NASA/TM – 20250006631

PACE Technical Report Series, Volume 14

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PACE Science Operations Plan - Revision C

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December 2025

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1. Introduction

This plan describes the routine operations performed by the PACE science instruments during the routine operations phase of the PACE mission (Phase E). This phase began after on orbit commissioning, spanning Launch plus 60 days. The operations are described in sufficient detail to enable their implementation by the combined activities of the Science Data Segment (SDS) and the Mission Operations Center (MOC) operational team members. This includes Earth-viewing science data collection and on-orbit calibration. It also includes specific spacecraft activities, such as attitude maneuvers (slews), which are required to support the instrument operations. It does not include commissioning phase operations, onboard science data handling and downlinking, anomaly detection and resolution, or decommissioning operations, which are described in separate documents. The following sections present the Science Operations Concept, the Operations Implementation in the MOC and SDS, and the Instrument Operations Planning performed by the SDS.

2. Science Operations Concept

This section describes the science operations performed during the routine operations phase of the PACE Mission. Section 2.1 summarizes the elements that are common to the operations of all three instruments. Sections 2.2 through 2.4 describe the specific operations for each instrument and the instrument configurations to be used in operations.

2.1. Common Operations Elements

The three PACE instruments, OCI, SPEXone, and HARP2, collect data in the reflective solar spectral range, i.e., from near-ultraviolet (near-UV) to short-wave infrared (SWIR). Therefore, useful science data can only be collected while the instruments are viewing the sunlit Earth. The boundary between the lit and dark Earth is known as the terminator, and the PACE polar orbit causes the subsatellite track to cross the terminator near the North and South poles. For the PACE equator crossing time of 1:00 PM (ascending), the southern terminator crossing is from darkness to daylight (in-crossing), and the northern crossing from daylight to darkness (out-crossing).

The Earth-viewing data collection periods for all three instruments are specified relative to the terminator crossings. This is illustrated in Figure 1, which shows a nominal PACE instrument orbit-in-the-life. Details of the specific activities for each instrument are described in the following sections.

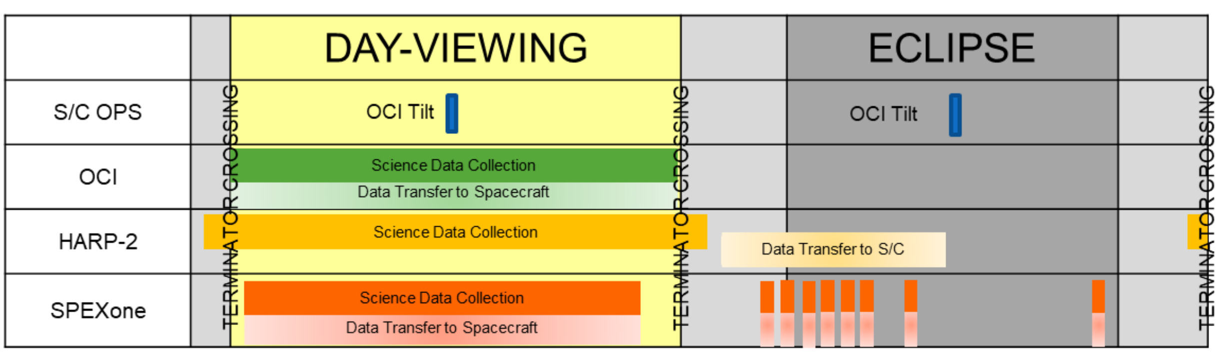

Figure 1. PACE Instrument Nominal Orbit-in-the-Life

2.2. OCI Operations

The OCI operations plan meets or exceeds the following Level-1 Science Requirements [1]:

PACE shall provide:

- *Two-day global coverage of OCI science measurements to solar zenith angle of 75 degrees and sensor view zenith angles not exceeding 60 degrees,*
- *Mitigation for Sun glint such that less than 9% of the 2-day OCI global coverage area is missed due to the glint mitigation process or due to exceeding a calculated glint coefficient of 0.005, based on Cox & Munk (1954) model with wind speed of 7 m/s*
- *Monthly characterizations of OCI instrument detector and optical component temporal stability, include lunar observations through the Earth-viewing port that illuminate all detector elements*
- *Daily characterizations of OCI instrument detector and optical component changes using an independent, on-board capability that illuminates all detector elements*

The data collection activities and instrument configurations are described below.

2.2.1. Data Collection Activities

The OCI data collection activities during routine operations consist of Earth data collection, solar calibration, lunar calibration, and spectral calibration. The solar and lunar calibrations are both described in detail in OCI-SCI-PLAN-0124 and PACE-SYS-TN-0047 [2, 3].

2.2.1.1. Earth Data Collection

The Earth data collection is performed each orbit between the in-crossing and out-crossing terminators, as shown in Figure 1, except during solar calibration orbits as described below. This data collection cycle exceeds the global coverage requirement; data collected beyond 75 degrees solar zenith will be useful for aerosol and cloud products, and future improvements in atmospheric correction algorithms may allow valid ocean color products to be generated above this limit as well.

OCI is tilted forward and aft during Earth data collection to mitigate Sun glint, to meet the Sun glint mitigation requirement. The instrument is mounted on a tilting cradle that is part of the spacecraft and provides a tilt range of +/- 20 degrees. OCI is tilted 20 degrees aft during the southern part of the data collection cycle (from the in-crossing terminator to near the subsolar point) and 20 degrees forward during the northern part. The tilt change activities are shown in Figure 1 as spacecraft operations. The tilt change takes about 40 seconds; the timing of the tilt change is staggered to avoid a persistent coverage gap. The tilt change from forward to aft is performed during the eclipse part of the orbit, and the timing of this activity is not critical.

2.2.1.2. Solar Calibration

Daily solar calibrations are a Level 1 requirement and are necessary to meet the radiometric stability requirements for the OCI data products specified in the requirements. Daily solar calibrations are performed using a bright (highly reflective) solar diffuser. In addition, monthly calibrations are performed using a separate bright diffuser to track the degradation of the daily diffuser, and also using a dim (lower reflectivity) diffuser to track the linearity of the OCI radiometric response. All solar calibrations are performed at the northern terminator crossing.

Because the solar calibration requires spacecraft slews that would interfere with data downlinks, the calibrations are scheduled for orbits that have no northern station contacts.

The OCI solar calibration assembly (SCA) is designed to be operated with the boresight pointed directly at the Sun. To accomplish this, the tilt is changed from forward to aft, and a spacecraft slew is required, before the calibration measurement is performed. In addition, the diffuser must avoid stray light from the bright Earth limb during the measurement. To meet these requirements, the science data collection is ended early in the orbits when the solar calibration is performed; this allows time to complete the tilt change and spacecraft slew and perform the calibration measurements before Earth stray light affects the calibration, shortly after the northern terminator crossing. The detailed timing is described in Section 3.3.2.

The OCI daily solar calibrations will also include measurements using the SWIR detector assembly (SDA) pulse calibration assembly (SPCA), to monitor the SWIR band extended impulse response ("hysteresis") following bright targets. The SPCA boresight is aligned with that of the SCA. The timing of these measurements is also described in Section 3.3.2.

2.2.1.3. Lunar Calibration

The lunar calibrations allow OCI to view the Moon through the instrument Earth view, to meet the lunar calibration requirement. The lunar calibration is performed twice per month, at lunar phase angles of 7 degrees before and after the full Moon. The twice-monthly calibrations reduce the uncertainty in the temporal response trends derived from these measurements. The lunar measurements also include a "stare" measurement of the Moon, as an alternative source for monitoring the SWIR band hysteresis.

The lunar calibration requires large spacecraft slews to re-orient the instrument field-of-view from the Earth to the Moon. The sequence is as follows: a set-up slew, starting immediately after the northern terminator crossing, to orient the OCI scan plane close to the Moon; two "sweep" slews to cause OCI to scan the moon; a "stare" slew and inertial hold, to cause OCI to view a cross-section of the lunar disk; and a slew to return the spacecraft to the nadir orientation. OCI data collection will include Moon observations spanning both sweep maneuvers, stare observations, and deep space observations during the return slew. The calculation of the set-up slew is described in Patt and Eplee (2018) [4].

