Concept of Operations for OSIRIS-REx Optical Navigation Image Planning

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Optical navigation (OpNav) is a critical subsystem of the OSIRIS-REx asteroid sample return mission, which operated in the vicinity of near-Earth asteroid (101955) Bennu from August 2018 through April 2021. A substantial amount of mission resources across multiple subsystems and institutions is required to ensure that the OpNav data are successfully acquired. The KinetX OpNav team, part of the Flight Dynamics System (FDS), is responsible for performing required analysis to develop the OpNav operations plans; requesting, reviewing and verifying the plans; and ultimately using the image data for critical navigation operations. The FDS team, responsible for the mission navigation, is operated by KinetX Aerospace with management and operations support from NASA's Goddard Space Flight Center. The Science Processing and Operations Center (SPOC), located at the University of Arizona's Lunar and Planetary Laboratory, is responsible for generating the planning products for all science and most OpNav data. These plans are integrated into the spacecraft sequences, tested, and commanded by the Mission Support Area (MSA) at Lockheed Martin Space. To ensure mission-critical navigation image data are successfully acquired, the plan is developed through a waterfall of planning cycles over the course of 3 months prior to onboard plan execution. During the initial strategic planning for a mission phase, detailed analysis is performed by the OpNav team to conceptualize the concept of operations (ConOps) for image data collection. This phase OpNav Narrative is included along with other strategic planning documents for the key ground segment stakeholders to review and provide feedback. The detailed OpNav plans get defined in the tactical planning cycle, which spans 8 to 3 weeks before the week-long integrated sequence is executed on-board the spacecraft. During the tactical cycle, the initial OpNav Request is submitted along with the science requests, kicking off development of the science and OpNav plans. Once the initial plan is drafted, interfaces are exercised so that the plan can be reviewed and iterated, if necessary. A rigorous schedule is followed by the planning teams during the implementation cycle, spanning the last 18 days before uplink, to ensure all the necessary integration, testing, and reviewing can occur on time. The development of the OpNav planning ConOps, including responsibilities, interfaces, timelines, and procedures, took extensive collaboration across mission elements and institutions. The process was robust throughout the 137 weeks of continuous Optical Navigation Operations at Bennu, which concluded on April 9th, 2021

I. Introduction

Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) is a NASA New Frontiers mission that will return a sample from the near-Earth asteroid (101955) Bennu [1]. The spacecraft launched on 8 September 2016 and began a two-year cruise to rendezvous with asteroid Bennu in late 2018. Figure 1 illustrates the proximity operations (ProxOps) schedule, which began in August 2018 with the first optical navigation (OpNav) image of Bennu acquired from a range of ~2,184,000 km. The spacecraft arrived at Bennu on December 3, 2018, entered into a spaceflight record-setting orbit on December 31, 2018, and first observed Bennu's particle ejection phenomena in OpNav images on January 6, 2019. The Site Selection Campaign began with a Detailed Survey phase, followed by lower orbital and reconnaissance flybys spanning from February to December 2019. The prime and backup sites were announced in December 2019, kicking off the Sample Acquisition Campaign, which consisted of low reconnaissance fly overs of the two sample sites, two rehearsals, and finally the successful touch-and-go (TAG) sample collection event on October 20, 2020 [2]. On April 7, 2021, OSIRIS-REx performed one final flyby of Bennu to observe the post-TAG surface.

Bennu's properties and environment presented unique, unanticipated operational challenges that required augmentation to the mission and science plans to successfully perform TAG [3]. OpNav is a critical component of the Flight Dynamics System (FDS), required to successfully achieve the challenging navigation needs of the mission [4,5,6]. OpNav uses measurements extracted from spacecraft images to assist in the navigation and orbit determination (OD) of the spacecraft. Three instruments are primarily used for navigation: the high-resolution PolyCam and the medium-angle MapCam instruments in the OCAMS suite [7], and the wide-angle NavCam 1 in the TAGCAMS suite

[8]. A substantial amount of mission resources across multiple subsystems and institutions is required to ensure that the OpNav data are successfully acquired.

