation for all levels. Specific validation processes are presented in Sections 6 through 9 for individual instruments.

The SWFO Program product suite will provide continued availability of coronal and solar wind products currently derived from DSCOVR and other heritage instruments. SWFO instruments are expected to meet stringent calibration standards, which will translate into improved L2+ product accuracy. Technological progress in instrument hardware, and in data telemetry, processing and distribution, will lead to high spatial resolution and fast refresh rates for several SWFO products. These advances for the SWFO L2+ product suite, in combination with the utilization of these data in new space weather models, promise to offer important new information to space weather forecasters and other users to improve the timeliness and accuracy of warnings, watches, and alerts. It is essential, therefore, that the SWFO L2+ products are validated on-orbit.

As already mentioned, the PLC includes the PLPT period at its end. The PLPT period encompasses NOAA Science Tests based on heritage space weather instruments. After launch of GOES-U and SWFO-L1, the output of each product is monitored for obvious performance outliers, and compared against reference "ground truth" measurements appropriate in type and quality to assess the degree to which expectations, as outlined in the Level 2 Requirement Documents, have been met. For the CCOR imagers, the reference measurements come from LASCO and other coronagraphs including research instruments such as PUNCH. For the in situ instruments, there will be an opportunity to perform more straightforward comparisons with instruments by DSCOVR and ACE, and research missions such as Comprehensive Solar Wind Laboratory for Long-Term Solar Wind Measurements (WIND) and IMAP.

Ideally, validation would test each product over its entire dynamic, temporal, and (for images) spatial range over a sufficiently long time such as a part of a solar cycle. Table 6 provides an overview of the approaches and considerations for each product.

**Table 6. SWFO product validation approaches and considerations.**

| Data Product | Approach | Considerations |
|---|---|---|

| | | |
|---|---|---|
| Coronal White Light Intensity | Validation via comparison with the same product for LASCO; and intercomparison between products between CCOR-1 and -2. | Widest possible range of coronal conditions; intensities and speeds of Earthward-moving CMEs; range of stray light conditions |
| Solar wind plasma density | Validation via comparison with the same product for DSCOVR and other Lagrange 1 space weather monitors including research instruments | Widest possible range of solar wind conditions including CMEs, other ejecta, high-speed streams, and shocks (and particle events for STIS) |
| Solar wind plasma velocity | | |
| Solar wind plasma temperature | | |
| Suprathermal ion differential flux | Validation via comparison with a related product for ACE | |
| Magnetic field | Validation via comparison with the same product for DSCOVR and other Lagrange 1 space weather monitors including research instruments | Widest possible range of magnetic field structures including CMEs, shocks, and CIRs |

The following key CWG assumptions [TBR] will ensure Flight hardware and Ground data products are calibrated optimally, duplication of effort is minimized, and expectations for post-launch data product maintenance and trending are fully satisfied to maintain performant space weather products.

1. Instrument Vendor is responsible for monitoring Flight/Instrument performance and creating the Flight LUTs (i.e flight tables) throughout the life of the mission.
2. Instrument Vendor is always responsible for creating the flight LUT/commanding change file (i.e. instrument level change).
3. NCEI is responsible for generating and monitoring ground calibration file updates.
4. Any CWG member (including NCEI) has the authority to recommend flight LUT or ground calibration table changes.
5. CWG approves any suggested changes to flight- or ground- LUTs.
6. Vendor tools required for NCEI’s Ground cal/val roles be developed and transitioned to NCEI in a manner usable within NCEI’s IT infrastructure (i.e. commented code, no black box executables, not requiring complicated administrator level privileges, etc).

# PART 2: SOLAR OBSERVATIONS

Each one of the sections in Part 2 of this document corresponds to an instrument type. It includes scientific characterization of that instrument's products, a dataflow description, and instrument calibration and L1b product validation plans; and anomaly resolution. Activities are described as a function of the SWFO project lifecycle and expand on the general descriptions of cal/val activities in Section 4.1.

Summaries related to instrument requirements and pre-launch calibration methodologies are given in the document to provide the reader with important background information, while exhaustive and the most up-to-date details can be found in calibration and system performance verification plans; test description documents and readiness reviews; and GPA documents provided to the Flight Project by the instrument and spacecraft vendors. These GPAs include fully calibrated data products: L1b for most instruments and L2 for CCOR. Post-launch calibration methodologies are described in the text, in some cases more details can be found in the appendixes. The GS plans briefly summarize validation of fully-calibrated data GPAs, instrument calibration and calibrated data product performance monitoring, and fully calibrated data GPA and calibration table testing and update procedures. Finally, post-launch instrument anomaly resolution plans are described briefly in this Plan. As changes are made to the calibration plans, they will be updated accordingly within the SWFO configuration management system.

# 6. COMPACT CORONAGRAPH

In this section, all of the information applies to both CCOR-1 and CCOR-2 unless explicitly called out.

Measurements from the CCORs will be used to characterize the coronal activity; coronal white-light intensity from CCOR-2 is a KPP for the SWFO Program. Coronal images are crucial in identifying CMEs and other geoeffective structures. Numerical weather prediction models such as WSA-Enlil at the NWS use the images to derive their input and will have applications in space weather forecasts and nowcasting. Thus, the images form the foundation for several forecasting and nowcasting capabilities, especially those related to geomagnetic storms.

## 6.1 Sensor Description

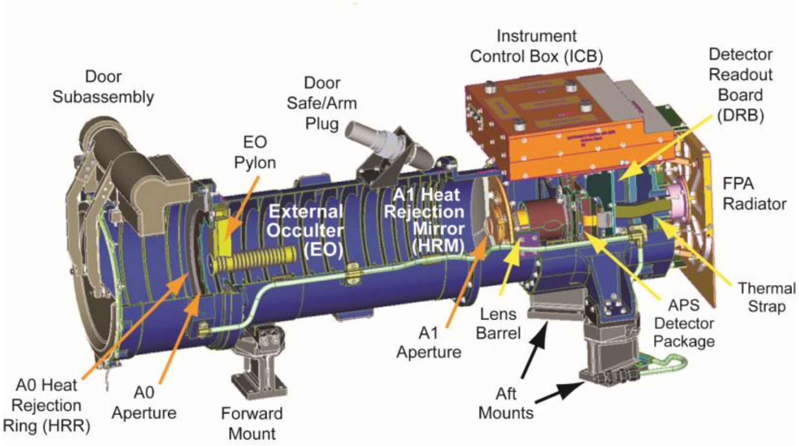

**Figure 5. The CCOR-1 instrument.**

NRL is building two nearly identical CCOR instruments for the SWFO Program: CCOR-1 to fly on the GOES-U Spacecraft (Fig. 5), and CCOR-2 which will be hosted on SFWO-L1. Both instruments are part of the SWFO Program, however the GOES-R Program is programmatically and technically responsible for the fabrication and performance of both CCOR instruments for SWFO. CCOR has evolved in design from STEREO's COR1 & 2 coronagraphs and similar instruments, such as heliospheric imagers. The CCOR is developed as an efficient design with modest size, weight and power parameters compared to earlier instruments. CCOR-1 on board GOES-U will have a field of view (FOV) of 3.7-17 $R_{Sun}$ while SWFO-L1's CCOR-2 FOV will be 3.0-22 $R_{Sun}$. Both CCORs are designed to detect faint light from the corona and CMEs with a brightness threshold of $10^{-11}$ the brightness of the Sun. It features novel designs for stray light control elements such as baffles and light traps, and advanced electronics for its focal plane assembly.

CCOR produces 2048x1920 pixel images at a 14-bit depth and a nominal rate of 2.5 seconds. The instrument supports on-board processing functions such as pixel binning. During solar energetic particle (SEP) events, an on-board program will review the images and scrub them as necessary to remove artifacts due to energetic particle contamination.

Each CCOR will have a time resolution of 15 minutes with a data latency of 30 minutes. Data latency is defined as the difference between the time when image acquisition is completed at the instrument and the time when Level 3 products are generated at SWPC and available to the forecaster.

## 6.2 Data Levels

CCOR image files are in standard Flexible Image Transport System (FITS) format. The CCOR data levels differ slightly from the general definitions in Section 3. The CCOR definitions are:

**Level 1a:** Image in Digital Number (DN or DN/sec, float) with bias, defects, best known exposure time available in the header, and time stamped to beginning of integration. Sun-center position is available in header (WCS). L1a is at full spatial resolution. These images will be provided as input to L1b, L2, and directly to Level 3 products. Housekeeping and ancillary data required for higher-level processing is included here, e.g. spacecraft location and attitude.

**Level 1b (CCOR-1 only)**: Image in DN with straylight and scattered light removed. Image is at full spatial resolution and time stamped to the beginning of the integration interval. These images will be provided as input to L2 and directly to Level 3 products.

Functionally these real-time data levels have the minimum calibration applied as needed to be used as inputs into operational SWPC tools for CME identification and tracking, which rely on coronagraph difference images—where one L1 image is subtracted from the next L1 image. For CCOR-2, L1a is sufficient because CCOR-2 is on SWFO-L1, and as such will not have a changing level of background brightness due to stray light. CCOR-1 on GOES-U may have significant stray light from Earthshine, and the direction and pattern of that stray light could change significantly over CME timescales due to the orbit of GOES-U. Thus, L1b includes an extra step of background light subtraction.

For both CCOR-1 and CCOR-2, L1a is the input for the L2 fully calibrated data product.

The L2 data product is the fully calibrated product:

**Level 2:** Derived from Level 1a with calibration applied; detector flat field, vignetting, and geometric distortion corrected; background subtracted; and in physical units.

Thus, most of the prime and derived measurement requirements from the L2RD and the Resource Allocation Document (RAD) will be verified at this level.

The physical unit for CCOR image intensity is Solar Brightness ($B_{sun}$). $B_{sun}$ is a fixed value defined as TBD.

**Level 3:** Used to define data latency for operational users. May be spatially binned.

## 6.3 Review of Requirements

These are the Coronal White Light Requirements from the L2RD

**Table 7. Coronal White Light Requirements**

| Data Products and Specifications | Threshold: CCOR-1 | Threshold: CCOR-2 |
|---|---|---|
| **Image Center and Orientation** | Sun-centered, Solar North aligned | Sun-centered, Solar North aligned |
| **Field of View (FOV)** | 3.7-17 Rsun for SWFO GOES-U | 3-22 Rsun for SWFO-L1 |
| **Minimum Intensity** | 1x10-11 BSun | 1x10-11 BSun |
| **Maximum Intensity** | 1x10-8 BSun | 1x10-8 BSun |
| **Spatial Resolution** | <50 arcsec for SWFO GOES-U | <70 arcsec for SWFO-L1 |

| | | |
|---|---|---|
| **Maximum Acquisition Time** | 30 seconds | 30 seconds |
| **Measurement Accuracy** | ±10% | ±10% |
| **Refresh Rate** | 15 min | 15 min |

## 6.4 Instrument and Algorithm Development

The vendor for CCOR is NRL. The vendor will build the instrument and conduct pre-launch commissioning to confirm that the instrument meets required specifications. For the algorithms, the vendor will write GPAs for levels L0b through to L2. These GPAs will be adapted by SWPC and NCEI into algorithms that run operationally and retrospectively with minor differences between the two, including operating architecture, while using the same base code components where practical. The SWFO AWG with input from the SWPC, NCEI, and the vendor will write the ATBDs for the higher data levels. SWPC leads the authorship of the ATBDs. Again, these ATBDs will subsequently be developed into working algorithms.

The algorithms will be developed before the instrument goes live in flight, and are likely to be subsequently modified based on PLC, PLPT, and long-term trending analysis. **For example, the "true" stray light pattern and time dependence from Earthshine is not currently known, models based on ray tracing will be used initially and updated as in-flight data is collected and analyzed.** Initial algorithms will make assumptions on the amount of data that needs to be averaged and subtracted, or how to model the stray light. These algorithms will subsequently be modified to create the best possible CCOR data products.

## 6.5 Pre-launch Verification & Validation

Relevant on-ground testing includes the instrument-only tests for detector noise and performance (bias, dark current, gain, linearity, detector defects) with and without external light sources, as well as instrument throughput (component level and/or system level), stray light rejection, vignetting pattern, FOV, optical distortion, and resolution. Additional details are provided in the NRL-provided Calibration Plan for CCOR (SSD-PLN-CC023 Rev -).

## 6.6 Post Launch Commissioning

The PLC will validate the pre-launch calibrations and determine the nominal stray light, and ideally the eclipse stray light, conditions. They will also test the health of the instrument and lead to a beta data release. Additional details are provided in the NRL provided Calibration Plan for CCOR (SSD-PLN-CC023 Rev -).

### 6.6.1 Compact Coronagraph-1 Post-Launch Testing

**Table 8: Compact Coronagraph-1 Post-Launch Commissioning Tests**

| Activity | Description | Dependencies | Estimated Duration (Cumulative Days until completion) |
|---|---|---|---|
| **Power On**<br>**PLC-001** | Confirm detector aliveness | Spacecraft power and command telemetry | 15 days (to allow spacecraft to outgas) |
| **Instrument Vent**<br>**PLC-001** | Slowly vent the instrument, continue detector tests | | 15 days (30 days) |
| **Initial Synoptic Observations**<br>**PLC-003** | Fully open instrument door and begin synoptic observations | Sun-pointing, spacecraft thermal stability | 5 days (35 days) |
| **Exposure Time Tuning**<br>**PLC-004** | Exposure time is varied for optimization | Sun-pointing, spacecraft thermal stability | 5 days (40 days) |
| **Stellar Transit Analysis**<br>**PLC-005** | Observing corona and surround star field | Sun-pointing, spacecraft thermal stability | 15 days (55 days) |
| **Off-pointing Analysis**<br>**PLC-006** | Observing corona with pointing from offset from Sun-center (2-5 arcminutes) | MOST coordination; spacecraft thermal stability | 1 day (56 days) |
| **Roll Analysis**<br>**PLC-007** | Observing corona with spacecraft rolled (4x90 deg increments) | MOST coordination; spacecraft thermal stability | 1 day (57 days) |
| **Deep Exposure Analysis**<br>**PLC-008** | Observe corona with increased exposure time | Sun-pointing, spacecraft thermal stability | 15 days (72 days) |
| **Earthshine Analysis**<br>**PLC-009** | Observing corona with Earthshine present | When orbital conditions allow; Sun-pointing, spacecraft thermal stability | 10 days |
| **Eclipse Mode Analysis**<br>**PLC-010** | Observing corona through eclipse event | When orbital conditions allow; Sun-pointing | 5 days |

### 6.6.2 Compact Coronagraph-2 Post-Launch Testing

The CCOR-2 will involve activities PLC-001 through PLC-008. The schedule of these activities will be significantly affected by SWFO-L1 spacecraft operational requirements such as sun-pointing duration and telemetry during cruise phase. The CCOR-2 PLT plan is TBD and is being constructed in cooperation with SWFO MOST and NRL.