The lunar calibration slews are designed to maintain instrument keep-out-zone (KOZ) constraints, in particular to keep Sun and Earth shine from the OCI radiator. To prevent Earth shine on the radiator, OCI will view the moon at a specified scan angle, not at the scan center. The baseline observation scan angle is 30 degrees.

2.2.1.4. Spectral Calibration

The spectral calibration is performed during two orbits each month. This operation is performed during the tilt change period in the middle of the Earth data collection, with the instrument in a specific configuration to optimize the spectral measurements.

2.2.2. Instrument Configurations

The OCI configuration is tailored for each data collection operation to optimize the data quality. The specific data configuration parameters are defined in the scan tables stored on the instrument, as follows:

- The angular ranges of the rotating telescope assembly (RTA) in which data are collected. OCI supports up to 10 data collection "zones" over the 360-degree rotation of the RTA, which can each be configured independently. The zones include both data-collecting and no-data zones to cover the entire rotation.
- The data type (e.g., Earth, lunar calibration) per zone.
- The spatial aggregation factor (number of CCD pixels per science pixel in the spatial dimension) per zone for the hyperspectral data. A factor of 8 corresponds to 1 km pixels at nadir.
- The spectral aggregation factors for the hyperspectral data. Factors of 1, 2, 4 and 8 correspond to spectral band spacing of 0.625, 1.25, 2.5 and 5 nm, respectively. For a given configuration, the spectral aggregation is the same for all collection zones, but can be set independently for each of the 32 data "taps" of the hyper-spectral CCD arrays.
- Tap enable flags. The two taps at ends of the spectral range will normally be disabled.
- For the solar calibration operations, the solar calibrator position: Daily Diffuser, Monthly Bright Diffuser, and Dim Diffuser. The default position is Door Closed.

Each OCI configuration includes two data collection zones: the science data zone, which is specified for the particular operation; and the dark collect zone, which views the inside of the instrument to provide a zero-radiance level for every configuration. There are separate configurations for the Earth data, daily and monthly solar calibrations, lunar calibration modes, and spectral calibration, along with special diagnostic modes.

The RTA and aggregation configuration determines the instrument data rate, which must be maintained within specified limits. The data rate during data collection periods is limited to 40 Mbits/sec, and the orbit average data rate, which depends on both the configuration and the data collection periods, is limited to 20 Mbit/sec. The baseline parameters for the Earth data, solar and lunar calibration modes are shown in Table 1.

Details of the instrument configuration parameters are provided in OCI-ELEC-SPEC-0009 [5]. Specific values for each mode are documented in OCI-SYS-DESC-0114 [6]. The process for updating the scan tables is documented in OCI-SYS-HDBK-0011 [7].

Table 1. OCI Configurations for Operational Modes

Mode	RTA Angle Range (relative to nadir)	Spatial Aggregation	Spectral Aggregation
Earth data	-56.5 to +56.5	8	4*
Solar cal	-100 to -84	8	1
SPCA	85 to 151	8	8
Linearity	-95 to -90	1	1
Lunar sweep	27 to 35	1	4*
Lunar stare	17 to 83.5	8	8
Deep space	-56.6 to +56.5	8	4
Spectral 1	-16 to 16	8	1
Spectral 2	20 to 52	8	1

*Selected taps use spectral aggregation 2

2.3. HARP2 Operations

2.3.1. Data Collection Activities

The HARP2 data collection activities during routine operations consist of Earth data collection, lunar calibration, solar calibration, and daytime calibration. In addition, unlike OCI and SPEXone, the HARP2 data are stored on the instrument during collection and transferred during the back orbit, as shown in Figure 1. This is because the combined data generation rates of OCI, HARP2 and SPEXone exceed the SpaceWire capacity of the spacecraft. Thus, the HARP2 data transfer is scheduled as a separate activity from data collection.

2.3.1.1. Earth Data Collection

The HARP2 FOV extends 56.5 degrees forward and aft from nadir. The Earth data collection extends 120 seconds beyond the terminator crossings, to enable the full for-and-aft viewing range of the instrument to view the same locations. This is shown in Figure 1. In addition, before and after each Earth data collection period, a brief interval of dark data is collected with the shutter closed to provide a zero-radiance measurement.

2.3.1.2. Lunar Calibration

HARP2 data collection is scheduled during parts of the OCI lunar calibration slews when the Moon is within the FOV. Although only a small part of the HARP2 FOV views the Moon during these slews, this provides visibility on changes in the overall instrument radiometric response in combination with the solar calibration.

2.3.1.3. Solar Calibration

The HARP2 solar calibration is performed by covering the instrument aperture with a nearly-opaque shutter and illuminating the shutter by allowing the Sun to shine through a corner of the FOV. This allows flat-field measurements over the entire FOV. The desired direction of the Sun vector is 49 degrees from the instrument +Z (nadir) axis, and rotated approximately 20 degrees from +X (forward) toward –Y. To achieve this, a spacecraft slew is required.

The HARP2 solar calibration will be performed weekly, just before the start of the eclipse period in the selected orbit. Details are provided in PACE-SYS-TN-0281 [8].

2.3.1.4. Daytime Calibration

There are two types of HARP2 daytime calibration: alignment and flatfield. Each type of calibration is performed approximately monthly, during high-elevation overpasses of targets specified by UMBC. During the scheduled calibration activities, normal Earth-viewing data collection is briefly interrupted by the calibration data collection and then resumed for the remainder of the daylit orbit.

2.3.1.5. Data Transfer

The HARP2 data transfer must be performed at a time when OCI is not collecting data to stay within the SpaceWire capacity. During nominal orbits this can occur at any time between the terminator out-crossing and in-crossing. During lunar calibration orbits, the transfer will be scheduled to start after all data collection has been completed. The HARP2 data transfer rate is approximately 2x the Earth-viewing data collection rate.

2.3.2. Instrument Configurations

The HARP2 configuration is specified by the Acquisition Scheme Type (AST) with values Full Calibration (AST0), Half Calibration (AST1), SCI Calibration (AST2) and SCI (AST4). AST4 is used for Earth data collection. The configurations for each AST specify the binning scheme and image size as described in the HARP2 Telemetry Manual [9].

2.4. SPEXone Operations

2.4.1. Data Collection Activities

The SPEXone data collection activities during routine operations consist of Earth data collection, eclipse calibration, and deep space data collection.

2.4.1.1. Earth Data Collection

The current baseline Earth data collection strategy is as follows. Data collection is started at the terminator in-crossing. The instrument collects partial data for the first 7.3 degrees (about 2 minutes), then full data for most of the collection period. At 7.3 degrees before the terminator out-crossing, collection is switched back to partial, and collection ends at the out-crossing.

2.4.1.2. Eclipse Calibrations

SPEXone performs calibration activities during each orbit eclipse period. There are two calibration sequences and 10 LED light level combinations, for a total of 20 unique calibrations. These combinations will be cycled through five times each week (100 orbits total, with two or three spare orbits each week). These calibrations will not be performed during the OCI lunar calibration orbits.

2.4.1.3. Deep Space Calibration

SPEXone will collect deep space data during the twice-monthly OCI lunar calibration slews. The data collection will start approximately one minute before the start of the OCI lunar sweep slews and continue for approximately seven minutes.

2.4.2. Instrument Configurations

The SPEXone configurations for each operation are specified using the Measurement Parameter Set (MPS) tables. The internal calibrations also require setting the LED light levels. The MPSs are defined in SPX1-TN-0017 [10].

3. Operations Implementation

3.1. Mission Capabilities Overview

The following sections summarize the flight segment and ground segment capabilities that are relevant for science operations.

3.1.1. Flight Segment

The spacecraft command and data handling (C&DH) subsystems manages all commands for the observatory. The commands uplinked by the ground segment can either be executed in real time or stored for execution at a later time. The latter are uplinked as command loads that are stored in onboard memory. In either case, the C&DH routes the command to an instrument or a spacecraft subsystem according to the destination in the command header. All routine science operations will be performed using stored commands.