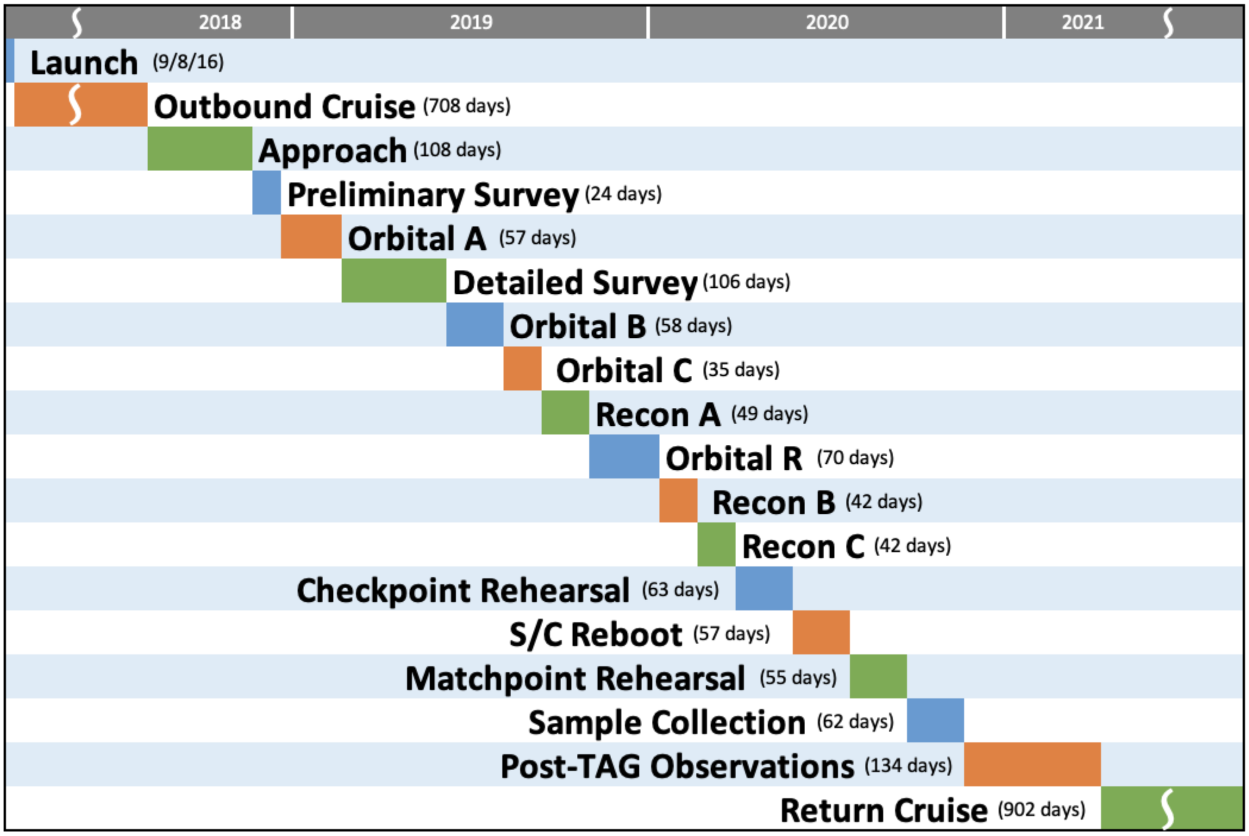

Figure 1 OSIRIS-REx mission timeline

The successful 137 weeks of continuous OpNav operations can be credited to architecture of the ground system and the exceptional performance and rigor of the operations teams. The OpNav team is responsible for performing required analysis to develop the OpNav operations plans; requesting, reviewing and verifying the plans; and ultimately using the image data for critical navigation operations. The FDS team, responsible for the mission navigation, is operated by KinetX Aerospace with management and operations support from NASA's Goddard Space Flight Center. The Science Processing and Operations Center (SPOC), located at the University of Arizona's Lunar and Planetary Laboratory, is responsible for generating the planning products for all science and most OpNav data. These plans are integrated into the spacecraft sequences, tested, and commanded by the Mission Support Area (MSA) at Lockheed Martin Space. The MSA is also responsible for building the sequences for the NavCam instrument [8], which is one of several instruments utilized by the OpNav subsystem. On the downlink side, the SPOC is responsible for reconstructing the packetized image data into the specified file formats and delivering them to FDS. The FDS team processes the OpNav data, performs the OD, designs the trajectory, and calculates the maneuver parameters.

Each mission phase is defined by unique engineering and science objectives that require thorough analysis and planning starting 3 months before the phase begins. Spacecraft sequences are built to span a full week, with tactical planning kicking off 8 weeks before uplink, and the implementation cycle starting 3 weeks out. The overlapping phase and sequence planning cycles present a key challenge to the team. This text discusses details of the image planning process with an FDS/OpNav focus.

II. Strategic planning and development of OpNav ConOps Narrative

Each OSIRIS-REx mission phase is unique in terms of trajectory geometries, spacecraft constraints, and science and navigation objectives. Strategic planning for a mission phase is kicked off 3 months before the phase is slated to begin, and the plan must be approved before the tactical planning kickoff occurs 8 weeks prior to the phase start. Materials from various ground system teams are collected into a package, called the phase technical change request (TCR), that is reviewed, revised, and approved by the key ground system stakeholders. One of the key components of the phase TCR is the OpNav Narrative, containing phase-specific details about the navigation imaging concept of operations (ConOps).

A. Phase TCR

The phase TCR typically consists of several documents prepared by various elements of the ground system, described in Table 1.

Table 1. Overview of contents within the phase TCR.

Document Name	Produced by	Description
Maneuver Playbook	FDS – Maneuver Team	Details about maneuver designs
OpNav Narrative	FDS – OpNav Team	OpNav ConOps with supporting analysis results
Science Phase Plan	SPOC – Science Planning Team	Science requirements and supporting analysis results demonstrating how the objectives will be achieved through data collection
Mission Plan Workbook	Project Systems Engineering – Mission Operations Manager	Spreadsheet containing details about the plan by day, including: data volume totals per instrument, DSN tracking, spacecraft partition filling, data downlink values and criticalities, spacecraft configuration, science activities, and navigation deliveries
Planning Templates	MSA – Spacecraft Operations Team	A collection of day-long spacecraft configurations that specifies windows of opportunity for OpNav and science observations

B. OpNav Narrative

Some aspects of the OpNav ConOps were developed and known before the start of proximity operations based on the flight system design, attitude pointing and stability capabilities, spacecraft thermal constraints, instrument commanding constraints, and efforts to minimize operational complexity. However, there are unique aspects of each phase that must be analyzed and developed into a detailed plan. The OpNav Narrative is a compilation of reference information and various analyses detailed in this paper. The results from these analyses are used to assess the required instruments, pointing, and commanding parameters to successfully capture mission-critical OpNav images of Bennu.