## 6.7 Post-Launch Product Testing

The PLPT is designed to verify that the instrument measurements and the accuracy of the data products meet requirements throughout the lifetime of the instrument. Most of the PLPT is needed for a fully calibrated data product (i.e. L2) which removes all detector and instrument artifacts, as well as stray light and non-K-corona contributions. The PLPT tests for CCOR rely on (1) nominal data collection taken while the spacecraft is at-station (2) data from the PLC tests and (3) instrument-level ground test results.

### 6.7.1 L1a Product Testing

For the CCOR L1a data products, the raw data has corrections for the detector, the metadata has been transformed to physical units, and has information needed to calculate the coordinate of each pixel in the image. At this point, the relevant calibration measurements are those listed below. They were measured on ground and by the vendors via PLCs. The PLPT process will consist of independent verification of these elements, which are needed to compare product performance to L2RD requirements.

- **Detector bias and dark current**: NCEI will validate that the bias and dark current are being accurately subtracted (i.e. the histogram of a short dark exposure centers at zero). Bias and dark current are measured in every nominal image with the opaque detector pixels. During PLC, before the door opens, it will be important to establish uniformity of the dark current to understand how representative of the full detector dark current the opaque pixels are.
- **Detector defects**: NCEI will validate that detector defects are accurately flagged in image data. Data from the Alternate Processing Site (APS) Performance Test can be used for this activity.
- **Focus**: To be verified using stars (known point sources) as a reference. Stars are visible in standard CCOR images. Results will be compared to the vendor on-ground Focus Check and in-flight Star Calibration results. Synoptic images can be used for this test.
- **Pointing**: Image center and orientation: Image center and orientation will be determined by comparing stars in the field-of-view to known star locations. These will be compared to housekeeping data including the Solar Ultraviolet Imager (SUVI) guide telescope. Synoptic images can be used for this test.
- **Field of view:** The FOV is verified using stars seen in CCOR and comparing them to known star locations and pre-flight test results. The FOV and the optical distortion in the FOV are tightly coupled and the same methods are used to verify both. Synoptic images can be used for this test. The requirement is taken to mean FOV to within 10% of lower and upper boundary independently. Because the angular radius of the sun changes as a function of orbit, the Solar Radius is specified to be a fixed value of 0.25 arc degrees TBC in the sky.
- **Resolution:** The instrument resolution can be calculated using stars, which are point sources. The size of a star in CCOR is the spatial resolution. The results will be compared to pre-flight test results. Synoptic images can be used for this test.
- **Cadence:** The image cadence is verified by inspection of the metadata.
- **Conversion of metadata information to physical units**: NCEI will validate that the conversion to physical metadata units is accurate based on vendor-provided conversion formulas. This will be cross-checked with known information, such as multiple temperature readings, or dark current calculations.
- **Latency:** Will be verified by inspection based on image exposure time, and L3 product generation time at SWPC.
- **Calibration tables:** Ground calibration Table Elements that pertain to data products up to L2 will be updated by NCEI, verified by CWG, and sent to all necessary parties,

including OSPO and NRL, when those values are calculated and/or updated the course of the cal/val activities. The initial determination of the calibration values will be provided by the vendor prior to PLC, and NCEI will validate the table corresponds to those provided values and is in the appropriate format as determined pre-flight. Updates to the flight-LUTs and ground calibration tables will be made based on PLC and PLPT activities, these updates will be coordinated with the vendor, SWPC, NCEI, and the full AWG/CWG.

### 6.7.2 L1b Product Testing

CCOR L1b is the operationally focused product that calibrates out background light, specifically for CCOR-1.

- **Real-time background light calibration**: One month worth of data (ending at the current date of observation) will be used to generate a background image that is subtracted from the L1a data to isolate the K-corona. Our current baseline is to use the monthly minimum intensity per line of sight. Corrections for forward-weighting more recent data and accommodations to Earthshine are being analyzed by the vendor (documentation is included in the Giver/Receiver list).

### 6.7.3 L2 Product Testing

For the CCOR Level 2 data products, the data are fully calibrated in physical units with full metadata. This product is created from L1a data and has both operational and retrospective versions. The difference between retrospective and operational products is in the background subtraction: NCEI retrospective data will subtract 1 month of data that includes both past and future times. SWPC operational data will subtract 1 month of data that only includes past times. The exact methodology will be developed in PLPT.

The relevant calibration measurements are:
[list TBD, subject to change based on GPAs and vendor-provided test plan]

- **Image intensity (brightness):** The coronal white light intensity requirements are listed in units of $B_{sun}$ and thus in calibrated units. The full intensity range (and sensor linearity) is measured in pre-launch testing where calibrated light sources are available and validated in-flight with the onboard Light-Emitting Diode (LED) during PLC. Intensities on the linear part of the photon transfer curve (PTC) can be verified in flight by observing stars that are of a known brightness in the CCOR wavelength range. Maximum brightness can be determined with a photon transfer curve calculated with the onboard LED as part of the in-flight APS Performance Test or with long exposures. Intensities can also be cross-calibrated with simultaneous LASCO coronagraph observations. Image intensity is validated for uniformity across the field-of-view after flat field and vignetting corrections, and stray light have been removed. The intensity of a star crossing the FOV will be validated against its known brightness on a fully calibrated image sequence.
- **Retrospective background light calibration**: Calculated with a smoothed monthly minimum brightness image. This will be tracked over time to quantify changes in the stray light and instrument performance.

### 6.7.4 Calibration and Validation Tools

The CCOR CWG has agreed on a list of tools which are necessary for efficiently and effectively achieving KPP. These are tools which will be provided by NRL to NCEI. NCEI will operate these tools throughout the lifetime of the CCOR instruments. Depending on agreements between Program and NRL, NRL may also use some of these tools after IOC to monitor instrument health. Trending analysis will be conducted using many of these tools.

- **GetEarthMoonPosition:** Given a date and spacecraft position parameters, returns the Earth and Moon position in helioprojective coordinates.
- **PlotSCPosition:** Plot the position of the spacecraft and highlight the period of eclipses.
- **GetSunPosition:** Compares image center via stars versus spacecraft provided attitude.
- **PlotStars:** Plots the measured vs. actual positions of stars to derive optical distortions.
- **GetStars:** Outputs stars in image FOV and their luminosity.
- **GetAttitudeFromStars:** Output the image center in helioprojective coordinates using stars in the FOV.
- **CheckDistortion:** Computes 2D functions to describe optical distortion.
- **PlotTemp:** Monitor the detector temperature as it varies with orbit and spacecraft operations
- **LEDImageAnalysis:** Image analysis of the detector with LEDs on.
- PTC: Use an image sequence to produce a plot of the photon transfer curve.
- **OptimalBias:** Given temperature and throughput, calculates the gain to maximize area of image in the linear phase of the photon transfer curve.
- **ComputeExpTime:** Computes ideal exposure time.
- **SeparateDiffractedSL:** Uses a sequence of images to estimate the diffracted straylight distribution.
- **AnalyzeRoll:** Uses images from rolled PLT sequence to determine diffracted straylight distribution.
- **AnalyzeOffPoint:** Uses images from offpointing PLT sequence to determine the relationship between pointing geometry and stray light.
- **ComputeFCorona:** Uses a sequence of images to estimate the distribution of the F-corona for a specific period of time.

## 6.8 Operational Life Phase

TBD, subject to information from the vendor. CCOR will need to have periodic ongoing calibration activities for degradation and sensor trending analysis, instrument throughput, and noise level. These tests are similar to those of PLC, but not as extensive in time. While the calibration will be monitored periodically, it is unknown how frequent ground calibration tables or flight LUT updates will be needed. All such changes will be discussed by the CWG.

### 6.8.1 Operational Calibration

Operational calibrations are covered by PLPT activities (see previous Section "Post-Launch Product Testing"). Much of the trending analysis data will be taken during routine calibration sequences built into normal operation. The following list shows the parameters that will be monitored to ensure the quality of the data:

- Calibration factor
- Vignetting function
- Absolute pointing knowledge
- Diffracted light distribution
- Occulter Brightness (nominal and as a function of Earth elongation)
- Detector temperature
- LED illumination distribution
- Dead pixels

### 6.8.2 Anomaly Resolution

Anomaly resolution will be a collaborative effort by AWG and CWG. This will include SWPC, NCEI, instrument vendors, and the SWFO Program (Flight and/or Ground) as necessary. Further details of the SWFO process will be added as appropriate.

# PART 3: SOLAR WIND MEASUREMENTS

Each one of the sections in Part 3 of this document corresponds to an instrument type. It includes scientific characterization of that instrument's products, a dataflow description, and instrument calibration and L1b product validation plans; and anomaly resolution. Activities are described as a function of the SWFO project lifecycle and expand on the general descriptions of cal/val activities in Section 4.1.

# 7. SOLAR WIND PLASMA SENSOR

The SWiPS will measure the distribution of ions in the solar wind, the supersonic flow of hot plasma from the Sun. The measurements will be used to characterize geoeffective structures such as CMEs, corotating interaction regions (CIRs), interplanetary (IP) shocks, and high-speed flows associated with coronal holes. In this way, SWiPS will provide early warnings for changes in the interplanetary medium which may drive disturbances in geospace.

## 7.1 Sensor Description

The SWiPS design features two oppositely oriented top-hat electrostatic analyzers (ESAs), with a common toroidal entrance aperture, as shown in Figure 6. The ESAs apply an electric field between two curved surfaces that allow charged particles in a narrow energy range access to the microchannel plate (MCP) detectors, located above and below the top and bottom ESAs. The electric field is stepped rapidly through 128 fixed values in the range 16-3,100 V, providing measurements in an energy-per-charge range of 170-33,000 eV/q, corresponding to proton velocities of 180-2,510 km/s.

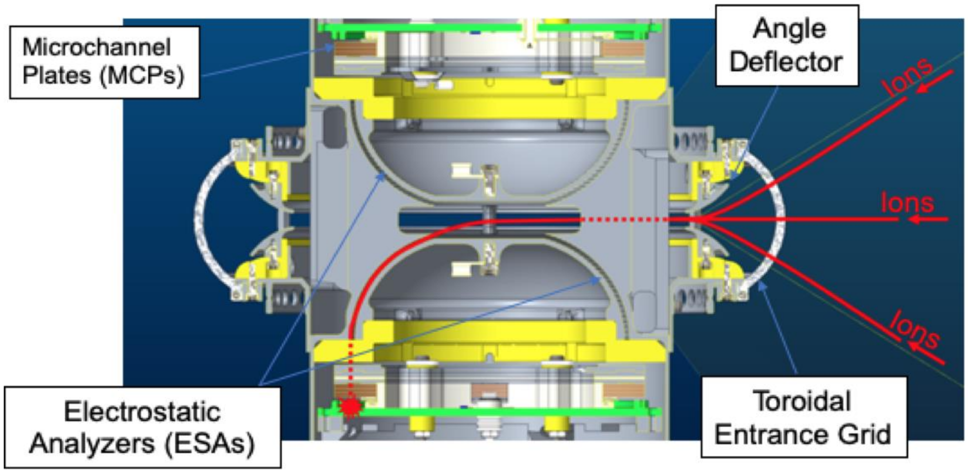

**Figure 6. The Solar Wind Plasma Sensor instrument is composed of two back-to-back electrostatic analyzers. One is used in normal operations and the other, standby, is used for periodic cross**

**calib**rations to monitor changes in the operational sensor performance
[from swips_GPA_draft_01152021_v2]

The SWiPS design is based on the Ion and Electron Sensor (IES) flown on board the Rosetta mission [Burch et al., 2007]. The Rosetta IES uses one ESA to measure electrons and one ESA to measure ions. The SWiPS ESAs, however, are both used for measuring solar wind ions. The two SWiPS ESAs share the same electronics for driving the analyzer voltage, and only one ESA is used operationally, while the other is in standby mode. The standby ESA is used for periodic cross-calibrations with the operational ESA, to monitor changes in the operational sensor performance such as degradation in MCP gain.

The full SWiPS FOV is 90° by 45°. Each ESA deflects ions into 14 azimuthally arrayed anodes spanning 90°, comprised of ten 5°-wide anodes bounded on either side by two 10°-wide anodes. The elevation angle coverage is obtained using a deflection voltage at the entrance aperture of the instrument. The deflection voltage is swept through 19 steps with a maximum amplitude of 5.61 V for the highest ion energies, providing coverage of ±22.5° in 2.5° steps, symmetric about the ecliptic plane.

Each energy-elevation voltage step has a duration of 0.025 seconds. Counts are accumulated simultaneously by all 14 azimuthally arrayed anodes during each 0.025 second energy-elevation step. Since there are 19 elevation-angle deflector steps and 128 energy steps, a full energy-angle sweep is performed in 19 x 128 x 0.025s = 60s. The counts in each energy-angle bin are converted to fluxes using energy-angle-dependent geometric factors obtained from ground calibrations. Velocity distribution functions are calculated from the fluxes in Level-1b processing, and these are used to compute the density, velocity and temperature moments in Level-2 processing (described below in Section 7.5).

Instrument properties are summarized in Table 9.

**Table 9: Solar Wind Plasma Sensor Parameters.**

| Parameter | Value |
|---|---|
| Energy Range | 0.17-33 keV/q |
| Energy Resolution (ΔE/E) | 0.08 eV/eV |
| Analyzer Constant (k) | 10.7 eV/V |
| Geometric Factor (per anode) | 1.5x10$^{-5}$ cm$^{2}$sr eV/V |
| Field of View | 90 deg (azimuth)<br>48 deg (elevation) |
| Azimuth Resolution | 5 deg, φ<\|25 deg\|<br>10 deg, φ>\|25 deg\| |
| Elevation Resolution | 1.8-3.5 deg |

## 7.2 Data Levels

Data levels are defined in a manner similar to the basic definitions for all instruments:

- Level-0: individual data packets such as count rates (CRs) at fixed energy-azimuth-elevation steps.
- Level-0b: Unpacked frames containing complete energy-azimuth-elevation sweeps.
- Level-1a: Decommutated science and housekeeping packets at full-time resolution.
    - Science data include CRs at 128 energy bins, 14 azimuth bins, and 19 elevation bins.
    - Housekeeping data include the spacecraft attitude, and quality flags such as the Poisson error flag, checksum, and red/yellow/green limits for currents, temperature, CR saturation limits, etc.
    - Ancillary data are spacecraft ephemeris data.
- Level-1b: Phase space distribution function as a function of energy E, azimuth $\varphi$, and elevation $\theta$.
- Level-2:
    - For protons, derived plasma moments of density (n), velocity (vector **v**, in GSE and GSM coordinates), and temperature (T).
    - For alpha particles, density (n) and velocity vector (**v**).
    - Housekeeping data include instrument status, quality flags as above, error bars, and number of samples.