Commands can be stored as either an absolute time sequence (ATS) or relative time sequence (RTS). ATS commands are executed once according to the time tag included with the command. The stored ATS commands are updated with each command load uplinked to the spacecraft. Command loads are nominally uplinked weekly, to cover an operational week. The C&DH has two ATS buffers to ensure continuous operations; each buffer can store approximately 2000 commands.

RTSs are sequences of commands separated by wait times. They are used for repetitive activities for which the sequence and timing of the commands does not change. An RTS is executed by an ATS command, a command in another RTS, or a ground command directive. RTSs are loaded once in the C&DH, and an RTS can be executed any number of times after it is loaded. Multiple RTSs can be active concurrently, as long as the total command rate does not exceed the C&DH capacity.

The OCI instrument also has an RTS processor and storage that are identical to that of the C&DH. The current descriptions of spacecraft and OCI RTSs for routine operations is in PACE-OPS-LIST-0216 [11]. Detailed descriptions of the OCI RTS are contained in OCI-SYS-SPEC-0144 [12].

3.1.2. Ground Segment

The Ground Segment capabilities that are relevant for science operations are supported by the MOC and the SDS and are summarized in the following sections. Detailed descriptions are provided in PACE-GS-REQ-0066 [13] and SDS software design presentations.

3.1.2.1. MOC Capabilities

The relevant MOC capabilities are provided by the following subsystems:

- The Telemetry and Command subsystem performs the uplink of commands and stored command loads.
- The Timeline Management Tool (TMT) subsystem is used for Mission Planning and Scheduling of station contact scheduling, generating all RTA/ATS loads, and constraint checking.
- The Product Distribution and Remote Access subsystem performs the exchange of products with external entities.
- The Flight Dynamics Subsystem generates the orbit prediction and planning products that are used by the SDS to plan science operations.
- The Attitude Ground Subsystem supports calibration and other slew planning and execution, including mission constraint checking (e.g., keep-out zones) for all slews.

These subsystems and their interfaces are illustrated in the MOC Conceptual Architecture from PACE-GS-REQ-0066 (Figure 2).

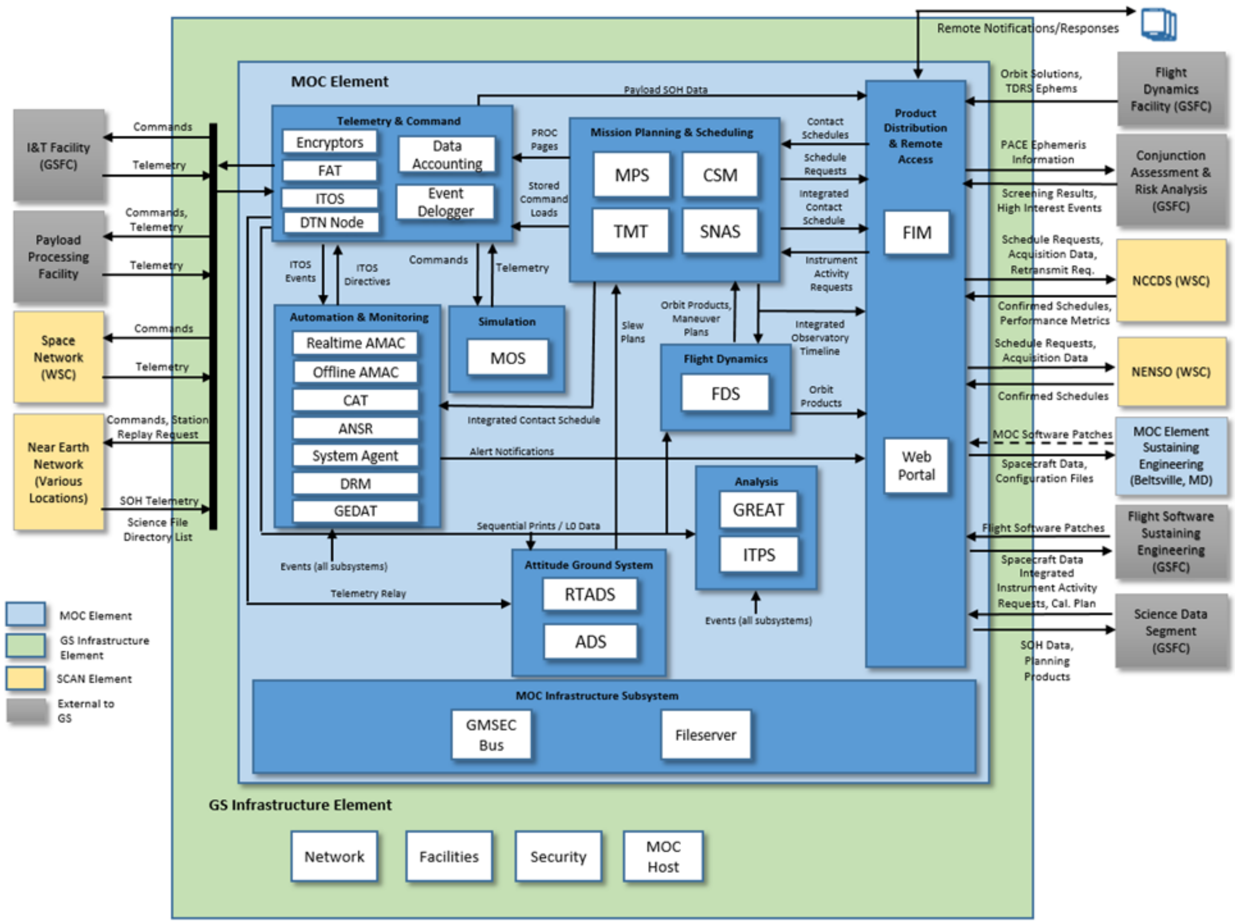

Figure 2. MOC Conceptual Architecture showing subsystems and interfaces.

3.1.2.2. *SDS Capabilities*

The SDS Science Operations Element (SOE) provides all the science operations capabilities within the SDS. The capabilities provided by the SOE are:

- The Calibration Planning Tool uses the predicted orbit ephemeris, terminator crossing predictions, and integrated contact schedule (ICS) to plan the instrument calibration schedules and slews.
- The Command Planning Tool uses the planning products to plan the science operations activities, generate the Integrated Instrument Activity Request (IIAR), and verify the Integrated Observatory Timeline generated by the MOC, as specified in PACE-OPS-ICD-0009 [14].

3.2. Planning and Execution

The following sections list the roles and responsibilities of the teams and individuals involved in planning and execution of science operations, summarize the planning process, and describe the development and maintenance of the operations command sequences.

3.2.1. Roles and Responsibilities

The following individuals and teams are responsible for various elements of science operations. For some of these (e.g., MOC personnel), detailed descriptions are provided in reference documents and are excerpted here.

The **Project Scientist** has overall responsibility for the development and maintenance of the Science Operations Plan.

The **Science Operations Board (SOB)** has responsibility for approving any changes to the plan during Phase E of the mission.

The GSFC **Earth Science Mission Operations (ESMO)** project has overall responsibility for the mission management, mission operations and intra-instrument operations during Phase E; these responsibilities are carried out by the Mission Director.

The **SDS Manager** is responsible for the SDS support for science operations.

The **Instrument Scientists** for each instrument are responsible for any updates to the operations plans for their instrument, including any changes to operational command sequences.

The **MOC Flight Operations Team (FOT)** are the core operators of the MOC systems. Their duties include development and maintenance of operations products, sending commands and loads to the Observatory, and mission planning activities.

The **MOC Flight Dynamics Analysts** generate and deliver orbit planning products and conduct instrument calibration slew planning.

The **SDS Operations Lead** is responsible for the technical direction of the SDS science operations activities, including calibration slew planning and any updates to science data collection.

The **SDS Operations Analysts** perform the weekly planning, scheduling and verification of the science operations activities.

3.2.2. Planning Process Summary

The detailed Mission Planning Cycle is described in the MOC Concept of Operations. The relevant steps for routine science operations planning are summarized here. The interfaces and exchange of products among the MOC subsystems and with SDS is illustrated in Figure 3, from PACE-GS-REQ-0066.