1. Reference plots

Phase angle, range, instrument resolutions, and size of Bennu in the instrument fields of view (FOV) are computed and plotted based on the reference trajectory. These plots help the analyst determine which instrument(s) are best suited for OpNav during the phase, as well as provide context for subsequent analyses.

2. Templates and OpNav cadence

The spacecraft operations team generates a collection of day-long spacecraft configurations that specifies windows of opportunity for OpNav and science observations that satisfy spacecraft operations constraints related to thermal conditions, power, telecommunications, etc. Figure 2 shows three example templates from the Recon A mission phase: an OpNav-only day, a day with a time-variable burn, and a science day. These templates schedule spacecraft activities such as daily high-gain antenna (HGA) tracks, maneuvers, thermal recovery periods, as well as periods where the SPOC can plan OpNav and science observations. The OpNav analyst adds the green markers for the requested observation cadence, at approximately the desired times. The frequency and number of images is driven by navigation performance requirements.

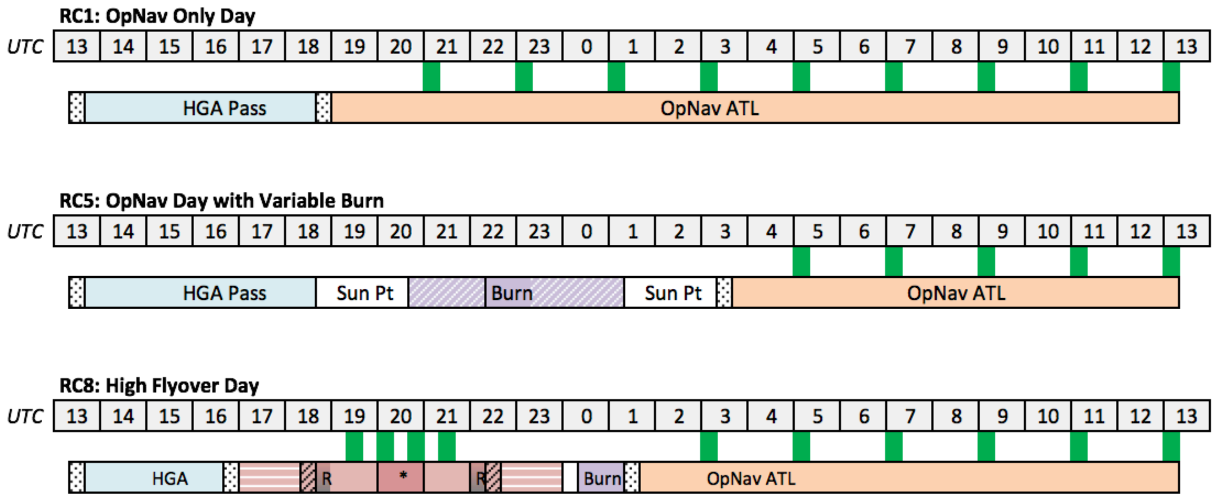

Figure 2. Example phase templates with OpNav imaging cadence represented by the green rectangles.

3. *OpNav blocks*

To simplify the instrument commanding for OpNav, a small set of sequence blocks were defined early in the mission before proximity operations. These blocks cover the various OpNav observation needs, and the phase-relevant ones are documented in the narrative for context and completeness. Details about the block logic, number of images, settling time, and duration are documented. There are three NavCam blocks and three OCAMS blocks that cover all the needs for navigation.

4. *Trajectory state error analysis*

The majority of OpNav pointing is commanded relative to nadir, which is computed onboard based on an uplinked spacecraft ephemeris. The ephemeris errors grow in time after the OD data cut-off (DCO), due to uncertainties in future forces perturbing the spacecraft's trajectory [9]. Once the nominal spacecraft trajectory is designed by FDS, OD covariance analyses are performed to generate the expected trajectory state errors (TSEs) that represent the knowledge uncertainties expected in operations. Additionally, Monte Carlo analysis is performed to bound the trajectory dispersions for OpNav images immediately following a maneuver [10], before a new spacecraft ephemeris is uplinked. These TSEs need to be taken into account in the observation planning to ensure that an image of Bennu is captured. An example plot of the TSEs from the Orbital A mission phase is shown in Figure 3. Each colored line represents a different OD ephemeris solution that is uplinked to the spacecraft 24 hours after the DCO. During this phase, it was important that Bennu not be clipped on the edge of the NavCam FOV. This analysis resulted in a 2x1 mosaic pointing scheme after orbit insertion (marked as M3A in Figure 3), since there was a possibility of Bennu trailing out of the FOV in a single NavCam image.