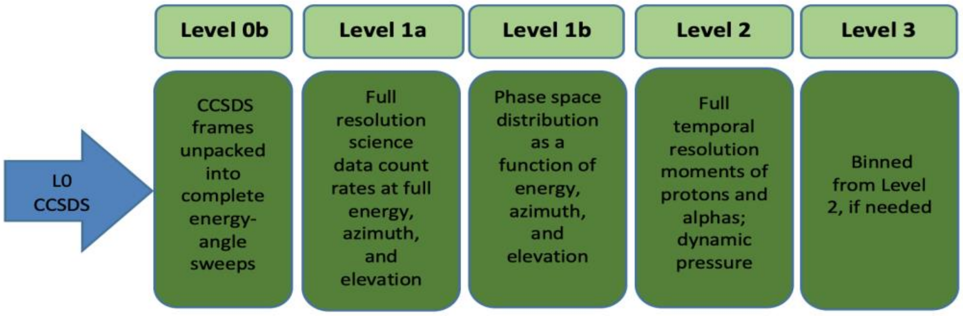

**Figure 7. Solar Wind Plasma Sensor data levels.**

The ground calibrations, the PLC, and the PLPTs described below are aimed at ensuring optimized instrument performance and quality of science data. NCEI will also verify that the SWiPS NetCDF data product files, at all levels, conform to expected formats and contain correct metadata, ancillary data, datasets, timestamps, etc. Discrepancies with expected file formats/contents will be managed as in Section 7.8.2 Anomaly Resolution.

## 7.3 Review of Requirements

This section reviews relevant L2 requirements expanding on the specifications provided in the RAD.

**Table 10: Measurement requirements and Solar Wind Plasma Sensor expected performance (from Table 2, Solar Wind Plasma Sensor performance characteristics, Solar Wind Plasma Sensor GPA document “26093-GPA-01 R2 C0 Submitted 12152021”).**

| Measurement | Requirement | Expected Performance |
|---|---|---|
| Cadence | 1/minute | 19*128*0.025 s = 1/ minute |
| Velocity Range | 200 to 2500 km/s | 180 to 2530 km/s |
| Velocity Accuracy | ± 10% | ± 10% |
| Density Range | 0.1 to 150 $cm^{-3}$ | 0. 1 to 150 $cm^{-3}$ |
| Density Accuracy | ± 10% | ± 10% (assessed after error correction, see Section 7.5.2.) |
| Temperature Range | 40,000 to 2,000,000 K | 10,000 to 2,000,000 K |
| Temperature Accuracy | ± 10% | ± 10% (assessed after error correction, see Section 7.5.2.) |
| Field of View | < 65 x 125 deg | 45 x 90 deg |

## 7.4 Instrument and Algorithm Development

The vendor for SWiPS is Southwest Research Institute (SWRI). The vendor will build the instrument and conduct pre-launch testing to confirm that the instrument meets measurement and design requirements. The vendor will write GPAs for levels L0b through (and including) L2. These GPAs will be adapted by SWPC and NCEI into algorithms that run operationally and retrospectively, including operating architecture, while using the same base code components where practical. The SWFO AWG with input from the SWPC, NCEI, and the vendor will write the ATBDs for the higher data levels. SWPC leads the authorship of the ATBDs. These ATBDs will subsequently be developed into working algorithms.

The algorithms will be developed before the instrument goes live in flight and may be subsequently modified based on PLC and PLPTs to correct instrument and/or GPA anomalies. These algorithms will subsequently be modified to create the best possible science quality data product for NCEI’s ground product cal/val work and will be archived and stewarded at NCEI for general retrospective use. For example, the real-time/operational SWiPS L2 processing computes density, velocity and temperature moments using sums of discrete distribution function values. Retrospective science processing may use integration over functional fits to fluxes or distribution function values to compute the density, velocity and temperature moments.

## 7.5 Pre-launch Verification & Validation

SWiPS measurement range and accuracy requirements apply to density, velocity and temperature moments computed in L2 processing. Level 1a and 1b data products are ion count rates and phase space densities (PSDs), respectively. Measurements of the solar wind PSDs are used to derive the SWiPS L2 data products. While there is no accuracy requirement on the count rate or PSD measurements, uncertainty in these measurements contributes to error associated with the derived L2 moments. Uncertainties obtained from lab calibrations, and L2 GPA error due to instrument resolution and discrete sums used for computing moments (discussed in Section 7.5.2, Ground Processing V&V), will be used by the vendor to verify that measurement accuracy requirements are met. The SWiPS design requirements relevant to Level 0-3 data products are data rate and field of view. These will be verified by ground instrument tests and analysis of Level 0-3 data products.

### 7.5.1 Ground Calibration

A brief overview of the ground calibration is provided here. For additional details, see the SWiPS Calibration Program Plan.

Density, velocity, and temperature moments are computed in L2 processing using PSDs calculated from fluxes (ions / eV-sr-cm$^2$-s) (see, e.g., swips_GPA_draft_01152021 v2 for details of L2 processing).

The flux in a given energy-angle-species bin is calculated operationally

$$j_{i,j,k,s} = \frac{C_{i,j,k,s}}{G_{i,j,k}\left(\frac{E_i}{q}\right)_s}$$

where $C_{i,j,k,s}$ is the count rate from L1a data, $G_{i,j,k}$ is the geometric factor and $(E_i/q)_s$ is the energy-to-charge ratio in units of eV. The indices *i*, *j*, *k*, and *s* specify energy E, elevation angle θ, azimuthal angle φ, and species, respectively.

The primary objective of the pre-launch calibration of SWiPS is to determine the instrument response quantified by the per-pixel geometric factor, $G_{i,j,k}$. The geometric factor is a convolution of the instrument responses in energy and solid angle

$$G_{i,j,k} = A_{eff.}\langle\frac{\Delta E}{E}\Delta\alpha\rangle_{i,j}\,\Delta\beta_k$$

where $A_{eff.}$ is the effective area of the instrument, including an energy-dependent detection efficiency, $<\Delta E/E\ \Delta\alpha>_{i,j}$ is the integrated energy-elevation response of the instrument, and $\Delta\beta_k$ is the azimuthal response. These response functions are obtained from laboratory beam calibrations. An example of the energy-elevation response from simulations of Rosetta IES is shown in Figure 8.

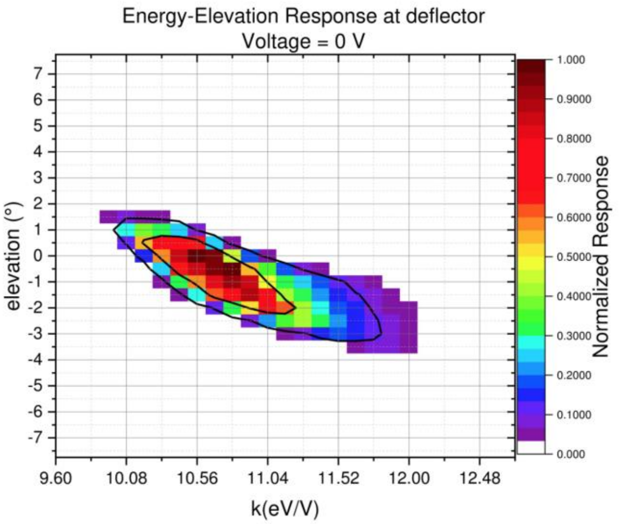

**Figure 8. Energy-Elevation response of Rosetta Ion and Electron Sensor. The contours indicate the tenth-maximum and half-maximum transmission envelopes [from SWiPS Calibration Program Plan, 26093-CPP-01 R2 C0, Rev. 1].**

SWiPS ground calibration and tests include

- Determination of the analyzer constant, *k*, (Table 9) and the FWHM energy bandpass widths
- Microchannel plate gain and discriminator tests
- Beam calibrations to determine geometric factors.

SWiPS beam calibrations will be performed at SwRI's ion calibration facilities, providing single- and multi-species mass-resolved ion beams from 30 eV/e to 51 keV/e.

### 7.5.2 Ground Processing Verification &Validation

This section describes how the SWiPS density, velocity, and temperature L2 data products are derived from the SWiPS ion flux measurements in the SWiPS GPA, and presents errors associated with computation of the L2+ data products.

Measurements of solar wind ion fluxes are used to derive density, velocity, and temperature Level-2 data products. The fluxes $j_{i,j,k,s}$ are first used to calculate the velocity distribution function

$$f_{i,j,k,s} = \frac{J_{i,j,k,s}}{2E_i} m_s^2,$$

where *i*, *j*, *k*, and *s* specify energy, elevation angle, azimuthal angle and species, respectively, and $m_s$ is the mass of ion species *s*, in AMU multiplied by 1.0453453 x$10^{-12}$ eV s$^2$ /AMU cm$^2$, which includes the conversion factors needed to express the velocity distribution function in units of s$^3$/cm$^6$. The density ($n_s$), velocity ($\boldsymbol{u}_s$) and temperature ($T_s$) are obtained from moments of the velocity distribution function, approximated by performing discrete sums over the SWiPS energy-angle grid:

$$n_s = \iiint f_s(\vec{v}) d^3v \cong \sum_{i=1}^{128} \sum_{j=1}^{19} \sum_{k=1}^{14} \left( \frac{v_{i+1}^3 - v_i^3}{3} \right) 2 \sin\left( \frac{\Delta \boldsymbol{\beta}_j}{2} \right) \sin\left( \overline{\beta}_j \right) \Delta\beta_j \Delta\alpha_k \, f_{i,j,k,s}$$

$$\boldsymbol{u}_s = \frac{1}{n_s} \iiint \boldsymbol{v} \, f_s(\vec{v}) d^3v$$

$$\cong \frac{1}{n_s} \sum_{i=1}^{128} \sum_{j=1}^{19} \sum_{k=1}^{14} \left( \frac{v_{i+1}^4 - v_i^4}{4} \right) f_{i,j,k,s} \begin{Bmatrix} \left[ \Delta\beta_j - \sin\left(\Delta\beta_j\right) \cos\left(2\overline{\beta}_j\right) \right] \sin\left( \frac{\Delta\boldsymbol{\alpha}_k}{2} \right) \cos(\overline{\alpha}_k) \ \hat{\boldsymbol{x}} \\ \left[ \Delta\beta_j - \sin\left(\Delta\beta_j\right) \cos\left(2\overline{\beta}_j\right) \right] \sin\left( \frac{\Delta\boldsymbol{\alpha}_k}{2} \right) \sin(\overline{\alpha}_k) \ \hat{\boldsymbol{y}} \\ \sin\left(\Delta\beta_j\right) \cos\left(2\overline{\beta}_j\right) \sin\left( \frac{\Delta\boldsymbol{\alpha}_k}{2} \right) \cos(\alpha_k) \ \hat{\boldsymbol{z}} \end{Bmatrix}$$

$$T_s = \frac{m_s}{3n_s} \iiint (\boldsymbol{v_s} - \boldsymbol{u}_s)^2 f_s(\vec{v}) \, d^3v$$

$$\cong \frac{m_s}{3n_s} \sum_{i=1}^{128} \left( \frac{v_{i+1}^5 - v_i^5}{5} \right) \sum_{j=1}^{19} \Delta\beta_j \sum_{k=1}^{14} \Delta\alpha_k \ I_T\left( \overline{\alpha}_k, \overline{\beta}_j \right) f_{i,j,k,s} - \frac{u_s^2 m_s}{3}.$$

where $\underline{\alpha}_k$ and $\underline{\beta}_j$ are the azimuthal and elevation angles at the centers of the $\alpha_k$ and $\beta_j$ measurement intervals, and $f_{i,j,k,s}$ are the discrete PSD measurements corresponding to each SWiPS pixel (see SWiPS GPA for full derivation).

Two possible sources of error associated with this approach are described below.

1) While the SWiPS energy measurement range corresponds to ion velocities bounding the required velocity measurement range (expected SWiPS performance: 180-2,530 km/s; required range: 200-2500 km/s), the complete distribution of ion velocities needed to obtain a bulk velocity to within accuracy requirements may contain velocities outside of the SWiPS measurement range (Fig. 9a). The problem worsens as the solar wind temperature increases, requiring measurement of ion energies significantly above 2500 km/s. Similar issues may arise near the boundaries of the angular measurements, where the complete distribution needed to obtain densities, velocities and temperatures within accuracy requirements falls outside the SWiPS measurement range. This source of error is expected to be significant only near the limits of the measurement range requirements.

2) If the velocity distribution is very narrow, with significant contribution to the full distribution coming from only a few SWiPS pixels, there may be significant error due to taking $f_{i,j,k,s}$ constant over the intervals included in the discretized sums used to compute moments, e.g., the error in the density will strongly depend on where (relative to the peak) the distribution is sampled. Under typical solar wind conditions with $v_{th}$=30 km/s (corresponding to $T = 10^5$ K and proton thermal energy 86 eV) and $u$ = 500 km/s, we have a narrow solar wind beam with arctan(vth/$u$) ≈ 3.4 deg. The SWiPS azimuthal and elevation angular resolutions are 5-10 deg and 2.5 deg, respectively, and at 1 keV (corresponding to ≈500 km/s proton velocity) SWiPS energy steps are ≈40 eV (swips_GPA_draft_01152021_v2, Table 3). In this case, we expect significant values of fi,j,k,s in only a few SWiPS pixels. The expected error worsens as the bulk velocity increases

and temperature remains constant or decreases. Under solar wind conditions with $T = 10^5$ K and $u = 2000$ km/s, we have arctan(vth/$u$) ≈ 0.86 deg and proton thermal energy =86 eV. At $u = 2000$ km/s (corresponding to proton energies ≈30 keV), SWiPS energy steps are ≈1 keV. In this case the velocity distribution will fall almost entirely in a single SWiPS energy-angle bin, or may straddle two neighboring bins, and we expect significant error in computed densities and temperatures.

The two sources of error are illustrated in Figure 9.

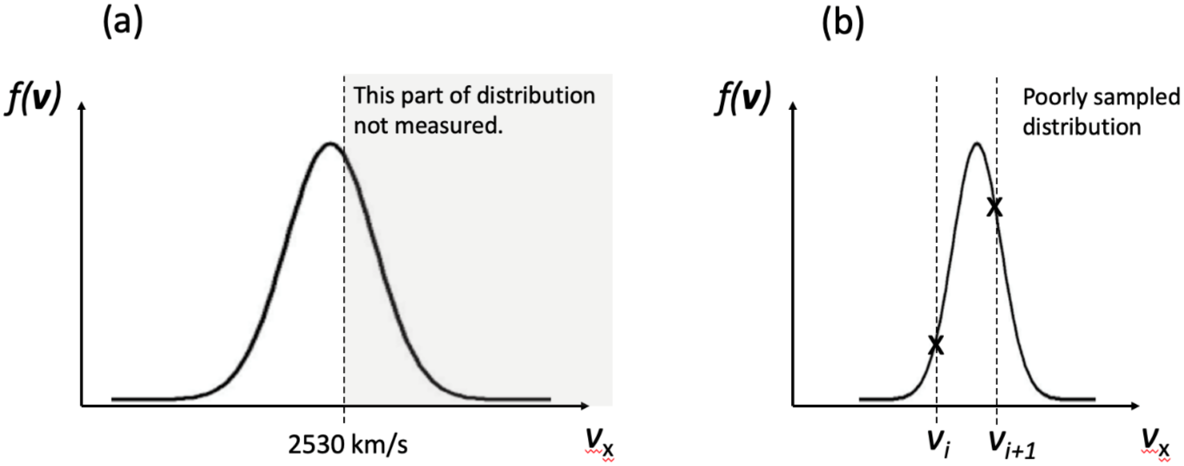

**Figure 9. Illustration of two possible sources of error associated with the method used in Ground Processing Algorithms to compute density, velocity, and temperature: (a) a significant portion of the velocity distribution function lies outside of the Solar Wind Plasma Sensor measurement range, and (b) assumption of constant values of $f_{i,j,k,s}$ in finite sums used to compute moments (i.e., Solar Wind Plasma Sensors pixels do not resolve the velocity distribution function).**

A forward model was developed by the SWiPS vendor to study the errors associated with the computation of velocity moments using the discrete SWiPS measurements. The numerical model uses simulated SWiPS measurements, obtained from an assumed Maxwellian solar wind input distribution, as inputs for the GPA. The GPA output can then be compared to the exact/known density, velocity and temperature of the input distribution to determine the error in each moment.