- The MOC generates the mission planning products (predicted ephemeris, terminator crossings and ICS) and delivers them to the SDS.
- The SDS generates the instrument calibration plan for three weeks in advance and the IIAR for the following two weeks and delivers them to the MOC.
- The MOC validates and constraint-checks the calibration slew plan and reports any violations to the SDS.
- The MOC uses the IIAR and calibration plan, along with the ICS and other spacecraft activity plans, to generate the ATS command load and the Integrated Operations Timeline (IOTL) for the following week and delivers the IOTL to the SDS.
- The SDS verifies the IOTL and reports any issues to the MOC.
- The MOC uplinks the command load to the spacecraft.

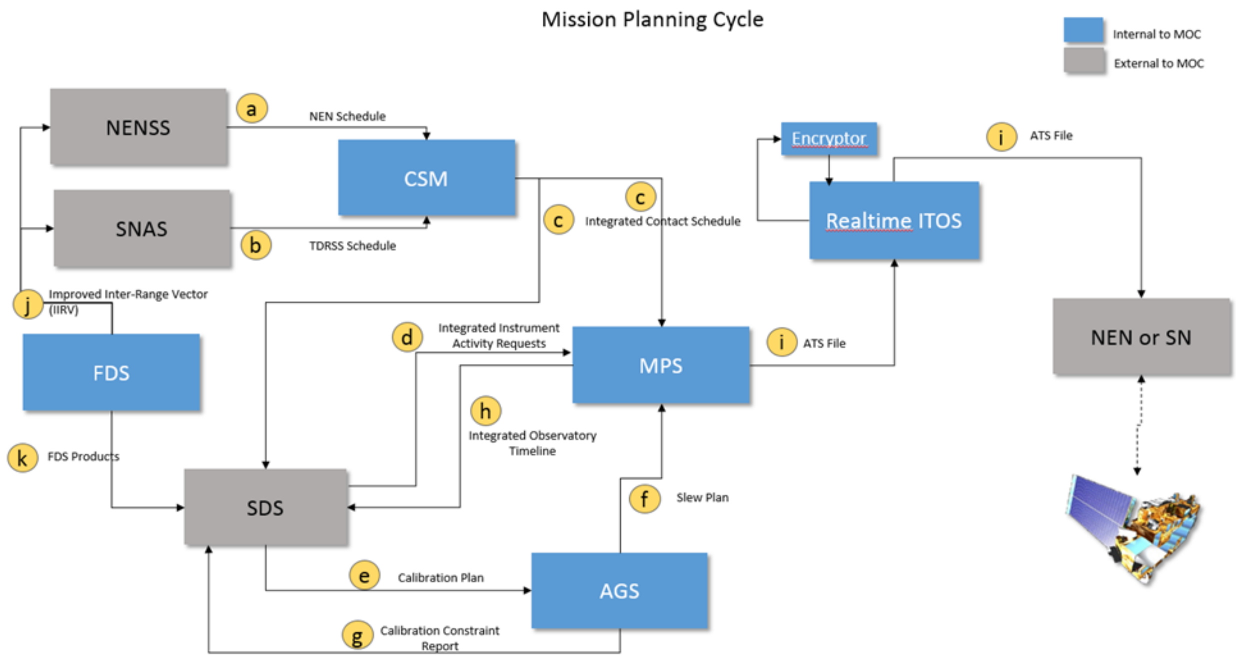

Figure 3. Mission Planning Cycle Interfaces and Product Exchange

3.2.3. Command Sequence Development and Maintenance

The set of RTSs and ATS commands to perform all routine science collection activities and calibration slews has been developed and documented in PACE-OPS-LIST-0216. The process for maintaining the flight command sequences is in PACE-GS-PLAN-0494 [15].

3.3. Science Operations Baseline

The following sections illustrate the routine science operations for a nominal orbit, an OCI solar calibration orbit, a lunar calibration orbit, and a HARP2 solar calibration orbit. The data collection and tilt change operations are initiated by an RTS invoked by an ATS command triggered by an IIAR activity. The spacecraft slews are performed entirely by ATS commands generated from the Calibration Plan.

3.3.1. Nominal Orbit

The science operations activities for a nominal orbit are illustrated in Figure 4. (Note that all figures show the +X axis of the spacecraft to indicate its orientation.)

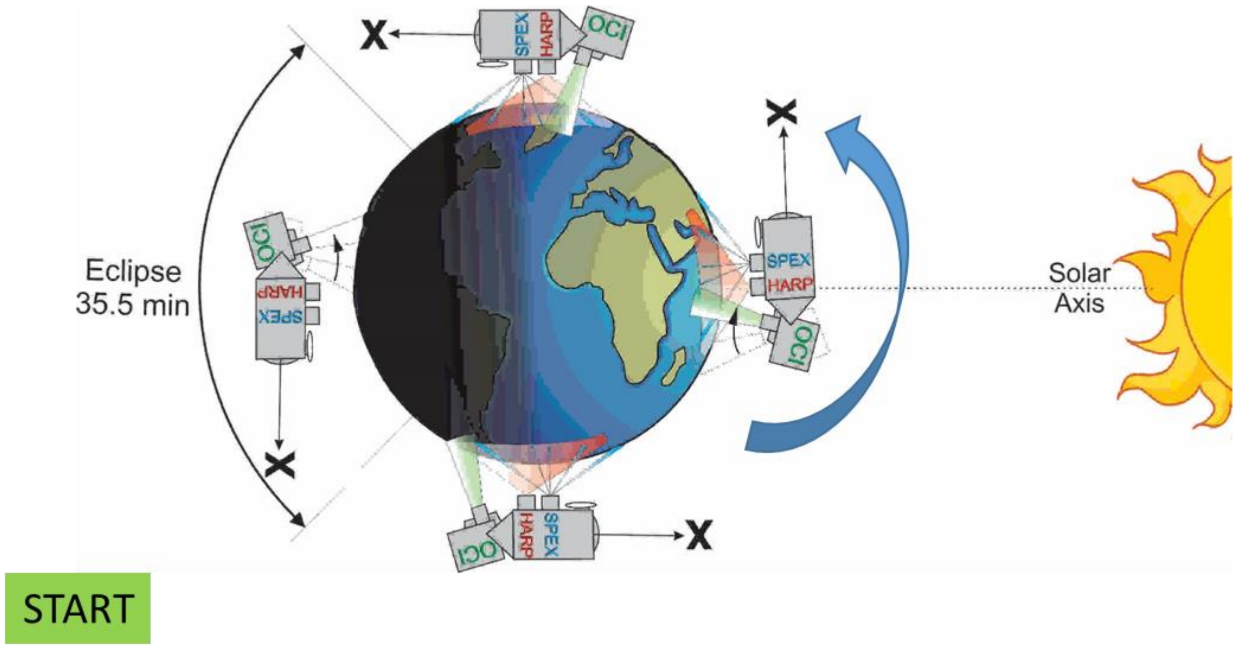

Figure 4. Nominal Science Operations Orbit

The sequence of operations starts just before the terminator in-crossing as follows.

1. Start science data collection before terminator in-crossing
    a. Start HARP2 data collection 200 seconds before in-crossing
    b. Start OCI data collection at in-crossing
    c. Start SPEXone data collection 1 second after OCI
2. Change OCI tilt from aft to forward near subsolar point
3. Stop science data collection before terminator out-crossing
    a. Initiate end of SPEXone data collection 120 seconds before out-crossing
    b. Stop OCI data collection at out-crossing
    c. Stop HARP2 data collection 120 seconds after out-crossing
4. Perform SPEXone internal calibrations in eclipse, starting 454 seconds after terminator out-crossing
5. Perform HARP2 data transfer to spacecraft in eclipse, starting 480 seconds after terminator out-crossing.
6. Change OCI tilt from forward to aft, 10 minutes before eclipse exit.

3.3.2. OCI Solar Calibration

The science operations activities for an OCI solar calibration orbit are illustrated in Figure 5. As stated in Section 2.2.1, the solar calibration is performed daily using the SCA daily bright diffuser, and once per month each for the monthly bright diffuser and the dim diffuser. As also stated, the daily bright diffuser calibration will be followed by SPCA data collection. All solar calibrations are scheduled for orbits that have no northern ground station contacts.