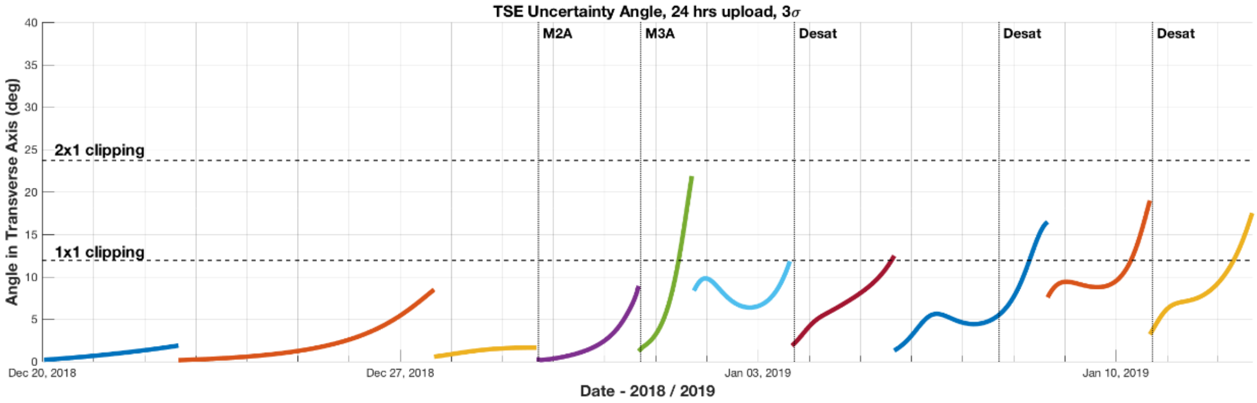

Figure 3. Example TSE uncertainties along the orbit transverse axis during the Orbital A phase.

5. *Pointing analysis*

The spacecraft has the ability to target the instrument deck ($+Z_{sc}$) to nadir, as well as slew attitudes relative to nadir. The NavCam is mounted such that the boresight is 6 degrees offset from $+Z_{sc}$; this was intended to center the illuminated portion of Bennu in the FOV while in the *safe home orbit* that comprises a large portion of proximity operations. The OpNav analysts conceptualize the design of the instrument pointing to ensure Bennu is optimally placed in the FOV, and that TSEs are taken into account. It has been common to require mosaicking along the orbit down-track (transverse) axis, as illustrated in Figure 4. The analyst calculates what nadir offset vectors are required to achieve the desired overlap and coverage area, and verifies it with a KinetX visualization tool called Fly-Point-Shoot (FPS) [11].

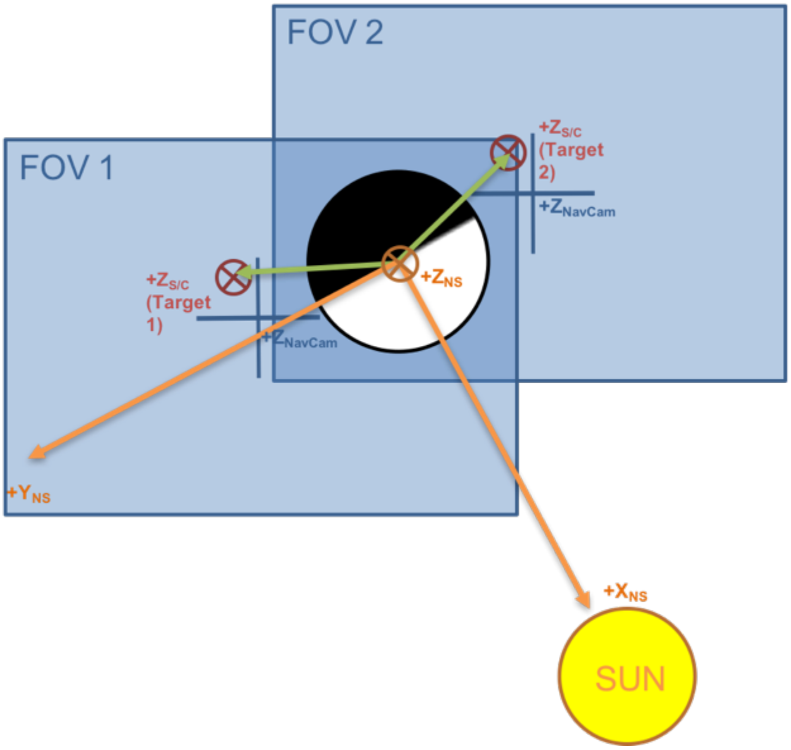

Figure 4. NavCam 2x1 Mosaic Diagram from the Orbital A phase.

During survey phases the spacecraft performs a series of hyperbolic flybys at varying phase angles. The goal of the pointing analysis is to simplify operational complexity as much as possible while still meeting the needs of the navigation team. Figure 5 plots an example of the angle between nadir and the center of illumination during the Detailed Survey phase. This plot is used to identify an average nadir offset that will work for an extended period of time to ensure the instrument is centered on the illuminated portion of the asteroid. The computed offset is then simulated in FPS to visually confirm the OpNav needs are being met with this simplified pointing approach.