The elements of the forward model are as follows:

1. Obtain model counts in each energy-azimuthal-elevation bin by convolving the instrument response (effective area) with an assumed Maxwellian velocity distribution function, integrating over velocity space.
2. Simulate the effect of saturation of electronics at high count rates (reduces mean counts at high count rates).

3. Create simulated number of counts in each bin using a random number generator to include Poisson statistics, detector noise and penetrating radiation.
4. Generate complete science packets with sweep counts and housekeeping data.
5. Run science data through the GPA to obtain velocity, density and temperature moments for comparison with moments obtained directly from integration of Maxwellian distribution functions.

Initial results from SWiPS forward modeling are shown in Figure 10.

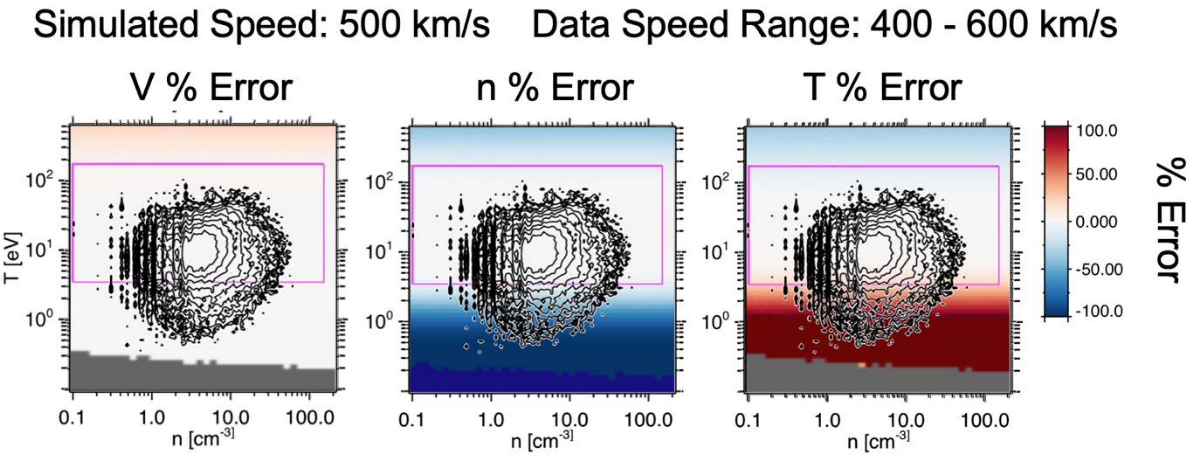

**Figure 10. Ground Processing Algorithm errors in velocity, density and temperature determined using Solar Wind Plasma Sensor forward modeling based on an assumed Maxwellian distribution.**

The forward model is being used to develop error correction lookup tables (ground calibration tables) that will be used in SWiPS ground processing to correct systematic errors in the SWiPS n, ***u***, and T measurements. The corrections reduce the error in reported n, ***u***, and T; however, results from the forward model show that SWiPS will not meet the 10% measurement accuracy requirement over the full n, ***u***, and T required measurement ranges (given in Table 9) when the corrections are implemented in ground processing. At time of writing [2022-3-15 CVP update], a measurement accuracy requirement waiver request is in preparation by the SWiPS vendor. The waiver request is expected to define the region of the required n, ***u***, and T measurement range space over which the 10% accuracy requirement is met and provide new relaxed error bounds in regions of this space where the 10% accuracy requirement is not met.

## 7.6 Post-Launch Commissioning

The PLC activities of Table 9 are planned prior to operational use of SWiPS. They are based on the SWiPS Calibration Program Plan where dependencies (activities 1-5) are specified. They will be supplemented with additional information from the vendor.

**Table 11: Solar Wind Plasma Sensor Post-Launch Commissioning activities (Post-Launch Commissioning from Solar Wind Plasma Sensor's Cal/Val plan, CDRWL 064, "26093-CPP-01 R2 C0", November 2020).**

| Activity | Description | Dependencies | Estimated Duration |
|---|---|---|---|
| PLC-001: Initial Low-Voltage Functional Test Procedure | Conduct initial power on, memory tests, exercising LVENG and LVSCI modes (interactive) | Instrument powered on | 1 day |
| PLC-002: SWIPS High Voltage Functional Test Procedure | Power on and testing of HV, includes HVENG and HVSCI mode testing, initial ramp-up of HV, testing select tables, ramp down of HV. | Activity 1 and >30d passive outgassing in LVENG mode | 1-2 days |
| PLC-003: Full Science Checkout | Exercising of all tables with HV enabled, includes execution of in-flight calibration script | Activity 2 completed | 1-2 days |
| PLC-004: SWIPS Thruster Operation Test (under development) | Verity SWiPS can operate near and/or during thruster firings | TBD | TBD |

Inter-calibration with other spacecraft at L1 such as ACE, WIND, DSCOVR, and IMAP may also be performed by the instrument vendor prior to operational use.

## 7.7 Post-Launch Product Testing

The PLPT activities of Table 12 are planned prior to operational use of SWiPS.

**Table 12: Solar Wind Plasma Sensor Post-Launch Product Testing activities.**

| Activity | Description | Dependencies | Estimated Duration |
|---|---|---|---|
| PLPT-001: Evaluation of Out-of-band Contamination | Look for evidence of out-of-band contamination in measurements and compare with known/likely sources. Quantify contribution to counts from out-of-band contamination. | PLC Activities 1-4 | Solar Particle Event (electrons and protons) |
| PLPT-002: Cross Instrument | Compare with n, ***u***, and T measurements from ACE/SWEPAM, Wind/3DP and DSCOVR/FC Compare flux measurements with STIS in region of energy overlap ~25-30keV | PLC Activities 1-4 | TBD, including periods of elevated *n*, ***u***, and *T* moments |

| | | | |
|---|---|---|---|
| Comparisons | | | |

The goal of SWiPS PLPT-001, Evaluation of Out-of-band Contamination, is to identify sources of counts not in the intended energy bandwidth, field-of-view, and/or particle species, and quantify their impact on the velocity, density and temperature measurements. The primary goal of SWiPS PLPT-002, Cross Instrument Comparisons, is to quantify differences with other solar wind measurements. Comparisons will be made with ACE-Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM), Wind-3DP and DSCOVR-FC, depending on availability. Characterization of differences with legacy solar wind measurements provided by PLPT-002 are critical for establishing continuity with legacy NOAA measurements and consistent space weather forecasting by SWPC.

## 7.8 Operational Life Phase

### 7.8.1 Operational Calibration

The SWiPS in-flight calibration will be performed periodically throughout the life of the instrument (planned cadence is 90 days, subject to change). The IFC includes MCP optimization and cross-calibration between SWiPS primary and standby ESAs. Long term trending of instrument science and housekeeping data will also be performed throughout the mission.

The following instrument parameters, analysis codes, calibration data and documentation have been requested by NOAA-NCEI for SWIPS instrument and ground processing V&V. These tools are needed for cal/val science analysis, long-term trending, and retrospective processing.

1) Parameter tables for ground processing needed by the SWiPS GPA, currently include:
    - swips_cal_inst_param_v0.csv - inst. parameters determined from ground calibrations, e.g., effective area, energy resolution, dead-time, etc.
    - swips_phi_anode_param_v0.csv - min, center, max, dphi of azimuthal anodes
    - swips_theta_dfl_settings_<LUT id>_v0.csv - parameters defining min, center, max, dtheta of elevation angles
    - swips_geofact_anXX_<LUT id> _<protons/alphas>.csv - geometric factors
    - Science Lookup Table - active, on-orbit, instrument configuration table (needed by ground processing GPA)
    - Engineering Parameter Table - Additional parameters required by the GPA stored configurable engineering parameter table (final format TBD)
    - Any additional parameters needed by GPA not currently included in above tables

2) IFC Analysis Codes and Documentation – In-flight calibration analysis codes and documentation describing analysis and interpretation of results (e.g., recommended MCP Voltage and/or GPA gain parameter adjustment). Commented Interactive Data Language (IDL) or Python source code is preferred. Administrative privileges should not be required to install and run the software.

3) Data from ground calibrations and simulations:
    - Energy-Angle Response functions
    - theta and phi response curves
    - Initial/ground MCP gain test data (TBD, pending discussions w/ vendor)

NCEI recommends that the following post-IFC GPA and instrument level maintenance tasks are performed by the SWiPS vendor:

1. Support periodic AWG/CWG meetings
2. Recommend GPA parameter table updates as needed
3. Analyze IFCs and recommend MCP Voltage and/or GPA gain parameter adjustments (flight LUT)
4. Generate on-board science table updates for upload to spacecraft as needed
5. Any additional instrument level maintenance recommended by the SWiPS vendor

These post-IFC tasks are included in the NCEI cal/val tool request v4.5 document, and are pending approval by the SWFO L1 program and SWiPS vendor.

#### 7.8.2 Anomaly Resolution

A generic anomaly resolution process is presented in Section 4.3.5. Anomaly resolution will be a collaborative effort by AWG and CWG, including SWPC, NCEI, instrument vendors, and the SWFO Program (Flight and/or Ground) as necessary. Scientific and technical exchanges will be held for identifying instrument and data processing algorithm issues and developing and implementing solutions to these issues. Descriptions of modifications to existing algorithms and new algorithms will be documented, and anomaly resolution status reports will be presented to the SWFO program and SWPC.

# 8. SUPRATHERMAL ION SENSOR

The STIS monitors the flux of SEPs as a function of energy in real time. As at lower energies (measured by SWiPS), protons are the dominant ion population. The STIS “open” telescope measures protons in the energy range between SWiPS and the NOAA Solar and Galactic Proton Sensor (SGPS) on the GOES-R- series observatories, with some energy overlap. The planned operational use for the STIS ion observations is to predict the arrival of shocks ahead of coronal mass ejections (CME) [Vandegriff et al., 2005]. The STIS “foil” telescope measures 10’s to 100’s of keV solar energetic electrons. These electron flux measurements support a correction for electron contamination in the “open” telescope and, in the future, may be used to provide a warning of solar radiation storms (solar energetic protons above 10 MeV) [Núñez et al., 2018].

## 8.1 Sensor Description

The STIS design is based on the SEP instrument onboard the Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft [Larson et al., 2015]. STIS consists of two solid-state telescopes (SSTs), one for ions (“open”) and one for electrons (“foil”), each consisting of a double stack of silicon detectors (Figure 11). The energy ranges are:

- Ions: 25 keV – 6 MeV (exceeding the required 50 keV – 2 MeV range)
- Electrons: 25 keV – 250 keV

STIS measures energetic particles as a function of their energy deposited into the silicon detectors. These are digitized in the STIS electronics and binned by a Field-Programmable Gate Array (FPGA) for processing and telemetering to ground.

Each telescope consists of a stacked pair of silicon detectors. The front detector is 300 microns thick and is divided into two active regions (AR): AR1, a 0.01 $cm^2$ pixel for measuring high flux levels, and AR2, a 1.0 $cm^2$ annular region around AR1 for measuring low flux levels and for anticoincidence with AR1 for rejecting cosmic rays that penetrate both ARs. The back detector consists of two 300-micron detectors bonded together to effectively create one thicker detector (AR3). AR3 detects penetrating particles (>6 MeV protons and >350 keV electrons) and operates in anticoincidence with AR1 and AR2 to create the required energy channels. The counting response is linear up to 30 kHz with a non-paralyzable dead time up to 100 kHz.

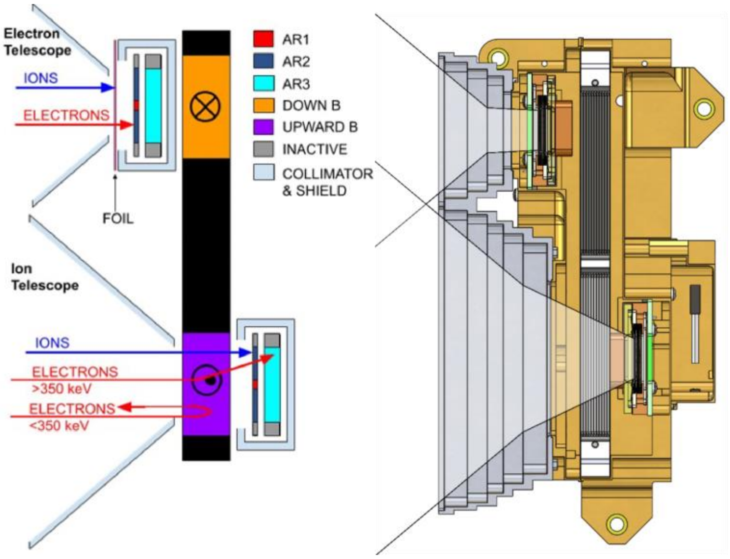

**Figure 11. The Suprathermal Ion Sensor telescopes.**

The aperture of the proton telescope is surrounded by yoked samarium-cobalt (Sm-Co) permanent magnets that prevent <350 keV electrons from reaching the detector. This design follows the magnetically-clean THEMIS design in which the component magnets are arranged such that their far-field dipole fields cancel, leaving a residual quadrupole field that falls off more rapidly with distance.

The lowest ion energy measured will depend on the thickness of the front detector dead layer, of TBD mm, and the noise in the lowest-energy threshold of the open telescope (see PLC-005). Nonetheless, it is expected to be lower than the 50 keV minimum requirement, as low as 30 KeV or possibly lower.

The exposed side of the electron telescope is covered with a 2.43-micron foil (aluminum-Kapton-aluminum) that stops <250 keV/nucleon ions from penetrating to the detector. This is the same thickness as the foil used on MAVEN/SEP. This technique of reducing ion contamination in electron measurements has also been used, for example, on ACE/EPAM, POES/MEPED, and GOES/MAGED. STIS electron channels above 250 keV are also sensitive to ions and usually will be heavily contaminated [Larson et al., 2015].

Each telescope has an 80° x 60° FOV whose center in the long dimension is aligned 50° from the solar direction by mechanical placement on the spacecraft and maintenance of spacecraft orientation during normal operations. This FOV should be free of obstacles. The FOV is defined by collimators consisting of multiple baffles that will reject sunlight successfully if the Sun is at least 5° outside the FOV (this angle during normal operations is 10°). The 900 Å aluminum layer deposited on the front of the “open” detector allows a 30 keV lower proton energy but is too thin to absorb solar x-ray and gamma-ray photons.