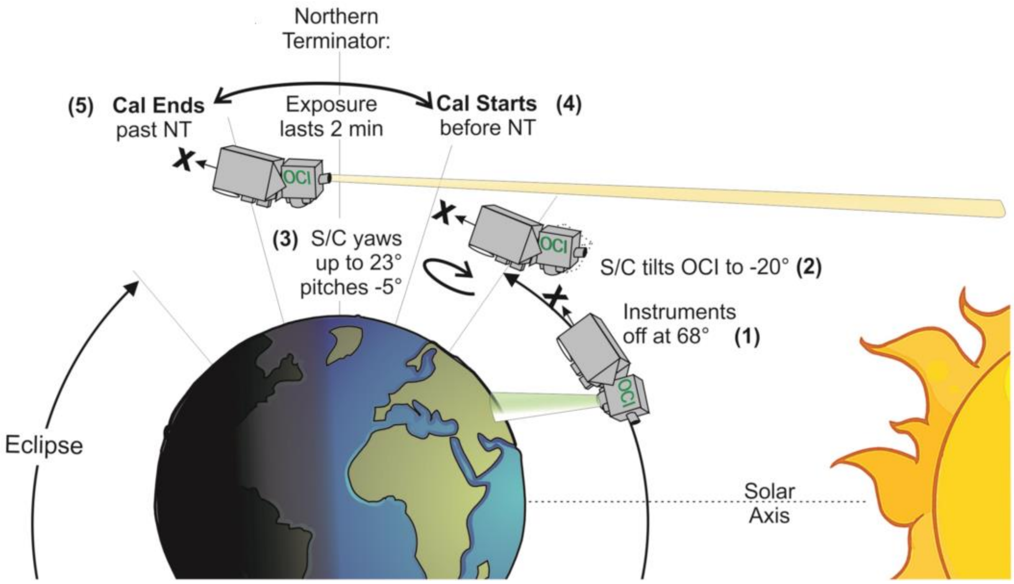

Figure 5. OCI Solar Calibration Orbit

The sequence of operations starts just before the terminator in-crossing as follows.

1. Start science data collection 200 seconds before terminator in-crossing as in 3.3.1.
2. Change OCI tilt from aft to forward near subsolar point.
3. Stop science data collection at 68 degrees solar zenith angle
4. Change OCI tilt from forward to aft.
5. Begin solar calibration slew.
6. Rotate OCI SCA into position and start OCI data collection 180 seconds before terminator out-crossing (includes SCA data collection, SCA return to closed position and SPCA data collection).
7. Perform slew to nadir orientation.
8. Perform SPEXone calibrations in eclipse as in 3.3.1.
9. Perform HARP2 data transfer to spacecraft in eclipse as in 3.3.1.

3.3.3. Lunar Calibration

The science operations activities for a lunar calibration orbit are illustrated in Figure 6. As stated in Section 2.2.1, the lunar calibration is performed twice monthly, during the orbits when the lunar phase is closest to 7 degrees. To meet orbital data volume constraints, HARP2 normal science data will not be collected during the lunar calibration orbit.

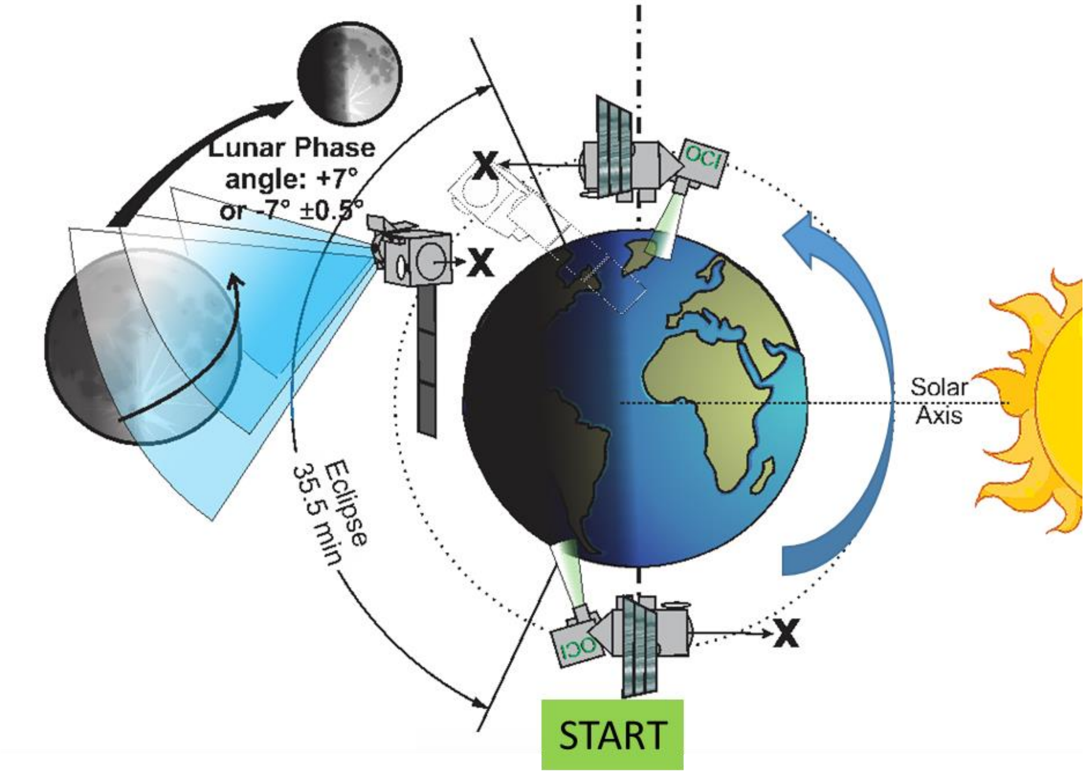

Figure 6. Lunar Calibration Orbit

The sequence of operations starts at the terminator in-crossing as follows.

1. Start OCI and SPEXone science data collection at terminator in-crossing.
2. Change OCI tilt from aft to forward near subsolar point.
3. Stop SPEXone science data collection 120 seconds before terminator out-crossing.
4. Stop OCI science data collection at terminator out-crossing.
5. Perform lunar calibration set-up slew starting at terminator out-crossing, completed within 420 seconds.
6. Perform lunar calibration data collection.
    a. Start HARP2 lunar data collection
    b. Start SPEXone deep space data collection
    c. Start OCI lunar sweep and stare data collection
    d. Perform lunar sweep and stare maneuvers
7. Perform return-to-nadir maneuver.
8. Perform OCI deep space data collection.
7. Perform HARP2 data transfer to spacecraft.
8. Change OCI tilt from forward to aft.

3.3.4. HARP2 Solar Calibration

The science operations activities for a HARP2 solar calibration orbit are illustrated in Figure 7. As stated in Section 2.3.1, the solar calibration is performed weekly. All solar calibrations are scheduled for orbits that have no northern ground station contacts.