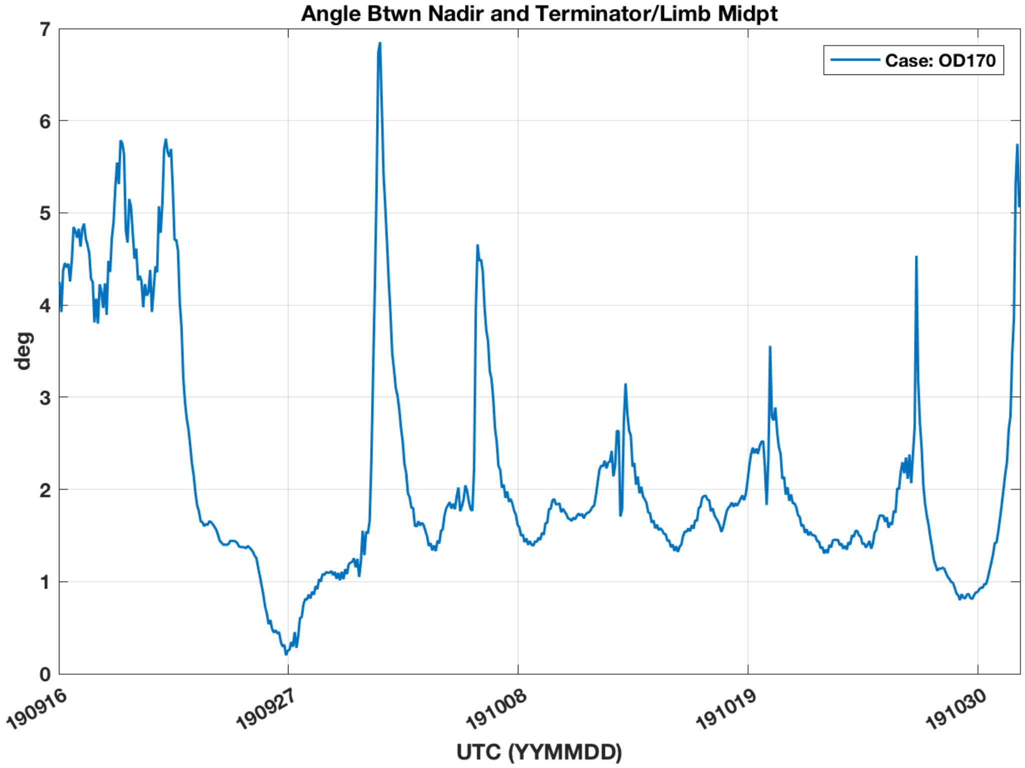

Figure 5. Plot of angle between nadir and center of illumination for NavCam during the Detailed Survey phase.

6. *Stray light analysis*

At high phase angles, the sunlight begins to impinge on the NavCam instrument boresight, creating a stray light effect on the images. This increased background signal can cause degradation in the image data if the exposure times are not properly reduced to prevent saturation. The Sun-boresight angle is plotted to identify periods where the exposure times for images need to be reduced; an example of this from the Detailed Survey phase is provided in Figure 6.

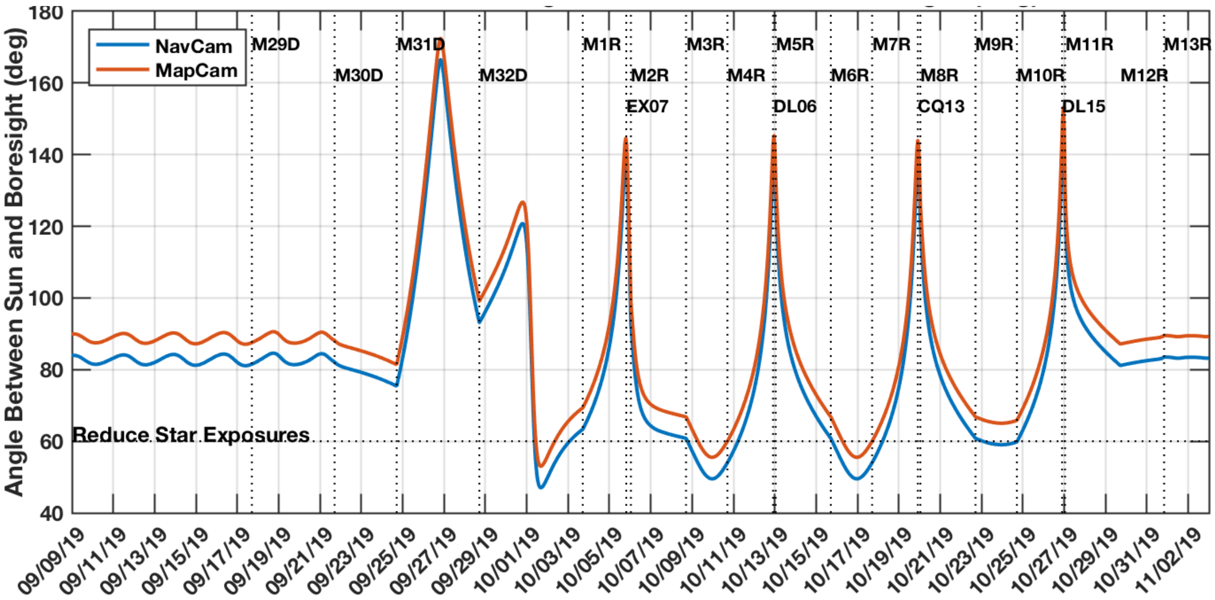

Figure 6. Sun incidence angle for NavCam and MapCam during the Detailed Survey phase.

7. Exposure time analysis

Trajectory-driven variations in viewing geometry such as range, phase angle, and solar distance require careful selection of exposure times that ensure well-exposed OpNav images of Bennu. The trajectory is run through a customized exposure time calculator tool [11] that computes the expected image signal levels for an array of exposure times based on geometry, camera models, and Bennu's physical parameters. The OpNav analyst tries to find an exposure time that works for the entire phase, given the dynamic range of the instrument. This is not always feasible, especially for survey phases; the goal is to determine a minimum set of exposure times that can be sequenced to minimize the burden on the planning teams.

8. OpNav commanding and pointing

The OpNav request summarizes the results of the analyses into a detailed plan of the OpNav cadence, pointing, and instrument parameters for each day and week of the phase. Typically, a plan can be built for a single day and then be re-used for many days or weeks of the phase, which greatly simplifies the planning and testing process.

III. **Tactical Cycle Planning**

The objective of the tactical phase is refining proposed activities to the point where they are handed off to implementation. Objectives and activities specified at the strategic level in the Mission Plan Workbook and Science Phase Plan are developed within the Science Operations Planning Group (SOPG) and Operations Working Group (OpsWG) and documented as discrete and mature activities for planning.