Current nominal STIS center energies for channels from the ion and electron telescopes are provided in Table 13 as an illustration. As defined by an uploaded table (flight LUT), the total number of event counter bins is 256, partitioned between the two telescopes and their event types (detector logic combinations) in a manner shown in Figure 11. (An alternative channel definition is provided by a pre-programmed set of logarithmically-spaced energies that does not require an uploaded table. With this definition, the number of event counter bins is 672 (48 per logic combination).) The reporting cadence is programmable from 1 to 512 s, with a current baseline of 15 s and a required upper limit of 5 min (300 s).

**Table 13: Nominal Suprathermal Ion Sensor channel central energies. Proton energies are from the O-2 logic and electron energies are from the F-2 logic (see Figure 13). Produced using 'swfo_stis_inst_response.pro' software provided January 2022 by D. Larson (University of California, Berkeley). Actual flight article energies will differ.**

| Protons (keV) | | Electrons (keV) | |
|---|---|---|---|
| 29 | 324 | 22 | 316 |
| 35 | 472 | 27 | 446 |
| 47 | 685 | 36 | |
| 62 | 1007 | 50 | |
| 83 | 1473 | 71 | |
| 114 | 2154 | 102 | |
| 160 | 3161 | 150 | |
| 226 | 5123 | 220 | |

The following are the housekeeping (HSK) data for STIS:

- Bias Voltage
- Bias Current
- Data Acquisition and Processing (DAP) Temperature
- +5V Digital Voltage
- +5V Analog Voltage
- –5V Analog Voltage
- Detector Front End (DFE) 1 Temperature
- DFE 2 Temperature
- Detector count rates
- Status
- Error counters
- State of Health packets (noise)
    - Noise Histograms
    - Baseline
    - Sigma

- Spacecraft attitude
- Spacecraft status
- Instrument(s) power status
- Instrument current draw

Select HSK data will be used in PLC and PLPT and in long-term trending. For example, the stability of the DFE 1 and 2 temperatures in normal operations will be monitored and used to evaluate the stability of the reported fluxes. (A sun shield was added to the design after PDR to improve the thermal performance.) Spacecraft attitude will be used to interpret STIS performance during maneuvers.

## 8.2 Data Levels

The data levels (shown in Figure 12) are defined as follows:

- Level-0: packed raw science and housekeeping (HSK) data collected by SWFO-L1
- Level-0a: raw data in the form of CCSDS packets; only used by UCB
- Level-0b: “raw” data (counts) in netCDF format to be provided to NCEI.
- Level-1a: full temporal and spectral resolution count rates. Includes HSK and ancillary data required for higher level processing
- Level-1b: calibrated data in flux units at the native (full) temporal and spectral resolution, corrected for dead time
- Level-2: calibrated fluxes with ACE/EPAM-like spectral resolution and full temporal resolution
- Level-3: to be defined by NOAA. May include temporal and/or spectral binning to meet specific product needs (TBD).

Figure 12. Suprathermal Ion Sensor data levels.

The ground calibrations, PLCs, and PLPTs described below are aimed at ensuring optimized instrument performance and quality of science data. NCEI will verify that the STIS NetCDF data product files, at all levels, conform to expected formats and contain correct metadata, ancillary data, datasets, timestamps, etc.

## 8.3 Review of requirements

This section reviews relevant Level 2 requirements expanding on the specifications provided in the RAD.

**Table 14: Measurement requirements and Suprathermal Ion Sensor expected performance as of Critical Design Review (November 8, 2021)**

| Measurement | Requirement | STIS Performance |
|---|---|---|
| Max Flux | $1.01 \times 10^{7} * E(keV)^{-1.6}$ | Meets requirement |
| Min Flux | $2.48 \times 10^{2} * E(keV)^{-1.6}$ | Meets requirement |
| Energy Range | 50 keV - 2000 keV | 25 keV - 6000 keV |
| Accuracy | ± 20% at max. Flux /<br>± 100% at min. (varying) | Requires modeling to meet requirement |
| Field of View | 80° by 60° | 80° by 60° |
| Refresh Rate | 5-minute cadence max. | 1-512 second programmable<br>15 second baseline |

## 8.4 Instrument and Algorithm Development

The STIS vendor is the University of California, Berkeley (UCB) Space Sciences Laboratory (SSL). The vendor will build the instrument and conduct pre-launch testing and simulations to confirm the instrument meets measurement and design requirements. The vendor will write GPAs for levels L0b through (and including) L2. These GPAs will be adapted by SWPC and NCEI into algorithms that run operationally and retrospectively, including operating architecture. The SWFO AWG with input from SWPC, NCEI, and the vendor will write the ATBDs for the higher data levels. SWPC leads the authorship of the ATBDs. These ATBDs will subsequently be developed into working algorithms.

The algorithms will be developed before the instrument goes live in flight and may be subsequently modified based on PLC and PLPT results to correct instrument and/or GPA anomalies. These algorithms will subsequently be modified to create the best possible science quality data product to be archived at NCEI for retrospective use.

## 8.5 Pre-launch Verification & Validation

A brief overview of the ground calibration is provided here. For additional information see the STIS Calibration Plan.

For a given STIS energy channel, the L1b GPA converts count rates to fluxes using

$$j = C / G \Delta E$$

where flux, $j$, is in units of particles/cm$^2$-s-sr-keV, $C$ (1/s) is the count rate (CR), $G$ (cm$^2$-sr) is the geometric factor, and $\Delta E$ (keV) is the energy width of the channel. *The primary objective of* *the pre-launch calibration of STIS is to determine the instrument response, quantified by the geometric factor and energy widths and centers.* The geometric factor and energy widths are used in Level-1 processing to convert count rates in L1a data to “calibrated” fluxes in L1b data. The energy centers are metadata that are critical for the proper use and interpretation of the L1b data. STIS ground calibrations will also include simulation of response to likely sources of out-of-band and cross-species contamination on-orbit, and determination of energy loss of protons in the dead layer of the open detector.

The geometric factor will be determined using a combination of laboratory beam calibrations, numerical modeling with GEANT4 (GEometry ANd Tracking code for simulation of the passage of particles through matter), and analytic calculation of effective area of the detector.

One product of the GEANT4 simulations is the response matrix (RM), which is a function of the incident particle type and energy E and the event counter bin number B. Conceptually, the RM is proportional to the response of a detector combination (anti-coincidence or coincidence) to a spectrum of particles that is flat in energy. Separate STIS RMs will be calculated for protons, electrons, alpha particles, photons, and the different detector combinations.

The observed count rate (CR) in each bin B is the convolution of the response matrix GB(E) in B with the incident flux j(E). The expected CR output is represented by the following measurement integral:

$$R_B = \int j_p(E) G_{p,B}(E) dE$$

For a differential number flux spectrum j(E) in particles/cm$^2$-s-sr-keV, the units of G are cm$^2$-sr. Inversion of the above equation to retrieve j(E) is a classic problem in environmental measurements that is complicated when the total count rates are from the detection of two species

$$R_B = \int j_p(E) G_{p,B}(E) dE + \int j_e(E) G_{e,B}(E) dE$$

where Gp,B(E) and Ge,B(E) are the response matrix elements in bin B for protons and electrons, and $j_p$(E) and $j_e$(E) are the environmental proton and electron energy spectra. In addition to the two-species response, the quantities Gp,B(E) and Ge,B(E) in general have finite responses outside the desired energy band, leading to out-of-band contamination. The L1b GPA described above is an approximate solution of this equation for the flux of one species.

The simulated nominal STIS response matrices for electrons and protons are given in Figure 13. The 256 bins are partitioned among the multiple logical combinations of the STIS detectors in the two telescopes (open (O) and foil (F)). The flat spectrum exaggerates the visual impact of protons above 10 MeV. Nonetheless, this RM indicates the possibility of significant contamination by >10 MeV solar and galactic protons if the spectrum is sufficiently hard. STIS measurements will be limited at the low end of the dynamic range by backgrounds from omnipresent galactic cosmic ray (GCR) protons (0.1-10 GeV) that vary slowly over a solar cycle. The 10-1000 MeV proton component of SEP events may also contaminate the STIS measurements. Characterizing, flagging and correcting cross-species and out-of-band contamination in the STIS measurements will be a substantial component of the STIS cal/val effort.

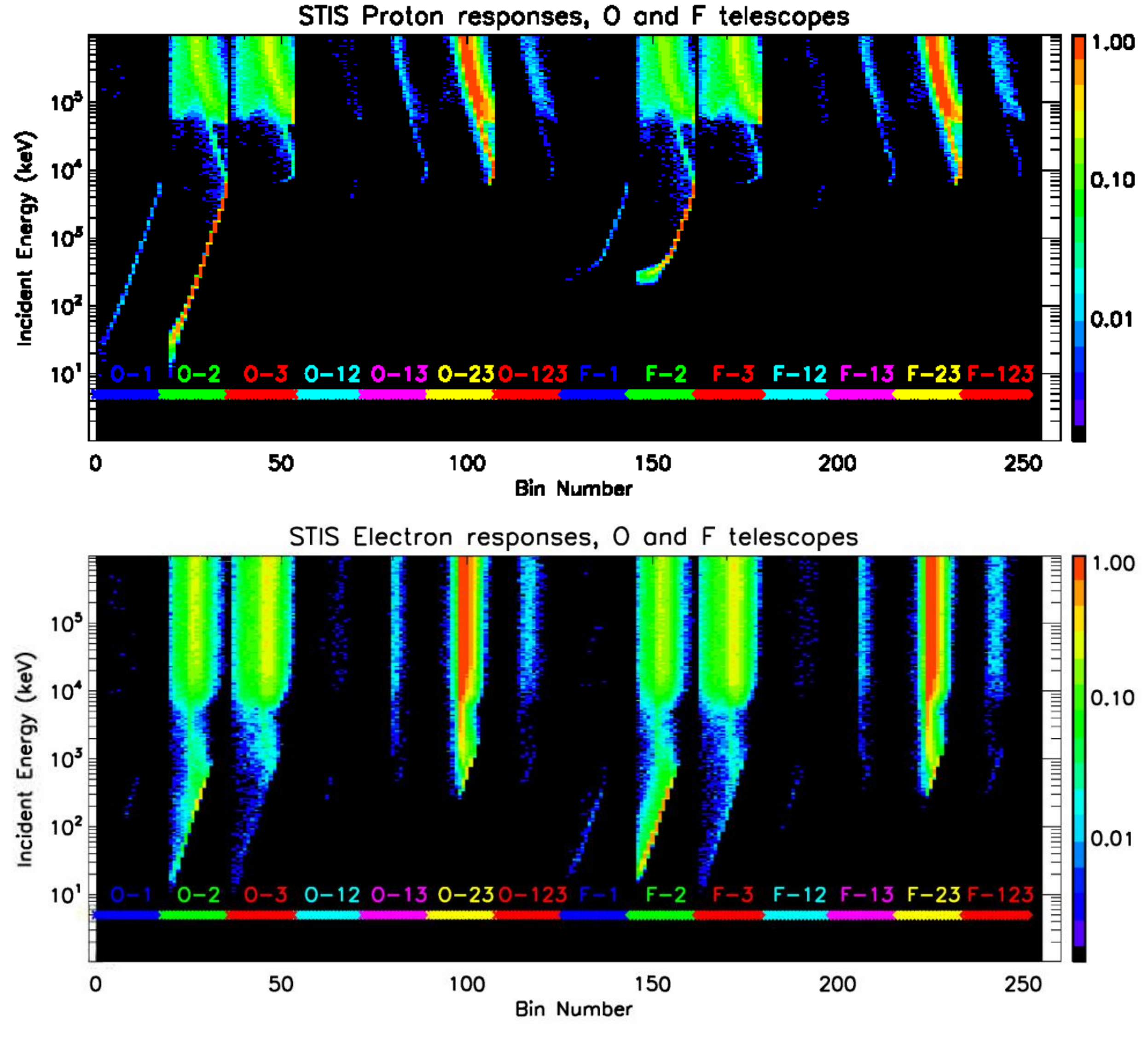

**Figure 13. Nominal Suprathermal Ion Sensor proton and electron response matrices (256 bins or event counters) as a function of incident particle energy E and bin B, as of January 2022. Produced using 'swfo_stis_inst_response.pro' software provided January 2022 by D. Larson (University of California, Berkeley). Actual flight article response matrices will differ.**

Laboratory calibrations will be performed using existing in-house equipment at UCB SSL including a Peabody 50 keV ion gun, B20 Chamber 45 keV electron gun, and Am241 radiation sources. The beam calibrations will verify instrument performance parameters including dead-layer thickness, response functions, energy range, energy resolution, background, sensitivity, peak counting capability, foil ion suppression and magnetic electron suppression systems, and field-of-view. The two pixels on the detector will be characterized separately. A separate test setup with a bright collimated light source will verify the STIS collimator light suppression characteristics. Uncertainties obtained from ground calibrations will be used by the vendor to verify that measurement accuracy requirements are met.

## 8.6 Post-Launch Commissioning

The PLC activities of Table 15 are planned prior to operational use of STIS. They are based on the STIS Calibration Plan where dependencies (activities 1-5) are specified. They will be supplemented with additional information from the vendor.

No calibration maneuvers are planned for STIS. The instrument is planned to operate continuously during all TBD spacecraft maneuvers. During a maneuver, any solar impingement on the telescope FOVs would cause a spurious signal that will have to be recognized and flagged. In addition, direct Sun in the FOV presents the risk of detector degradation if the detectors reach 100°C for TBD minutes. The design of maneuvers for the spacecraft and other instruments will have to ensure that this duration is not reached. In addition, the STIS data will have to be monitored for solar signals during maneuvers.

**Table 15: Suprathermal Ion Sensor Post-Launch Commissioning activities. Associated tools are summarized in Table 17.**

| Activity | Description | Dependencies | Estimated Duration |
|---|---|---|---|
| PLC-001: Initial Turn-on of Detector Bias Voltages | Perform initial turn-on of electron and ion voltages and optimize bias levels on solid state telescopes | Instrument powered on | TBD |
| PLC-002: Initial In Flight Calibration (IFC) | Command initial IFC and verify IFC commands, IFC table, IFC table upload and IFC update commands | PLC-001 completed | TBD |
| PLC-003: Initial IFC Verification and Analysis | Verify that STIS electronics are functioning properly and begin the on-orbit IFC trend process; Upload new IFC table if initial IFC results indicate it is needed | PLC-002 completed | TBD |
| PLC-004: On-orbit Calibration | Begin checkout of fluxes at high energies, beyond those available in ground calibrations, via comparison to THEMIS/SST and ACE/EPAM | PLC-003 and -005 | TBD |

| | | | |
|---|---|---|---|
| PLC-005: On-orbit Calibration Optimization | Adjust low energy noise threshold on each detector to be above the noise floor | PLT-005 | TBD |

## 8.7 Post-Launch Product Testing

The PLPT activities of Table 16 are planned prior to operational use of STIS. The tools to be used in PLPT are summarized in Table 17.