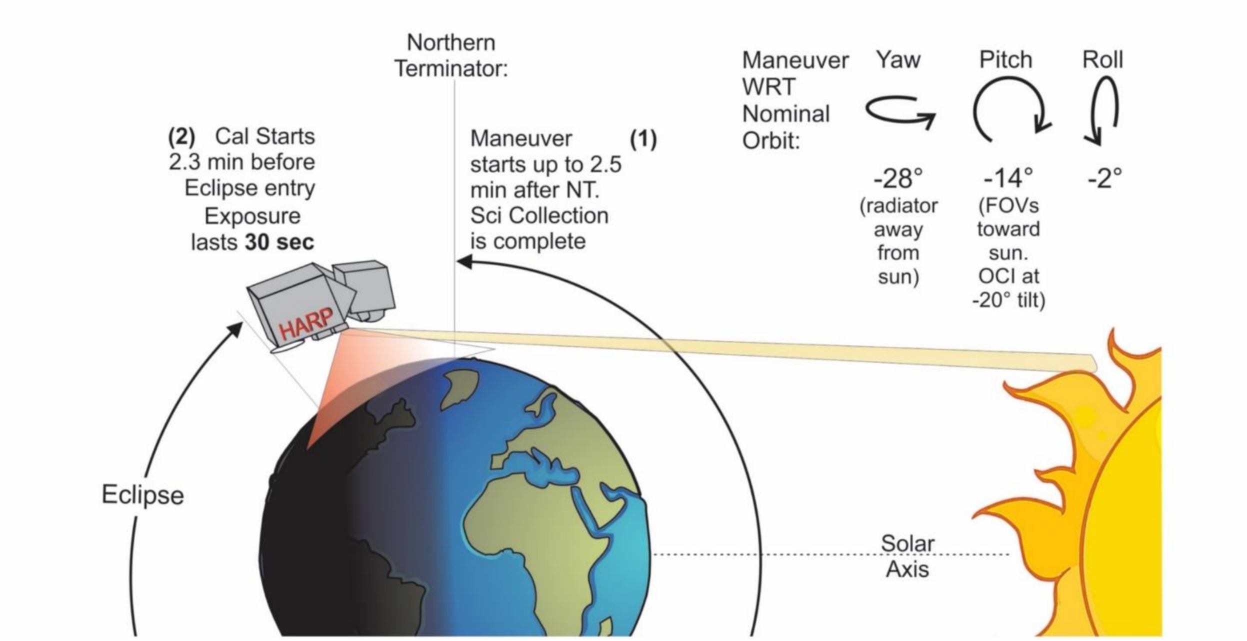

Figure 7. HARP2 Solar Calibration Orbit

The sequence of operations starts just before the terminator in-crossing as follows.

1. Start science data collection before terminator in-crossing as in 3.3.1.
2. Change OCI tilt from aft to forward near subsolar point.
3. Stop science data collection before terminator out-crossing as in 3.3.1.
4. Perform solar calibration slew starting 120 seconds after out-crossing.
5. Perform HARP2 solar calibration configuration starting 133 seconds after out-crossing.
6. Perform slew to nadir orientation 456 seconds after out-crossing.
7. Perform SPEXone calibrations in eclipse as in 3.3.1.
8. Perform HARP2 data transfer to spacecraft in eclipse as in 3.3.1.
9. Change OCI tilt from forward to aft in eclipse.

4. Instrument Operations Planning

Each week, the SDS Science Operations Analysts use the Command Planning Tool (CPT) to generate and submit a pair of instrument operations planning products to the Flight Operations Team to create an ATS for the spacecraft. These planning products comprise of an IIAR and a Calibration Plan and are generated using the input files provided by the MOC as detailed in Figure 3. The planning products span two operations weeks, as defined below. Sample IIAR and calibration plan entries are given in Appendices A and B.

4.1. Command Planning

4.1.1. Operations Week

The planning process is designed around the Operations Week, Monday 00:00 to Sunday 23:59:59. The planning period is the range of days covered by the planning products delivered to the MOC. This usually covers two Operations Weeks, or 14 days Monday through Sunday. The CPT defaults to create planning products using this default planning period unless there is a special request or spacecraft event.

4.1.2. Inputs

The inputs to the planning process from the MOC are:

- **Predicted ephemeris:** 30 days, delivered daily.
    - The predicted ephemeris files are used by the CPT to generate calibration activity candidates.
- **Orbit Terminator Crossing Predictions:** 30 days, delivered daily.
    - The orbit terminator crossing predictions are used to define orbit numbers.
- **Integrated Contact Schedule (ICS):** Nominally 14 days out, delivered Tuesday.
    - The CPT uses the latest ICS to schedule spacecraft activities around ground station contacts.

4.1.3. Outputs

The outputs from the planning process are the Calibration Plan and the IIAR. The Calibration Plan spans two operations weeks and is delivered each Tuesday (nominally) for the planning period starting the following Monday at 00:00. The IIAR also spans two operations weeks and is delivered each Tuesday for the same operations planning period. While both planning outputs are delivered to the MOC, the Flight Dynamics System also uses the Calibration Plan to schedule spacecraft slews. The syntax and format for the IIAR is given in PACE-OPS-ICD-0009. The activity requests use the Instrument Activities shown in bold below for each operation, as described in the ICD.

4.1.4. Generating Activities

The CPT ingests the MOC's input files and stores them into a database. The tool then calculates optimal times for routine and special activities for the requested planning period, including candidates for calibration activities. The results stored in a database.

The Integrated Contact Schedule is used to avoid any scheduling conflicts with ground station contacts. It is also an important structure to the timing and order of calibration activities. There are calibration sequences that require spacecraft slews, and a buffer orbit is planned between these types of activities as a routine operating procedure (Section IV.B).

Along with other in-house written tools, the CPT uses JPL ephemeris files processed by the Skyfield Python library to calculate and define spacecraft geometry. The PACE predicted ephemeris file is used to calculate eclipse times as well as nadir and subsolar latitude and longitude coordinates. This is also used to calculate the lunar phase angles needed to perform the monthly lunar calibrations. The CPT uses the monthly lunar calibrations, timed closest to the lunar phase of 7 degrees, as the basis of other special activity scheduling. As a result, lunar calibrations, including deep-space calibrations, are the first activities to be scheduled.

4.1.4.1. Off-Nominal or One-Off Activity Scheduling

In the event of a special activity request, the CPT has logic that accounts for a variety of scenarios outside of the automated routine scheduling workflow. Because the Operations Week default is not a static variable, the CPT can easily accommodate cases where an abbreviated planning period outside of the default 14-day Mon-Sun schedule is necessary. The CPT can also accommodate extra calibration activities in a planning period or schedule only routine operations without any calibrations at all.

4.1.5. Generating the Calibration Plan and IIAR

The Calibration Plan and the IIAR are generated for specified planning periods, 14 days by default, and output and formatted as JSON files. When generating activities, the CPT does most of the computing, calculations, and scheduling, and only needs to use a series of database queries to output the planning files themselves. When generating the Calibration Plan, the CPT logic adds a 10 second margin to spacecraft slew times so that there are no overlaps between slews and Ka-band ground station contacts. When lunar calibration times are being computed, the quaternions for the initial maneuver required to perform the calibration are also added to the Calibration Plan. The Flight Dynamics System also use the 14-day Calibration Plan with times and quaternions to schedule spacecraft slews ahead of one Operations Week.

4.1.6. Integrated Operational Timeline (IOTL)

The Flight Operations Team take the Calibration Plan and IIAR inputs as delivered by the SDS and build the spacecraft's ATS for the nominal planning period of 14 days. One of the MOC's outputs during this process is the IOTL, which gets delivered to the SDS for review. The IOTL must match the IIAR input times and order of events. The CPT ingests the IOTL and confirms activity scheduling and planning status.

4.2. Activity Plan Timing Configuration

4.2.1. Routine Operations

The following operations are performed in each orbit.

4.2.1.1. *Start science data collection* (**normScienceOrbitStart**).

This starts science data collection for all three instruments. It is triggered by the LightEntry in the Terminator Crossing Prediction.

4.2.1.2. *OCI tilt change aft-forward* (**normSubSolarTilt**).

This is performed in the middle of the orbit day period (the subsolar point) and is triggered by the LightEntry in the Terminator Crossing Prediction.

4.2.1.3. *Stop science data collection* (**normScienceOrbitStop**).

This stops science data collection for all three instruments. It is triggered by the DarkEntry in the Terminator Crossing Prediction.

4.2.1.4. *HARP2 data transfer* (**harpEclipseDataTransfer**).

This is performed during eclipse and triggered by the DarkEntry. It must complete before the next **normScienceOrbitStart** operation.

4.2.1.5. SPEXone dark calibration operations.

This performs the SPEXone dark calibrations during eclipse. It is triggered by the DarkEntry with a configurable time offset. There are 20 unique calibration sequences that are run (**spexCalibrationSequence10** through **spexCalibrationSequence29**), one per orbit. There are 102.5 orbits per week; during the operations week the series run five times; unused orbits correspond to the HARP2 solar and OCI lunar calibrations, as the dark calibrations are not performed in these orbits.