A. Cycle Overview

The tactical planning phase begins 8 weeks before each week-long sequence execution, starting with the SOPG's development of the science observation details and FDS's generation of an OpNav Request. Once this request is received by the SPOC, the plans are integrated into the science requests and implemented in the planning tool, J-Asteroid [12]. Once the plan is built, interface products are delivered to FDS to verify the implementation and reconcile any discrepancies from what was requested. The OpNav Checklist is built from the OpNav Request, with additional implementation details populated. Additionally, a set of OpNav Observation Reports are generated by J-Asteroid, containing specifications for the pointing and imaging plan. These planning interface products are ingested into FPS to verify that they have been built as intended. The sequence and planning files that the SPOC delivers to the MSA for integration into the flight products differ from the tailored files delivered to the OpNav team. The SPOC delivers three primary products to the MSA: (1) Asteroid Target Files (ATFs) that contain the pointing targets and times from which instrument sequence(s) are initiated; (2) sequences for all science instruments, including OCAMS PolyCam and MapCam OpNav but excluding TAGCAMS/NavCam sequences; and (3) an Uplink Product Build List (UPBL) that includes, among other things, the ATF execution schedule for each week-long integrated sequence, including ATF start and stop times.

At any given time, a number of weeks will be in various stages of planning, implementation, or execution. Weeks in the planning cycle count down from 8 to 0. These weeks, sometimes referred to as 'cycle weeks', are relative to execution and are also referred to as 'execution or E–X weeks'. The OpNav-focused process flow for the tactical phase of the 8-week planning cycle is illustrated in Figure 7. The initial OpNav request is built based on the OpNav Narrative and subsequent operational experience, and delivered to SPOC on the Monday of week E–7. The SPOC then implements the request and on the Thursday of week E–5, they deliver the OpNav Checklist and Observation Reports and hold a Reconciliation meeting to go over the plans. The OpNav team then reviews the plans and iterates with SPOC as necessary before the plans are handed off for the Implementation phase.

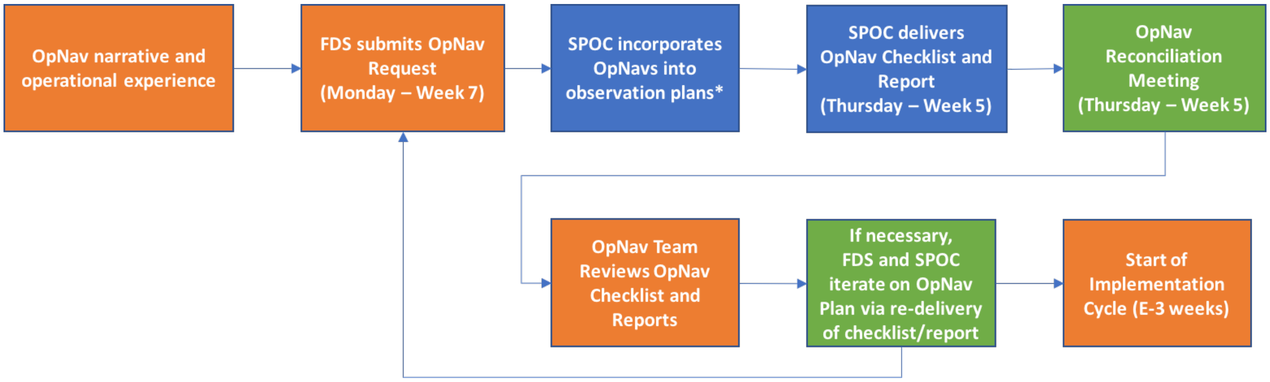

Figure 7. Tactical phase of the 8-week planning cycle (OpNav focus).

B. OpNav Request

The OpNav Request is a spreadsheet that contains details such as instrument type, timing constraints, cadence, pointing description, settle time, and instrument command block and input parameters. Each row of the spreadsheet represents one observation target that initiates one instrument block call. There are two different templates: one for TAGCAMS requests and one for OCAMS requests since they have different parameters. When co-incident imaging is required, both OCAMS and TAGCAMS sequences can be executed simultaneously.

Table 2 contains a list of all the column headers within the OpNav Request/Checklist template. Not all fields will be populated in the initial request, as some will be added during the planning cycle. During mission operations, the OpNav Request spreadsheet is copied by the SPOC, saved as the OpNav Checklist, and updated as the planning and sequencing is worked.

Because TAGCAMS was originally intended to be an engineering instrument, all NavCam images are commanded and processed through the OpNav pipeline. However, the science team found the wide FOV of the instrument useful for science context imaging as well as monitoring of the discovered particle ejection activity [13]. Since this was a late addition, the simplest implementation that allowed the OpNav team to properly verify the plan was to keep all requested and planned TAGCAMS imagery in the OpNav request. There are three types of TAGCAMS observations denoted in the OpNav request: OpNav, Science, and SciNav. SciNav observations are dual-purpose, achieving both OpNav and Science Observation Change Request (SOCR) science requirements with one observation. TAGCAMS observations requested for science are coordinated through the TAGCAMS Instrument Scientist (IS) with the OpNav team as the OpNav request is being created.

The initial OpNav Request is generated from the baseline OpNav Narrative associated with the mission phase and any current mission experience, including any SciNav images in the baseline.

Table 2. List of columns in the OpNav Request/Checklist spreadsheet template.