**Table 16: Suprathermal Ion Sensor Post-Launch Product Testing activities.**

| Activity | Description | Dependencies | Estimated Data Duration |
|---|---|---|---|
| PLPT-001: Backgrounds Trending | Characterize backgrounds and determine sources of backgrounds | PLCs 1-5 | Several Months |
| PLPT-002: Evaluation of Out-of-band Contamination | Look for evidence of out-of-band contamination in measurements and compare with known/likely sources. Quantify contribution to counts from out-of-band contamination. The energies of interest are those within the required (ions) or capable (electrons) ranges of STIS. GOES proton observations will also be measured above the STIS upper limit (6 MeV) to evaluate out-of-band contamination. | PLCs 1-5, PLPT-001 | Solar Particle Events (electrons and protons) |
| PLPT-003: Cross Instrument Comparisons | Comparisons with measurements from similar instruments on other spacecraft (e.g. ACE/EPAM). Performance will be compared within the specified ranges for fluxes. | PLCs 1-5, PLPT-001 | Solar Particle Events (electrons and protons) |

**Table 17: Suprathermal Ion Sensor calibratio/validation analysis tools (Post-Launch Commissioning and Post-Launch Product Testing).**

| Activity | Tools |
|---|---|
| **PLC-003: Initial IFC Verification and Analysis** | **UCB code for analyzing threshold and pulser tests conducted during IFC / LPT. Provides inputs to trend analysis.** |
| **PLC-004: On-orbit Calibration** | **This is a UCB tool that will not be transitioned to NCEI. The independence of the PLPT-003 tool(s) from this tool will provide a check on the correctness of the results.** |

| | |
|---|---|
| **PLPT-001: Backgrounds Trending** | **NCEI will adapt GOES-R+ SEISS tools used to evaluate backgrounds in silicon detector telescopes. Background levels will be compared with model GCR spectra (Matthiä et al., 2013) convolved with UCB-supplied response matrices. Provides inputs to trend analysis.** |
| **PLPT-002: Evaluation of Out-of-band Contamination** | **NCEI-developed tool adapted from POES MEPED analysis (Peck et al., 2015) will ingest UCB-supplied response matrices** |
| **PLPT-003: Cross Instrument Comparisons** | **NCEI will adapt several tools developed for GOES-R+ SEISS (e.g., linear, asynchronous (O'Brien et al, 2001), and Theil-Sen (Sen 1968) regression; accuracy measures (Morley et al., 2018)) as needed to STIS** |

Inter-calibration with SEP instruments on other spacecraft (PLPT-003) will be performed using STIS L1b and L2 data. Candidate instruments for inter-calibration are summarized in Table 18.

**Table 18: Candidate instruments for inter-calibration with Suprathermal Ion Sensor.**

| Observatory | Instrument | Location | Ion Energy Range (MeV/n) | Electron Energy Range (MeV) | Angularly Resolved? |
|---|---|---|---|---|---|
| ACE | EPAM | L1 | 0.05-5.0 | 0.04-0.31 | Yes |
| SOHO | COSTEP | L1 | 0.044-6.0 | 0.044-0.3 /<br>0.25-8.7 | No |
| Wind | 3DP | L1 | 0.02-6.0 | 0.025-1.0 | Yes |
| Aditya | ASPEX/STEPS | L1 | 0.02-20 | n/a | Yes |
| IMAP | CoDICE-Hi | L1 | 0.03-5.0 | 0.02-0.6 | Yes |
| SWFO-L1 | SWiPS | L1 | 0.00017-0.033 | n/a | Yes |
| MAVEN | SEP | Mars | 0.02-6.0 | 0.02-1.0 | Yes |
| GOES | SGPS | GEO | 1-500, >500 | n/a | Yes |

The highest priority comparisons are with EPAM, since EPAM ions are currently used for the shock arrival prediction and EPAM electrons are used for the HESPERIA REleASE SEP predictions [Núñez et al., 2018]. SWiPS and STIS will be compared where their energies overlap (25-33 keV) in order to achieve consistency between these SWFO-L1 measurements. Comparison with GOES/SGPS protons in the energy overlap region (1-6 MeV) is important for internal consistency of NOAA data. The main heritage for STIS is the SEP instrument onboard the MAVEN spacecraft. Comparison with MAVEN/SEP can be performed when SWFO-L1 and MAVEN lie on the same interplanetary magnetic field lines. STIS and MAVEN locations will be evaluated on the nominal Parker spiral, and comparisons will be made when they are close to being on the same magnetic field lines. Some instruments provide angularly-resolved data (at a slower cadence), which may be helpful for understanding the behavior of the wide-FOV STIS data. The two GOES/SGPS look directions, well inside the magnetosphere, do not provide information on anisotropies in the solar wind; rather, they will be used to diagnose time-variable geomagnetic shielding that affects the comparisons with STIS.

Data availability may be an issue. Some instruments will have been in space for three decades by the time of SWFO-L1 PLC, while IMAP/CoDICE-Hi will be undergoing commissioning simultaneously with STIS and therefore may not be available for cross-calibration until the operational life phase.

## 8.8 Operational Life Phase

### 8.8.1 Operational Calibration

The PLC-003 STIS IFC sequence will be performed periodically (about every 6 months) throughout the life of the instrument. The IFCs are performed using commandable test pulse generators created by the DAP board for each of the six analog channels. The IFC includes a threshold test and a pulser test. The threshold test sweeps through the threshold of pulses that are counted and is used to check noise performance of the detectors and electronics. The pulser test is an FPGA derived signal that is fed into the front-end electronics for the purpose of verifying the functionality of the electronics chain. Long term trending of instrument science and housekeeping data will also be performed throughout the mission.

### 8.8.2 Anomaly Resolution

A generic anomaly resolution process is presented in Section 4.3.5. Anomaly resolution will be a collaborative effort by AWG and CWG, including SWPC, NCEI, instrument vendors, and the SWFO Program (Flight and/or Ground) as necessary. Scientific and technical exchanges will be held for identifying instrument and data processing algorithm issues and developing and implementing solutions to these issues. Descriptions of modifications to existing algorithms and new algorithms will be documented, and anomaly resolution status reports will be presented to the SWFO program and SWPC.

# 9. MAGNETOMETER

Measurements made by the MAG will be used to characterize the IMF at L1, which is a KPP for the SWFO Program. IMF measurements at L1 play a crucial role in determining the amplitude of magnetic storms and other types of geomagnetic disturbances. The storms can have effects on power grids and oil pipelines via geomagnetically-induced currents, navigation systems, and radio or radar signals, such as ionospheric scintillation). The NWS uses IMF data for a variety of applications as part of NOAAs Space Weather forecasts and nowcasting including as input to NWP models.

These data form the foundation for several forecasting and nowcasting capabilities, especially those related to geomagnetic storms. The MAG data also provide critical contextual information to allow creation of higher-level plasma and particle data products and to improve calibration of the SWiPS and STIS instruments.

The SWFO-L1 MAG will provide magnetic-field measurements with a temporal resolution >1 Hz. The MAG suite consists of an inboard sensor located at approximately 5 m from the baseplate of the boom, and an outboard sensor located at approximately 6.6 m from the baseplate of the boom as shown in Figure 14.

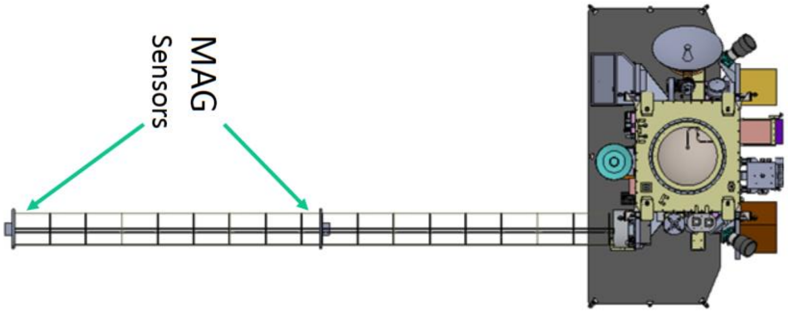

**Figure 14. The Magnetometer sensor mounted on the fully deployed boom.**

## 9.1 Sensor Description

The two MAG sensor units (SUs) are identical three axis vector fluxgate magnetometers based on a racetrack sensor design. The MAG sensor subcomponents, subsystem housing and nominal boom mounting are shown in Figure 15. The sensors are the same physical design as the successful RENU-2 rocket program, with the exception of the physical mount for boom accommodation. The racetrack design should improve signal-to-noise characteristics compared to traditional ring cores, while the MAG electronics has significant space flight heritage.

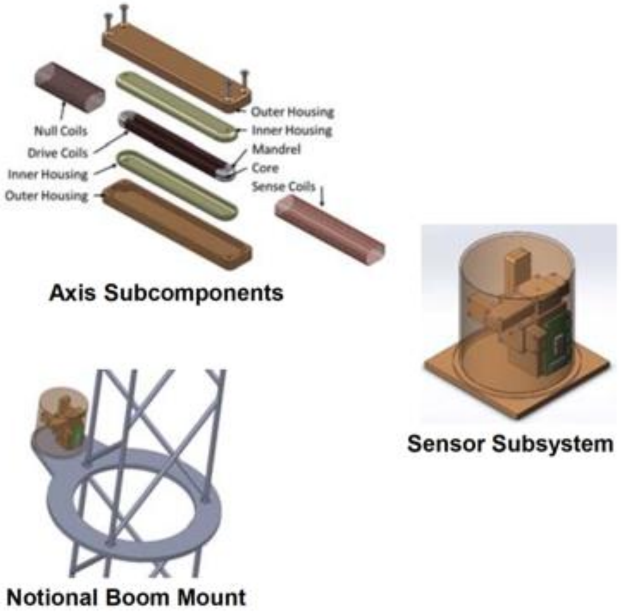

**Figure 15. The MAG sensor subcomponents, subsystem housing, and notional boom mounting.**

Table 19 shows the MAG requirements and expected performance from the instrument Preliminary Design Review (PDR). In addition to these requirements, the sensors will nominally sample each magnetic field vector component at 8 Hz, which meets the requirement of no less than one vector per second. Fundamental requirements on the individual sensor units include requirements on measurement range, measurement accuracy, noise, and resolution. As can be seen in Table 19, MAG performance at PDR exceeds all requirements. In order to meet these requirements, the sensor undergoes both ground and post-launch commissioning which determine the scale factor, zero offset, and alignment correction values which will be applied as part of the GPA.

**Table 19: The Magnetometer sensor requirements and expected performance as of Product Generation and Distribution Preliminary Design Review.**

| SWFO Level 2 Requirement | | | Expected Performance | Basis for Performance |
|---|---|---|---|---|
| Range | In-situ | ±250 nT | ±440 nT | Measurement |
| | Ground test | ± 65 µT | ± 65 µT | Design |
| Accuracy | \|B\| ≤ 100 nT | ≤ ±0.5 nT | ≤ ±0.3 nT | Measurement & Heritage |
| | \|B\| > ±100 nT<br>\|B\| < ±250 nT | ≤ ±0.5% | ≤ ±0.5% | Measurement & Heritage |
| | \|B\| ≥ 250 nT | < ±1000 nT | < ±1000 nT | Measurement, Heritage & Analysis |

| | | | | |
|---|---|---|---|---|
| Noise | Integrated [0.05, 0.5] Hz | 0.137 nT rms | 0.01 nT rms | Measurement |
| Quantization Error | \|B\| ≤ 250 nT | ≤ 0.05 nT | ≤ 0.03 nT | Design (\|B\| ≤ 400 nT) |
| | \|B\| ≤ 65,000 nT | ≤ 13 nT | ≤ 4.0 nT | Design |
| GPA Latency | l1b | ≤ 236 s | ≤ 230 s | Design, Heritage |

## 9.2 Data Levels 1a and 1b

Figure 16 shows the MAG data levels. The SWFO-L1 MAG will downlink instrument data from two on-board magnetometers at a rate of 8 Hz. In this section, only levels L1a and L1b are discussed, while further down Levels L2 and L3 are also discussed. Level L0 is the unpacked instrument telemetry CCSDS frames.

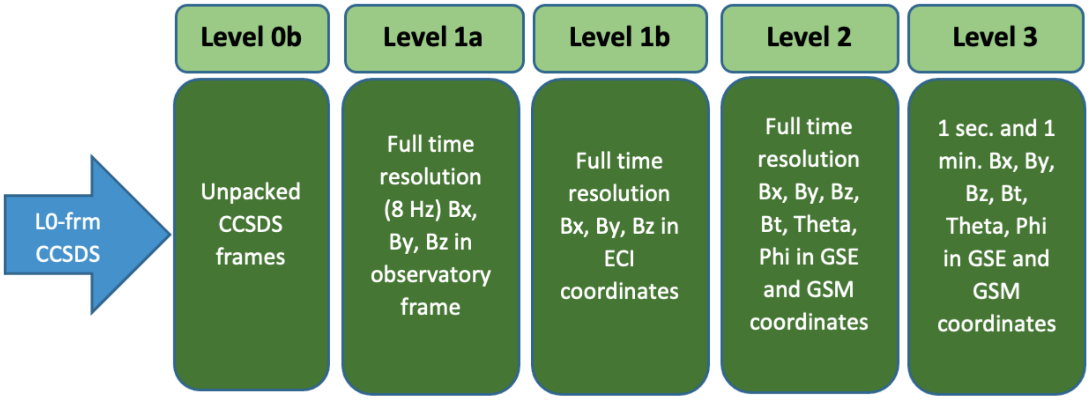

**Figure 16. Magnetometer data levels.**

### <u>L1a</u>

<u>Definition</u>: Derived from Level 0b at full resolution, time-referenced with physical units, and typically referenced to the sensor and/or spacecraft coordinate frames. Data may be calibrated and shall be annotated with ancillary information including data quality indicators, calibration coefficients and parameters for referencing the spacecraft to a defined coordinate system.

<u>Sensor data</u>: Full time resolution, calibrated in nanoTesla Bx, By, Bz in sensor coordinate frame, time stamped to the beginning of the integration interval.

<u>Data quality information</u>: Range, mode, data quality status, telemetry status, calibration version.

<u>Calibration coefficients</u>: Magnetometer Axis System to Magnetometer Sensor System (MSS), Transformations, Zero Levels, and Gains.

Input: L0b data

Output file type: NetCDF day files

**L1b**

Definition: Derived from Level 1a at full resolution, time-referenced with physical units, and referenced to a standard coordinate system (e.g. Earth Centered Inertial). Data are typically calibrated and annotated with ancillary information including data quality indicators, calibration coefficients and parameters for referencing the spacecraft and field of view to a defined coordinate system.

Sensor data: Full time resolution Bx, By, Bz in observatory coordinates, and time stamped to the beginning of the integration interval.

Data quality flags: range, mode, data quality status, telemetry status, and calibration version

Other: MSS to Magnetometer Boom System (MBS), and MBS to Observatory Axis System transformation information.

Input: L1a data

Output file type: NetCDF day files

## 9.3 Review of Requirements

The L2 requirements for the instrument are covered in the SWFO-L1 L2RD, including the RAD.