4.2.1.6. *OCI tilt change forward-aft* (**ociEclipseTilt**), triggered by the DarkEntry.

Table 2. Routine orbital operation activities.

IIAR Activity	Instrument	Time Reference
normScienceOrbitStart	ALL	ST-200
normSubSolarTilt	OCI	SSP +/- 2 deg
normScienceOrbitStop	ALL	NT-200
harpEclipseDataTransfer	HARP2	NT+480
spexCalibrationSequence10	SPEXone	NT+454
ociEclipseTilt	OCI	SDS Provided Time

4.2.2. Calibration Operations

Instrument calibrations are performed at various frequencies: daily, weekly, monthly. The calibration operations require modifications to the routine orbital operations. Calibration operations that require spacecraft attitude slews are planned using the CPT and delivered to the MOC via the Calibration Plan, which is used along with the IIAR as an input to the MOC's spacecraft command planning.

4.2.2.1. OCI daily solar calibration.

This operation is performed around the northern terminator crossing. It is planned on an orbit that does not have an OCI lunar calibration, an orbit that is separated by other solar calibrations by at least two orbits, and one that does not have a northern station contact. It consists of the following sequence of activities:

- Stop science data collection (**ociSolarCalOrbitStop**) at 68 degrees solar zenith (triggered by the DarkEntry).

- OCI Tilt Change forward-aft (**ociSolarCalOrbitTilt**) immediately after science data collection is stopped.
- Spacecraft slew specified in the Calibration Plan.
- OCI solar calibrator configuration and data collection (**OCISolarCalDailyBrightTarget**) triggered by the DarkEntry.

The solar calibration requires the following changes to the routine orbital operations:

- Stop science data collection at DarkEntry will not be performed.
- OCI tilt change forward-aft in eclipse will not be performed.

*4.2.2.2. OCI monthly diffuser calibration (**OCISolarCalMonthlyBrightTarget**).*

This operation is identical to the daily solar calibration except that the spare bright diffuser is used. It is performed on a different day than the OCI lunar calibration and HARP2 solar calibration on an orbit without a northern station contact. It must be separated from the daily solar calibration by at least two orbits.

*4.2.2.3. OCI monthly linearity calibration (**ociSolarCalDimTargetNewPTDI**).*

This operation is identical to the daily solar calibration except that the dim diffuser is used and OCI is configured for the linearity calibration. It is performed in an orbit without a northern station contact. It is nominally performed on the same day as the OCI monthly diffuser calibration and the daily OCI solar calibrations, only separated by at least two orbits. It is performed on a different day than the OCI lunar calibration and the HARP2 solar calibration.

Table 3. OCI solar calibration activities.

IIAR Activity	Instrument	Time Reference
ociSolarCalOrbitStop	ALL	SZA=68 deg
ociSolarCalOrbitTilt	OCI	SZA=68 deg
ociSolarCalDailyBrightTarget	OCI	TAQ – 120
ociSolarCalMonthlyBrightTarget	OCI	TAQ – 120
ociSolarCalDimTargetNewPTDI	OCI	TAQ – 120

4.2.2.4. Lunar and deep space calibration.

This operation is performed at least twice each month, of which two in orbits when the lunar phase is closest to 7 degrees. These orbits will be approximately one day apart. In addition to the changes required for collection of lunar and deep space calibration data, HARP2 does not collect science data during the daytime part of this orbit in order to stay within the orbital data volume allocation. The lunar calibration consists of the following sequence of activities:

- Start science data collection without HARP2 (**ociLunarCalOrbitStart**) triggered by the LightEntry.
- Stop science data collection without HARP2 (**ociLunarCalOrbitStop**) triggered by the DarkEntry.

- Spacecraft slew sequence specified in the Calibration Plan.
- HARP2 lunar data collection (**harpLunarCalibration**) triggered by the target time for the set-up slew in the calibration plan.
- OCI lunar sweep maneuver data collection (**ociLunarCalibrationScan**) triggered by the target time for the set-up slew in the calibration plan.
- OCI lunar stare data collection (**ociLunarCalibrationScan**) triggered by the target time for the stare slew in the calibration plan.
- SPEXone deep space calibration (**spexDeepSpaceCalibration**) triggered by the target time for the set-up slew in the calibration plan.
- OCI deep space calibration (**ociDeepSpaceCalibration**) triggered by the end activity time in the calibration plan.
- HARP2 lunar calibration data transfer (**harpLCEclipseDataTransfer**) triggered by the end activity time, after the OCI deep space calibration.

The lunar calibration requires the following changes to constraints on orbital operations:

- HARP2 normal orbit data collection will not be performed.
- SPEXone calibration operations in eclipse will not be performed.
- OCI tilt change forward-aft needs to occur after the OCI calibration data collection is complete.
- HARP2 data transfer needs to start after all OCI data collection activities are complete.

Table 4. Lunar and deep space calibration activities.

IIAR Activity	Instrument	Time Reference
ociLunarCalOrbitStart	ALL	ST-200
ociLunarCalOrbitStop	OCI and SPEXone	NT-200
harpLunarCalibration	HARP2	NT
ociLunarCalibrationScan	OCI	sLSFT
spexDeepSpaceCalibration1	SPEXone	NT+360
ociDeepSpaceCalibrationStart	OCI	eAT+90
harpLCEclipseDataTransfer	HARP2	eAT+240

4.2.2.5. HARP2 weekly solar calibration.

This operation is performed at least 7 days apart around the northern terminator crossing. It is performed on a different day than any OCI lunar calibrations and on an orbit with no northern station contact. It must be separated from the OCI daily solar calibration by at least two orbits. It consists of the following sequence of activities:

- Stop science data collection (**harp2SolarCalOrbitStop**) at DarkEntry.
- Spacecraft slew sequence specified in the Calibration Plan.
- HARP2 solar data collection (**harpSolarCalibration**) triggered by DarkEntry.

The HARP2 solar calibration requires the following changes to orbital operations:

- Nominal stop science data collection at DarkEntry will not be performed.
- SPEXone dark calibration will not be performed.

*4.2.2.6. OCI monthly Earth spectral calibrations (**ociSubSolarTiltES1** and **ociSubSolarTiltES2**).*

These operations are performed on two separate orbits per month during routine orbital data collection between lunar phases -51 and -7 degrees. They are scheduled during orbits without other calibration operations. This operation performs a reconfiguration of OCI for data collection but does not require any other changes to routine orbital operations.

*4.2.2.7. HARP2 alignment calibration (**harpAlignmentCalibration**).*

This operation is performed on one orbit per month during routine orbital data collection. This calibration does not involve spacecraft slews and does not have any constraints on station contact timing. There is a single alignment target, and multiple flatfield targets depending on season. The highest spacecraft altitude available is chosen by the Command Planning Tool for each target within a month and then scheduled during an orbit with no other calibration operations. It performs a reconfiguration of HARP2 for data collection but does not require any other changes to routine orbital operations. HARP2 instrument scientists chose alignment and flatfield targets when the instrument is viewing a certain Earth region with stable climate conditions seen from orbit.

*4.2.2.8. HARP2 flat field calibration (**harpFlatFieldCalibration**).*

This operation is performed on one orbit per month during routine orbital data collection. This calibration does not involve spacecraft slews and does not have any constraints on station contact timing. There is a single alignment target, and multiple flatfield targets depending on season. The highest spacecraft altitude available is chosen by the Command Planning Tool for each target within a month and then scheduled during an orbit with no other calibration operations. It performs a reconfiguration of HARP2 for data collection but does not require any other changes to routine orbital operations. HARP2 instrument scientists chose alignment and flatfield targets when the instrument is viewing a certain Earth region with stable climate conditions seen from orbit.

Table 5. Other weekly and monthly calibration activities.