	OpNav Request/Checklist Fields	**Populated by**	**Comments/Descriptions**
Fields present in both TAGCAMS and OCAMS requests	Background Sequence Name	FDS	Pre-determined by MSA, populated by FDS at Request inception
	ATF Name	SPOC	Filename of ATF produced by SPOC
	OpNav Report Name	SPOC	For tracking re-use days without SPOC re-delivering reports
	ATF Re-Use	FDS/SPOC	Notional identification of re-use from FDS in request (based on templates), updated by from SPOC in Checklist after integration with science plans
	Target ID	SPOC	Maps pointing targets to the J-Asteroid database
	Instrument	FDS	NavCam, MapCam, or PolyCam
	OpNav/Science/SciNav Request?	FDS	Identifies if the observation is for OpNav, science, or dual-purpose
	DOY	FDS	Day of year of the requested observation

	FDS Requested OpNav Epoch (UTC) w/bounds	FDS	UTC time of the requested observation, with bounds on how much it can shift during implementation
	Downlink Criticality	FDS	Reference to the criticality of the observation, which dictates the level of ground support if there is a problem downlinking the data
	OpNav Block Type	FDS	Allows FDS to select which type of OpNav block we intend to be used. Also required for MSA macro logic in TAGCAMS template.
	Settle Time (s)	FDS	This field is critical for planning TAGCAMS observations in J-Asteroid.
	Target Pointing Type	SPOC	A means for SPOC to communicate pointing implementation. Is useful for discussion and iteration during reconciliation.
Fields present only in TAGCAMS request	Instrument Sequence Name	MSA formula	Naming convention is formulaic based on exposure time and selected block type
	Minimum Imaging Time-at-Target Duration after settle (seconds)	MSA formula	This is the time that the spacecraft must be held at the target attitude after the settle time has completed in order to allow all the imaging to finish. The next slew for a non-TAGCAMS target cannot begin until this much time has elapsed since the previous Target Time plus settle. This field is critical for planning TAGCAMS in J-Asteroid, since SPOC does not build the actual instrument sequences, but rather plans with a placeholder sequence.
	Additional Time to End of Instrument Sequence (seconds)	MSA formula	This is the time it takes for the sequence to complete after the “Minimum Imaging Time-at-Target” time is reached This field is critical for planning TAGCAMS in J-Asteroid since SPOC does not build the actual instrument sequences, but rather plans with a placeholder sequence.
	Destination Partition	FDS/SPOC	Text field specifying where images should be routed to on the spacecraft.
	Partition ID (INT)	MSA formula	This field translates the input of the Destination Partition field into the partition integer value to which images should be routed.
	Exposure Time #1 (s)	FDS	Requested exposure time for the first image in the block.
	Exposure Time #2 (s)	FDS	Requested exposure time for the second image in the block, if applicable.
	Exposure Time #3 (s)	FDS	Requested exposure time for the third image in the block, if applicable.
	Exposure Time #4 (s)	FDS	Requested exposure time for the fourth image in the block, if applicable.
	Number of TAGCAMS Images	MSA formula	Formula identifies number of images based on selected block type
	Attitude Collection Rate (Hz)	MSA formula	Formula identifies accurate attitude collection rate based on selected block type
Fields present only in OCAMS	Exposure Time #1 (ms)	FDS	Requested exposure time for the first image in the block.

request	Exposure Time #2 (ms)	FDS	Requested exposure time for the second image in the block, if applicable.
	Number of Light Image Pairs	FDS	Number of times the two exposures are repeated
	Number of Dark Pairs	FDS	Number of times the two exposures are repeated for dark calibration images
	Filter (MapCam Only)	FDS	MapCam filter selection
	HEX Focus (PolyCam Only)	FDS	PolyCam focus selection
Fields present in both TAGCAMS and OCAMS requests	Target Pointing Specification	FDS	Description of requested pointing
	Image Criteria	FDS	Description of additional criteria that the observation must meet (e.g. coincident imaging with a known science observation)
	Estimated re-usable ATF start (UTC)	SPOC	Absolute start time of the ATF plan (and OpNav Observation Report)
	Estimated re-usable ATF end (UTC)	SPOC	Absolute end time of the ATF plan (and OpNav Observation Report)
	Comments	ALL	
	Assumptions	ALL	
	Criteria Met?	SPOC	If no, SPOC to put why and what is met

C. ATF re-use

Because ATFs contain time-relative and nadir-relative targeting, they can be re-used or shifted as schedules change or as part of an anomaly recovery. Some weeks can be planned exclusively with re-used ATFs for OpNav imaging, which allows the planning cycle to be shortened from 8 weeks to only 5 weeks. These weeks are identified during the phase TCR stage and noted in the OpNav Narrative.

The OpNav Request denotes which observations the OpNav team believes are eligible for re-use based on the TCR Mission Phase Template and the baselined OpNav Narrative. As part of detailed planning, the SPOC identifies which observations need to be built in a new J-Asteroid plan versus executed with a pre-built, re-useable ATF. The SPOC generates single-use ATFs in conjunction with science in J-Asteroid, and then populates the OpNav Checklist as usual for each target, with a yes/no indication of ATF re-use for each target, ATF names, OpNav Report Names, and the approximate ATF start and stop times based on the mission phase templates. By Thursday of E–5, the SPOC delivers the OpNav Checklist and any new OpNav Reports to the OpNav team. SPOC does not redeliver any previously delivered OpNav Reports corresponding to re-used ATFs, as FDS keeps a catalog of the re-usable ATF OpNav Reports for ingest into FPS.