## 9.4 Instrument and Algorithm Development

The vendor for MAG is SwRI/UNH. The vendor will build the instrument and conduct pre-launch testing to confirm that the instrument meets required specifications. For the algorithms, the vendor will write GPAs for levels L0b through to L2. These GPAs will be adapted by SWPC and NCEI into algorithms that run operationally and retrospectively, including operating architecture, while using the same base code components where practical. The SWFO AWG with input from SWPC, NCEI, and the vendor will write the ATBDs for the higher data levels. SWPC leads the authorship of the ATBDs. These ATBDs will subsequently be developed into working algorithms.

The algorithms will be developed before the instrument goes live in flight, and may be subsequently modified based on PLC and PLPT results to correct instrument and/or GPA anomalies. These algorithms will subsequently be modified to create the best possible science quality data product to be archived at NCEI for retrospective use.

## 9.5 Pre-Launch Verification & Validation

MAG measurement range and accuracy requirements apply to the geomagnetic field product at L2 processing. However, meeting this requirement is dependent on instrument design and ground testing and verification, while on-orbit the L2 product requirements are verified during PLC. An important part of instrument and indeed mission development is magnetic cleanliness. The SWFO mission magnetics working group (MWG) oversees the magnetics control program as part of flight development, ground testing, and verification programs.

### *Magnetics Control Program*

The SWFO-L1 magnetics control program was established to ensure on-orbit interplanetary magnetic field observations meet requirements during NOAA operations. The program approach is the creation of the Spacecraft Magnetic Control Plan (SMCP) (CDRL SE-20) [Kraft, 2022a], which establishes the Magnetic materials, design, analysis, and testing requirements for the SWFO-L1 Spacecraft (S/C) and Observatory. This plan is written to ensure that no S/C steady or time-varying magnetic field interferes with the MAG Payload's ability to meet requirements, and to ensure that no operations in the vicinity of the MAG Payload result in stray magnetic fields or damage to the Payload.

The SWFO-L1 SMCP ensures that all program elements follow best magnetic cleanliness practices from design through launch. Ball Aerospace meets the driving magnetic cleanliness requirements (SRD 3.12) through rigorous systems engineering, detailed materials selection and design, early engagement of the supply chain, testing from the component to the integrated Observatory level, and strict control of tools and materials in all fabrication, integration and test facilities, including the launch pad. To this end, Ball Aerospace partners with the Government and the MAG Instrument Contractor through the monthly MWG meetings. Thermal stability affects magnetic cleanliness (Loto'aniu et al, 2019; Schnurr et al., 2019). Thermal variations and gradients indirectly affect magnetic cleanliness by degrading MAG Sensor measurement stability and driving currents in conductors through the Seebeck effect. Therefore, the MAG Sensors' thermal isolation interface requirement lies within the purview of the MWG.

### *Magnetics Working Group*

The charter of the MWG is to:

1. Maintain the magnetic field error budget for the SWFO-L1 observatory
2. Establish and monitor magnetic field allocations of the subsystems
3. Provide guidance to the spacecraft and instrument engineers on how to meet the magnetic field requirements
4. Review designs to determine if analytically they will meet the magnetics requirements

5. Assist vendors in developing accurate test and measurement procedures for the magnetic field of components and instruments prior to integration with the spacecraft
6. Assist in developing accurate observatory test and measurement procedures, ensuring proper execution of the various magnetic field test/measurement procedures.

## 9.6 Ground Calibration

### *Instrument Level*

The instrument level ground calibration activities are described in the MAG CDR (Torbert et. al., 2021) and the MAG instrument calibration plan (CDRL 064, Smith, 2021). Instrument ground calibration is led by the UNH team, while the Space Research Institute (IWF), in Graz, Austria provides engineering and calibration support. NASA Goddard Space Flight Center (GSFC) magnetics facilities are also utilized. Ground calibration follows two steps:

Pre-calibration – at IWF
- Instrument offsets, noise, relative gain, linearity

Ground Calibration (absolute calibration) – at GSFC
- Instrument orthogonality, offsets, gains, and linearity

Pre-calibration is where the sensor-sensor control board (SCB) subsystem is integrated, tuned, and performance verified. Engineering (EDU) sensor model(s) are first used for pre-calibration and calibration and the process is repeated for sensor flight models (FMs). The FMs further undergo comprehensive performance tests (CPT) to verify performance including gains, offsets and sensitivity. Figure 17 shows photos from calibration testing of the EDU SCB and Sensor at IWF facilities, and the magnetic test facility (MTF) at NASA-GSFC used for instrument calibration.

**Figure 17. Impressions from engineering testing at Space Research Institute facilities and magnetic test facility at NASA-Goddard Space Flight Center (Tobert et. al., 2021).**

The equation below describes the basic conversion of sensor measurement, $C_i$, in counts to corrected magnetic field, $B_i$, in nanoTeslas (CDRL 064, Smith, 2021).

$$B_i = A\left[\left(G_{i0} + G_{i1}\Delta T\right)C_i + \left(O_{i0} + O_{i1}\Delta T\right)\right] \tag{9.1}$$

Here, $G_i$ and $O_i$ are the Gain and Offsets for sensor axis *i*. $\Delta T = T_i - T_{ref}$ is the sensor and electronics temperature relative to a reference temperature, $T_{ref}$. The alignment matrix, *A*, along with *G* and *O* matrices and temperature dependencies are determined during ground calibration. Values, particularly for offsets *O*, are recomputed during on-orbit calibrations.

### *Spacecraft Level*

Determining the magnetic signature from the spacecraft at the MAG sensor locations is critical to providing accurate measurements that meet operational requirements. Although good estimates of the expected spacecraft magnetic field are given by component unit testing and modeling, to verify compliance to SWFO-L1 magnetic requirements, a series of spacecraft and Observatory level tests are also performed. The spacecraft level ground calibration is described in the SMCP (CDRL SE-20) [Kraft, 2022a] and the SWFO-L1 CDR [Kraft, 2022b].

### *Swing Test - Static Magnetic Field Testing (Power-Off)*

After spacecraft integration a “swing” test is performed for the static magnetic field component due to internal magnets and materials. Figure 18 shows the swing test setup. The spacecraft is hung from a crane with magnetometers placed around it to detect magnetic fields when the spacecraft undergoes a series of quasi-free swings with lateral displacements of approximately 40 cm. The number of swings is a minimum of four and a maximum of twelve. After each swing, the spacecraft is rotated about the X axis and the test repeated. Data from surrounding magnetometers are collected and using algorithms derived from heritage Ball Aerospace algorithms, the static magnetic dipole moment of the spacecraft can be calculated.

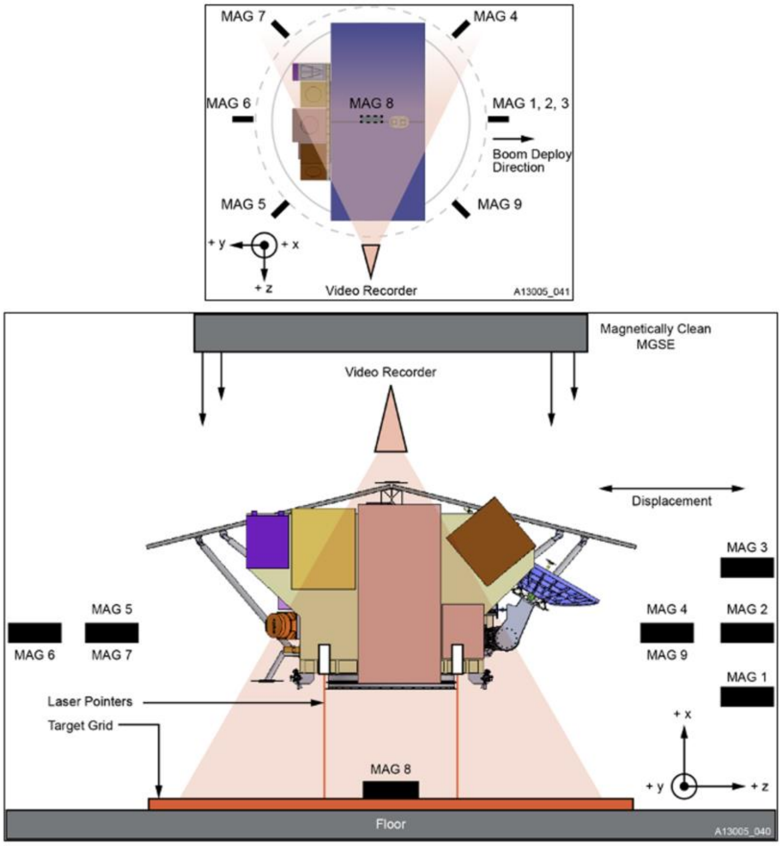

**Figure 18. Swing test system. (Top) Plan view. (Bottom) Vertical view. The video recorder is oriented at ~45° to image the grid below the spacecraft [Kraft, 2022b].**

### *Dynamic Magnetic Field Testing (Power-On)*

Following swing testing, the spacecraft is lowered onto a magnetically clean stand and the test magnetometers are rearranged as shown in Figure 19. A series of magnetometers located along the boom deployment axis are used to provide multiple data points on the magnetic field decay rate to ensure requirements are met. With power-on, the spacecraft is cycled through each of its operational modes with special attention paid to the Observation mode. Extended measurements are performed during this mode, which includes a full battery charge/discharge cycle (including switching solar array strings on and off), RF switching, full sweep of gimbal motion, reaction wheel spin up/down and heater power switching. This provides data to verify the dynamic magnetic field observed at MAG sensor locations meet requirements.

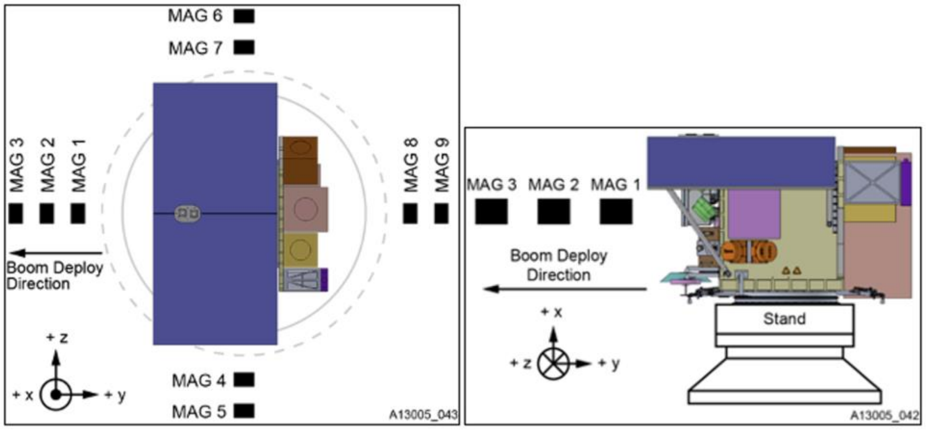

**Figure 19. Test set-up for static and dynamic testing for current loops and transients. (Left) Plan view. (Right) Vertical view [Kraft, 2022b].**

## 9.7 Ground Processing Verification & Validation

The ground data processing algorithms include calibration matrices (*A*, *G* and *O*) as defined in Eqn. 9.1 above. Correct application of the calibration within the ground processing will be tested using DSCOVR data and DSCOVR calibration tables. Once final SWFO-L1 MAG ground derived calibration values are available, these values will be used with proxy and model SWFO-L1 MAG data to validate correct application of the calibration in ground processing.

## 9.8 Post-Launch Commissioning

The instrument PLC activities are shown in Table 20. Besides these activities, another important event is boom deployment, which will provide information on the level of spacecraft magnetic field during stow and initial estimates of offsets during deployment. The recommended plan for in-flight calibrations, providing updates to the offsets in Eqn 9.1, is described below.

**Table 20: Magnetometer instrument Post-Launch Commissioning activities.**

| PLC Activity | Description | Estimated Data/Analysis Duration |
|---|---|---|
| In-flight Calibration | Determine DC offsets | 2 weeks (after each calibration maneuver) |

| | | |
|---|---|---|
| Inter-Sensor Difference Comparison | Determine S/C DC field, relative bias | 2 weeks |
| Inter-Sensor Ratio Comparison | Validate relative instrument gains | 2 weeks |
| MAG Sensitivity to Interference | Quantify magnetic field changes for all three axes of each magnetometer due to satellite time-varying and constant fields | Passive Test performed over duration of Observatory Activation; Analysis will take 2 months. |
| In-situ Noise Floor | Validate performance parameters (noise floor, relative phase, relative amplitude as a function of frequency) | 1 month – need calibrated data (attempt) |
| Phase test | Detect potential changes in the sensor | 5 days after test (thermal stability; 10 minutes/axis; pass/fail result – no actionable information) |
| Comprehensive/Limited-Performance | System checkout and verification on power-up | 5 Days after turn-on |

### ***On-orbit Offset Determination***

The recommended on-orbit offset determination plan is also described in Loto’aniu (2022). We recommend that the SWFO MAG on-orbit offset calibrations follow a combination of two approaches in the PLC and the operational phase. This combination is designed to provide optimal performance of the instrument and satisfy the data availability requirement. The overall calibration approach is similar to the one employed on the DSCOVR [Zinchini, 2015]. The DSCOVR plan consisted of two parts: spacecraft maneuvers (rolls and slews); and analysis of Alfvenic perturbations of the IMF.

The MAG instrument vendor (UNH/SwRI) has proposed to implement a modified version of the Davis-Smith (Alfvenic) technique (Belcher et al., 1969; Smith et al., 1998; Torbert et al., 2021], and provide related algorithms, data, and documentation. NOAA/NCEI will develop and provide a calibration maneuver analysis algorithm in consultation with all participants of the CWG of the SWFO GS. NCEI will start with the GOES-R calibration maneuver analysis algorithms and modify them as required for the SWFO-L1 mission while validating them with DSCOVR data as a proxy.

The recommendation is for the use of spacecraft maneuvers as the primary on-orbit offset calibration method, with the Alfvenic method used for X-axis offset determination and as a calibration monitoring tool to watch for any significant changes in the offsets in-between maneuvers.

In summary, we recommend a combination of two approaches to ensure the mission meets the data availability requirement:

1. A roll- and slew-based calibration described below.
2. A manual version of the UNH/SwRI-proposed Alfvenic calibration technique applied after a maneuver.

### *Coordinate Systems*

XYZ Coordinates

In describing the maneuvers, we define a Cartesian coordinate system with the following axes:

- X is a direction through the spacecraft and parallel to the Sun-Earth line.
- The Y-Z plane is oriented at right-angles to X. The orientation of Y-Z in the plane is not important for our purposes here. X, Y and Z form an orthogonal coordinate system.
- For simplicity we also assume that the MAG internal sensor axes are aligned with the above-described X, Y and Z. This is subject to an angular error of TBD degrees/axis.