IIAR Activity	Instrument	Time Reference
harp2SolarCalOrbitStop	ALL	NT-200
harpSolarCalibration	HARP2	NT+360
ociSubSolarTiltES1	OCI	SSP +/- 2 deg
ociSubSolarTiltES2	OCI	SSP +/- 2 deg
harpAlignmentCalibration	HARP2	SDS Provided Time
harpFlatFieldCalibration	HARP2	SDS Provided Time

5. References

1. Program Level Requirements for the PACE Project (PLRA), PACE-SYS-REQ-0007
2. OCI On-orbit Calibration Plan, OCI-SCI-PLAN-0124
3. PACE Lunar/Solar Calibrations, PACE-SYS-TN-0047
4. Patt, F. S. and R. E. Eplee, "Strategy and Requirements for the PACE OCI Lunar Calibration," NASA/TM 2018-219027, Volume 7
5. DAU Digital Card (DDC) FPGA Specification, OCI-ELEC-SPEC-0009
6. OCI Flight Data Collection Tables, OCI-SYS-DESC-0114
7. OCI Operations Handbook, OCI-SYS-HDBK-0011
8. PACE Solar Calibration for HARP2, PACE-SYS-TN-0281
9. HARP2 Telemetry Manual, Version 11
10. SPEXone MPS Database, SPX1-TN-0017
11. PACE Operational RTS List, PACE-OPS-LIST-0216
12. OCI Autonomous Response and Relative Time Sequence Detail Specification, OCI-SYS-SPEC-0144
13. PACE MOC Concept of Operations, PACE-GS-REQ-0066
14. PACE Mission Operations Center (MOC) to Science Data Segment (SDS) IRD/ICD, PACE-OPS-ICD-0009
15. Flight Operations Product Configuration Management Plan, PACE-GS-PLAN-0494

Appendix A – Sample IIAR Activity Entries

This appendix lists samples of instrument activities for all instruments included in the IIAR. The syntax is described in PACE-OPS-ICD-0009.

Routine Science Orbit Activities


```
{
  "instrument": "ALL",
  "startTime": "2025-125-00:42:51.000",
  "activity": "normScienceOrbitStart"
},
{
  "instrument": "OCI",
  "startTime": "2025-125-01:09:12.000",
  "activity": "normSubSolarTilt"
},
{
  "instrument": "ALL",
  "startTime": "2025-125-01:32:09.000",
  "activity": "normScienceOrbitStop"
},
{
  "instrument": "SPEX",
  "startTime": "2025-125-01:42:33.000",
  "activity": "spexCalibrationSequence11"
},
{
  "instrument": "HARP",
  "startTime": "2025-125-01:43:29.000",
  "activity": "harpEclipseDataTransfer"
},
{
  "instrument": "OCI",
  "startTime": "2025-125-02:07:25.000",
  "activity": "ociEclipseTilt"
},
```


OCI Solar Calibration


```
{
  "instrument": "ALL",
  "startTime": "2025-125-14:36:06.000",
  "activity": "ociSolarCalOrbitStop"
},
{
  "instrument": "OCI",
  "startTime": "2025-125-14:36:07.000",
```

"activity": "ociSolarCalOrbitTilt"
},
{
"instrument": "OCI",
"startTime": "2025-125-14:39:19.000",
"activity": "ociSolarCalDailyBrightTarget"
},
{
"instrument": "OCI",
"startTime": "2025-126-05:24:30.000",
"activity": "ociSolarCalDimTargetNewPTDI"
},
{
"instrument": "OCI",
"startTime": "2025-128-14:46:52.000",
"activity": "ociSolarCalMonthlyBrightTarget"
},
{
"instrument": "HARP",
"startTime": "2025-125-14:50:19.000",
"activity": "harpOCISCEclipseDataTransfer"
},

HARP2 Solar Calibration

{
"instrument": "HARP",
"startTime": "2025-129-08:57:45.000",
"activity": "harpSolarCalibration"
},
{
"instrument": "HARP",
"startTime": "2025-129-08:59:45.000",
"activity": "harpSCEclipseDataTransfer"
},

Lunar and Deep Space Calibrations

{
"instrument": "OCI&SPEX",
"startTime": "2025-132-04:49:56.000",
"activity": "ociLunarCalOrbitStart"
},
{

"instrument": "OCI&SPEX",
"startTime": "2025-132-05:39:13.000",
"activity": "ociLunarCalOrbitStop"
},
{
"instrument": "HARP",
"startTime": "2025-132-05:42:33.000",
"activity": "harpLunarCalibration"
},
{
"instrument": "SPEX",
"startTime": "2025-132-05:48:33.000",
"activity": "spexDeepSpaceCalibration1"
},
{
"instrument": "OCI",
"startTime": "2025-132-05:49:33.000",
"activity": "ociLunarCalibrationScan"
},
{
"instrument": "OCI",
"startTime": "2025-132-05:52:27.000",
"activity": "ociLunarCalibrationStare"
},
{
"instrument": "OCI",
"startTime": "2025-132-05:55:57.000",
"activity": "ociDeepSpaceCalibrationStart"
},
{
"instrument": "HARP",
"startTime": "2025-132-05:58:32.000",
"activity": "harpLCEclipseDataTransfer"
},

HARP2 Daytime Calibrations

{
"instrument": "HARP",
"startTime": "2025-145-06:19:14.000",
"activity": "harpFlatFieldCalibration"
},
{
"instrument": "HARP",
"startTime": "2025-149-10:23:18.000",

"activity": "harpAlignmentCalibration"
},

OCI Subsolar Tilt Spectral Calibrations

{
"instrument": "OCI",
"startTime": "2025-129-18:15:32.000",
"activity": "ociSubSolarTiltES1"
},
{
"instrument": "OCI",
"startTime": "2025-129-19:53:53.000",
"activity": "ociSubSolarTiltES2"
},

Appendix B – Sample Calibration Plan Entries

This appendix lists samples of calibration slew entries included in the calibration plan. The syntax is described in PACE-OPS-ICD-0009.

OCI Solar Calibrations


```
{
  "calibrationType": "OCI Daily Solar",
  "timeAtQuaternion": "2025-125-14:41:19.000",
  "targetQuaternion": [
    0.42320896269520425,
    -0.9005761959681395,
    -0.07962346982805123,
    0.05930254802743279
  ],
  "endActivityTime": "2025-125-14:45:19.000"
},
{
  "calibrationType": "OCI Monthly Dim New PTDI",
  "timeAtQuaternion": "2025-126-05:26:30.000",
  "targetQuaternion": [
    0.4281047170453607,
    -0.8982775330188684,
    -0.08009106337579742,
    0.05838875306411223
  ],
  "endActivityTime": "2025-126-05:28:30.000"
},
{
  "calibrationType": "OCI Monthly Bright",
  "timeAtQuaternion": "2025-128-14:48:52.000",
  "targetQuaternion": [
    0.44707240336864973,
    -0.8890324536275394,
    -0.0819646475865647,
    0.05503961381756476
  ],
  "endActivityTime": "2025-128-14:50:52.000"
},
```


Lunar Calibration


```
{
  "calibrationType": "Lunar",
  "timeAtQuaternion": "2025-132-05:49:33.000",
```

"targetQuaternion": [
-0.8221126213686311,
0.2800869625249381,
0.4642133615120047,
-0.17374719049146276
],
"startLunarForwardScanTime": "2025-132-05:49:33.000",
"lunarForwardScanEndQuaternion": [
-0.8493582213882274,
0.24470686159107752,
0.4304467055650972,
-0.18282450110115525
],
"startLunarReverseScanTime": "2025-132-05:51:15.000",
"lunarReverseScanEndQuaternion": [
-0.8221126213686311,
0.2800869625249381,
0.4642133615120047,
-0.17374719049146276
],
"stareTimeAtQuaternion": "2025-132-05:53:27.000",
"stareTargetQuaternion": [
-0.8360661776268344,
0.2625095979729835,
0.4475167980595209,
-0.17835574858992165
],
"endActivityTime": "2025-132-05:54:27.000"
},

HARP2 Solar Calibration

{
"calibrationType": "HARP2 Solar",
"timeAtQuaternion": "2025-129-08:57:45.000",
"targetQuaternion": [
-0.43052715387824914,
0.7387094434237608,
0.30639607087544307,
0.418421050763633
],
"endActivityTime": "2025-129-08:59:15.000"
},

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