RTN Coordinates

The Radial-Tangential-Normal (RTN) system is currently used by the vendor in developing and validating their on-orbit calibration method. The RTN depends on the location of the spacecraft:

- +X (or ~R, where “~” means “approximate” or “approximately in the direction of”): directed from the Sun toward the spacecraft
- +Y (or ~T): cross-product of the Sun's rotational axis with R
- +Z (or ~N): The cross product ~RxT

### *Magnetometer Y- and Z-axis Calibration Maneuver (X-axis roll)*

Purpose

To obtain the magnetometer Y- and Z-axis zero offsets

Specifications

- The maneuver consists of one or more 360-degree rotations about the X-axis
- For the duration of the maneuver, it is desired to maintain the rotation axis within 2 degrees of the spacecraft X-axis throughout the maneuver

Constraints

- SWFO-L1 must be at least 20 Earth radii (RE) upstream from the Earth (outside Earth's bow shock)
- The MAG in its normal operating mode
- The MAG boom is deployed
- Spacecraft should be in its nominal configuration, i.e. in the default power mode.
- Space Weather conditions:
    - Solar wind conditions should be calm and total interplanetary magnetic field (Bt) fluctuations should < +/- 2 nT (TBC) for at least one of the 360 rotations.
    - There should always be consultation with the SWFO CWG and, during the operational phase of the mission, SWPC forecasters for go/no-go conditions during lead up to rolls.
    - The SWFO CWG will be able to review these constraints and provide recommendations to go ahead with the maneuver under conditions which are less ideal than what has been described above.

Timeframe

- Duration: repeat 3-10 times (as many as possible) during each maneuver event to increase the probability of finding a quiet period. The maximum number of rolls is 10.
- Frequency of maneuvers: As many as needed during PLC; approximately monthly or less frequently thereafter. If the MAG offsets during PLC are stable (do not change significantly from one calibration to the next), the maneuvers can be spaced 3 months.

### *Magnetometer X-axis Calibration Maneuvers (Y- and Z-axis slews)*

Purpose

To obtain the MAG X-axis zero offsets

Specifications

- The maneuver consists of a partial (less than full) rotation about one of the Y- and Z-axes with the following angles. The angular restrictions are TBD for SWFO-L1. For DSCOVR the angles are as follows:
    - Initial -30 degrees pitch to Sun pointing attitude
    - Slew to +60 deg about the Y (or Z) axis
    - Slew from +60 to -60 deg
    - Slew back to sun pointing
    - For the duration of the maneuver, it is desired to maintain the rotation axis within 2 degrees of the spacecraft Y- or Z-axis throughout the maneuver

Constraints

- SWFO-L1 must be at least 20 RE upstream from the Earth (outside Earth's bow shock)
- The MAG in its normal operating mode
- The MAG boom is deployed
- Spacecraft should be in its nominal configuration, i.e. in the default power mode
- Space Weather conditions:
    - Solar wind conditions should be calm and total interplanetary magnetic field (Bt) fluctuations should < +/- 2 nT (TBC) for at least one of the 360 rotations.

  - There should always be consultation with SWFO CWG and, if done during the operational phase of the mission, SWPC forecasters for go/no-go conditions during lead up to rolls.
- The SWFO CWG will be able to review these constraints and provide recommendations to go ahead with the maneuver under conditions which are less ideal than what has been described above.

Timeframe

- Duration: repeat 5 or more times during each maneuver event to increase the probability of finding a quiet period.
- Frequency of maneuvers: once during the ascent to L1 and once after the spacecraft is in orbit.

### *Calibration Workflow*

We recommend the following workflow to obtain the MAG offsets on-orbit:

1. After completion of the first X-axis roll maneuver, the Y and Z-axis offsets are determined using the modified GOES-R algorithm.
2. After the Z-axis slew maneuver, the X and Y-axis offsets are determined using the modified GOES-R algorithm.
3. The GPA MAG calibration table used on the ground is updated with Y and Z-axis offsets from 1. and X-axis offset from 2.
4. The modified Davis-Smith method is used to calculate X, Y and Z offsets and validated against the values in the updated calibration table.This analysis should be repeated as many times as needed to obtain a statistically significant set to determine how well the Alfvenic method can determine X-axis offset for a given epoch.
5. In subsequent X-axis roll maneuvers, the Y- and Z-axis offsets are determined using the modified GOES-R algorithm.
6. The calibration table is updated with Y and Z-axis offsets from 5.
7. The modified Davis-Smith method continues to be used to calculate X, Y and Z offsets.
8. The Y and Z-offsets from #5 are compared to values from #7, and if they are comparable within a tolerance of 0.5 nT (TBC) and if X-axis offset from #7 has a standard deviation below a tolerance of 0.3 nT (TBC) the mean X-axis offset from #7 is used to update the X-axis offset in the calibration table. Otherwise, the X-axis offset in ground calibration table is not updated.

### *Maneuver Schedule for PLC and operations*

PLC:

The day numbers in the following are based on DSCOVR and are meant only as a guide. The actual day numbers will depend on the specific SWFO-L1 mission schedule.

- Day L+3-4: MAG activation, data collection starts, boom deployment, and MAG internal calibrations start. There could be advantages in doing an early calibration maneuver. However, if instruments and some subsystems are not activated this early offset determined may not be accurate. Furthermore, the spacecraft needs to be outside the magnetosphere and magnetosheath regions (~10-15 RE) for reliable offset determination.

- Days L+5-14: Other instrument activations and related activities.
- Day L+15: Other instruments should already be activated if possible. Perform magnetometer calibration rolls (rotation about X-axis to be described in detail in Section 6 below). SWFO-L1 should be well upstream of Earth's bowshock (e.g., >=20 RE).
- Day L+16: Perform magnetometer calibration slews (rotation about either Y or Z-axis, to be described in detail in Section 5 below) as done on DSCOVR. For SWFO-L1, we recommend at least one off-pointing slew maneuver to establish the X-axis offset baseline.
- Between Launch Orbit Insertion and commissioning: During the commissioning period, we recommend regular X-roll maneuvers to determine Y and Z-axis offsets; and 1-2 Y- and/or Z-slews to determine the X-axis offset.

## 9.9 Post-Launch Product Testing

The PLPT activities of Table 21 are planned prior to operational use of MAG.

**Table 21: List of Post-Launch Product Tests (PLPTs).**

| PLPT Activity | Description | Estimated Data/Analysis Duration |
|---|---|---|
| PLPT-001: Product level Inter-Sensor Comparisons | Validate that inboard and outboard data products are consistent with each other. Helps with relative accuracy. | 2 weeks |
| PLPT-002: Product level Noise | Determine product noise level | 2 weeks |
| PLPT-003: Product level Inter-Satellite Comparison | Determine product relative accuracy | 6 weeks |

The goal of MAG PLPT-001 is to compare the inboard and outboard sensors for consistencies. This provides a relative accuracy. It is expected that after calibration, the two sensors should have a relative accuracy of ~1 nT. We can also check the level of spacecraft fields at the sensor locations by using the gradiometric method. The primary goal of MAG PLPT-002 is to determine the level of noise in the product. The goal of MAG PLPT-003 is to determine the accuracy of the MAG product relative to other space asset magnetic field measurements at L1 such as ACE, DSCOVR and IMAP.

## 9.10 Operational Life Phase

### 9.10.1 Operational calibration

During operations, offset calibrations should continue with regular (monthly or farther apart, e.g., 3-monthly) X-roll maneuvers to determine Y and Z-axis offsets. This should be complimented with continued use of the modified Davis-Smith method to determine X-axis offset, while in-between maneuver periods the modified Davis-Smith method is used to monitor all the axes for any anomalous changes. Furthermore, all PLPTs will continue to be monitored throughout the operational life of the mission.

### 9.10.2 Anomaly Resolution

The AWG and CWG will discuss and determine actions and resolutions for anomalies. Scientific and technical exchanges will be held for identifying instrument and data processing algorithm issues and developing and implementing solutions to these issues. Descriptions of modifications to existing algorithms and new algorithms will be documented, and anomaly resolution status reports will be presented to the SWFO program and SWPC.

# APPENDICES

## APPENDIX A: REFERENCES

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# APPENDIX B: ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| ACE | Advanced Composition Explorer |
| AFSCN | Air Force Satellite Control Network |
| APS | Alternate Processing Site |
| AR | Active Region |
| ATBD | Algorithm Theoretical Basis Document |
| AWG | Algorithm Working Group |
| C2 | Command and Control |
| cal/val | Calibration and Validation |
| CBU | Consolidated Backup facility |
| CCB | Configuration Control Board |
| CCOR | Compact Coronagraph |
| CCR | Configuration Control Request |
| CDRL | Contract Data Requirements List |
| CIR | Corotating Interaction Regions |
| CME | Coronal Mass Ejection |
| CMO | Configuration Management Officer |
| CR | Count Rate |
| CONOPS | Concept of Operations |
| CONUS | Continental United States |
| COOP | Continuity of Operations |
| COTS | Commercial Off-the-Shelf |
| CVP | Calibration and Validation Plan |
| CWG | Calibration Working Group |
| CWLI | Coronal White Light Intensity |
| DLR | German Aerospace Center |
| DN | Digital Number |

| | |
|---|---|
| DOC | Department of Commerce |
| DOD | Department of Defense |
| DSCOVR | Deep Space Climate Observatory |
| DSN | Deep Space Network |
| EELV | Evolved Expendable Launch Vehicle |
| EM | Engineering Model |
| ERB | Enterprise Risk Board |
| ESA | Electrostatic analyzers |
| ESPA | EELV Secondary Payload Adapter |
| F&PS | Functional and Performance Specification |
| FCDAS | Fairbanks Command and Data Acquisition Station |
| FIPS | Federal Information Processing Standards |
| FITS | Flexible Image Transport System |
| FOC | Full Operational Capability |
| FOT | Flight Operations Team |
| FOV | Field of View |
| FPGA | Field-Programmable Gate Array |
| FSDE | Flight Software Development Environment |
| GCR | Galactic Cosmic Ray |
| GEARS | Ground Enterprise Architecture Services |
| GEO | Geostationary Orbit |
| GFE | Government-Furnished Equipment |
| GFP | Government Furnished Program |
| GOES | Geostationary Operational Environmental Satellite |
| GPA | Ground Processing Algorithm |
| GPS | Global Positioning System |
| GRT | Ground Readiness Team |

| | |
|---|---|
| GS | Ground Segment |
| GSFC | Goddard Space Flight Center |
| HGA | High-Gain Antenna |
| HSK | Housekeeping |
| I&T | Integration and Test |
| ICD | Interface Control Document |
| IED | Ion and Electron Sensor |
| IF | Intermediate Frequency |
| IFC | In-Flight Calibration |
| IMAP | Interstellar Mapping and Acceleration Probe |
| IMF | Interplanetary Magnetic Field |
| IOC | Initial Operational Capability |
| IOO | Instrument of Opportunity |
| IP | Interplanetary |
| IRD | Interface Requirements Document |
| IT | Information Technology |
| ITAR | International Trade in Arms Regulation |
| JASD | Joint Agency Satellite Division |
| KPP | Key Performance Parameters |
| L1 | Lagrange point L1 |
| L1RD | Level 1 Requirements Document |
| L2RD | Level 2 Requirements Document |
| LASCO | Large Angle and Spectrometric Coronagraph |
| LED | Light-Emitting Diode |
| L *n* | Level *n* (*n*=0,1a,1b,2,3) |
| L *n* RD | Level *n* (n=1,2,3) Requirements Document |
| LOI | Launch and Orbit Insertion |

| | |
|---|---|
| LUT | Lookup Table |
| MAG | Magnetometer |
| MAVEN | Mars Atmosphere and Volatile Evolution |
| MBS | Magnetometer Boom System |
| MCP | Microchannel Plate |
| MIS | Mission Information System |
| MOC | Mission Operations Center |
| MOM | Mission Operations Manager |
| MOST | Mission Operations Support Team |
| MSS | Magnetometer Sensor System |
| MWG | Magnetometer Working Group |
| NASA | National Aeronautics and Space Administration |
| NCEI | National Centers for Environmental Information |
| NESDIS | National Environmental Satellite, Data, and Information Service |
| NGE | NESDIS Ground Enterprise |
| NICT | National Institute of Information and Communications Technology |
| NIST | National Institute of Standards and Technology |
| NOAA | National Oceanic and Atmospheric Administration |
| NPR | NASA Procedural Requirements |
| NRC | National Research Council |
| NRL | Naval Research Laboratory |
| NSN | Near Space Network |
| NSOF | NOAA Satellite Operations Facility |
| NSOSA | NOAA Satellite Observing System Architecture |
| NSTO | National Science and Technology Council |
| NWP | Numerical Weather Prediction |
| NWS | National Weather Service |
| O2R | Operations to Research |

| | |
|---|---|
| OCONUS | Outside of the Continental United States |
| OPPA | Office of Projects, Planning, and Analysis |
| ORD | Operational Requirements Document |
| OSGS | Office of Satellite Ground Systems |
| OSPO | Office of Satellite Products and Operations |
| OURD | Observational User Requirements Document |
| PD | Product Distribution |
| PDR | Preliminary Design Review |
| PG | Product Generation |
| PGD | Product Generation and Distribution |
| PlasMag | Plasma Magnetometer |
| PLC | Post Launch Commissioning |
| PLPT | Post-Launch Product Testing |
| PORD | Performance and Operational Requirements Document |
| PRO | Product Readiness and Operations |
| PSD | Phase Science Densities |
| PSE | Program Systems Engineering |
| PTC | Photon Transfer Curve |
| PUNCH | Polarimeter to Unify the Corona and Heliosphere |
| RAD | Resource Allocation Document |
| R2O | Research to Operations |
| $R_E$ | Earth Radius |
| RF | Radio Frequency |
| RM | Response Matrix |
| $R_{Sun}$ | Solar radius (symbol) |
| RTS | Relative Time Sequence |
| RTSWNet | Real Time Solar Wind Network |

| | |
|---|---|
| SAN | SWFO Antenna Network |
| SECCHI | Sun Earth Connection Coronal and Heliospheric Investigation |
| SEP | Solar Energetic Particle |
| SEV | Sun-Earth-Vehicle |
| SEZ | Sun Exclusion Zone |
| SGPS | Solar and Galactic Proton Sensor |
| SHM | Safehold Mode |
| SOE | Sequence of Events |
| SOHO | Solar and Heliospheric Observatory |
| SPEC | Specification |
| SPP | Solar-Pointing Platform |
| SS | Space Segment |
| SSL | Space Science Laboratories |
| SST | Solid-State Telescopes |
| STEREO | Solar Terrestrial Relations Observatory |
| STIS | SupraThermal Ion Sensor |
| SU | Sensor Unit |
| SUVI | Solar Ultraviolet Imager |
| SWEPAM | Solar Wind Electron, Proton, and Alpha Monitor |
| SWFO | Space Weather Follow On |
| SWFO-L1 | Space Weather Follow On – Lagrange 1 |
| SWiPS | Solar Wind Plasma Sensor |
| SWIS | Solar Wind Instrument Suite |
| SWPC | Space Weather Prediction Center |
| SwRI | Southwest Research Institute |
| T&C | Telemetry and Command |
| TBC | To Be Confirmed |

| | |
|---|---|
| TBD | To Be Determined |
| TBR | To Be Revised |
| TBS | To Be Supplied |
| TT&C | Tracking, Telemetry, and Command |
| UCB | University of California, Berkeley |
| V&V | Verification and Validation |
| WCDAS | Wallops Command and Data Acquisition Station |
| XFM | X-Ray Flux Monitor |