Between delivery of the initial OpNav checklist at week E–5 and the final OpNav request submission during week E–3, changes to the OpNav request could affect the observations that were originally planned to be re-used ATFs. Even simple modifications in exposure time, which are possible up to the final OpNav request submission deadline of E–18 days, could invalidate a previously planned re-use ATF for a given day. A revision to the OpNav request could mean selection of a different, pre-existing re-ATF or generation of new sequences.

Creating re-usable ATFs also results in scenarios where an ATF may be stopped onboard before the entire set of targets has been executed. For example, an OpNav ATF with 10 targets may be stopped after only four to fit between two other activities in a re-use scenario. This requires additional management by the spacecraft background sequence. To support this, the SPOC defines the ATF start and stop times.

D. OpNav Checklist, Observation Reports, and Reconciliation meeting

A weekly OpNav reconciliation meeting corresponding to the delivery of the OpNav Checklist and Report is scheduled for Thursday afternoon of week E–5. This weekly meeting provides a regular forum for presenting an overview of the plans just delivered, as well as opportunity to discuss status of other weeks.

The OpNav Checklist mirrors the OpNav Request, but contains implementation details from SPOC that are used by FDS to verify the OpNav implementation. Prior to the delivery of the OpNav checklist, the SPOC is responsible for verifying aspects of the OCAMS OpNav implementation including flight rule checking and verifying that the OCAMS sequence inputs match the OpNav request.

The OpNav Reports are text JavaScript Object Notation (JSON) files containing specifications for the slewing, pointing, and imaging plan from the J-Asteroid planning tool. The OpNav Report is a tailored interface that represents the OpNav-specific plans without most of the science observation details.

E. Review of OpNav plans

Following delivery of the OpNav Checklist and corresponding OpNav Reports, the OpNav team performs verification of the OpNav timing and pointing with respect to the OpNav request. The OpNav Checklist is inspected by the OpNav analyst, and any unmet requests are identified and either accepted or re-worked.

The OpNav reports are ingested into the FPS software and used to verify correct pointing implementation. There is no formal sign-off of the OpNav checklist at this stage; but discrepancies identified by FDS are reconciled with the SPOC through weekly reconciliation meetings and can result in re-delivery of the OpNav Request/Checklist as necessary. Any changes to the OpNav imaging based on operational experience can be incorporated into the plan via an update to the latest OpNav Request or Checklist.

F. Weekly TCR inputs

A TCR is populated by the ground teams for each weekly sequence. A high-level daily summary of the OpNav information is delivered by the OpNav team and pasted into the TCR, as shown by example in Table 3. Days containing OpNav observations which are deemed critical for retransmit are noted to ensure appropriate staffing coverage. A summary of the criticality definitions for OpNav downlink and retransmit criteria are provided in Table 4.

Table 3 Example OpNav TCR Inputs

DOY	Weekday	Date	# NavCam OpNavs in D/L	# PolyCam OpNavs in D/L	# MapCam OpNavs in D/L	Retransmit Criticality
34	Mon	2/3/20	9	0	9	4
35	Tue	2/4/20	8	0	8	5
36	Wed	2/5/20	9	0	9	2
37	Thu	2/6/20	9	0	9	5
38	Fri	2/7/20	5	0	5	2
39	Sat	2/8/20	9	0	9	5
40	Sun	2/9/20	9	0	9	5

Table 4. OpNav downlink/retransmit criticality definitions.

Criticality Level	Description/Summary	OpNav Downlink Designators
1	**Potential loss of mission**	N/A
2	**Large schedule impact and/or loss of critical science** Missed maneuvers or loss of critical science results in significant schedule impact, requires multiple weeks and significant re-planning to recover.	OpNav observations preceding a criticality 2 maneuver late update (loss of OpNav images would preclude execution of late update.) OpNav observations preceding a critical ephemeris uplink that causes loss of critical science or un-recoverable loss of OpNav images, resulting in delay to mission.

		Same-pass retransmit capability protects against this except during loss of entire pass.
3	**Loss of science with no near-term schedule impact** Missed maneuver or loss of critical science that does not have an immediate schedule impact, but could require re-planning or new observations later in the mission.	OpNav observations preceding a criticality 3 maneuver late update (loss of OpNav images would preclude performance of late update.) OpNav observations preceding an ephemeris uplink that if missed, would cause loss or degraded science (but no immediate schedule impact). *Same-pass retransmit capability protects against this except during loss of entire pass.*
4	Loss or degradation of science that does not need to be made up and has no schedule impact.	OpNav observations important for trajectory reconstruction or science but that do not precede a late update or ephemeris update. *No retransmit, or next day retransmit would be attempted where possible.*
5	No activities planned or no impact from loss of uplink/downlink	No critical OpNav observations

IV. Implementation Cycle Planning

The implementation phase is a highly coordinated period where defined activities are built, tested, verified, uplinked, executed, and (if needed) given late updates.

A. Cycle overview

An OpNav-focused process flow of the implementation cycle is illustrated in Figure 8. The OpNav implementation process begins with the submission of the final OpNav request on Thursday of week E–3, although typically there are no late changes to the plan and the tactical plan is sufficient to move forward. The SPOC operations engineer makes any necessary final adjustments to the OpNav plans and completes verification of the implementation details of OCAMS OpNav observations. On Monday of week E–2, the final OpNav checklist and OpNav report are delivered by the SPOC. The OpNav team performs inspection and analysis of the final products and provides sign-off in the SPOC Jira system by Tuesday of week E-2. Any errors caught at this stage would likely trigger a late-breaking update to the delivered products that would require team members to work off-shift; therefore, changes to products at this point are limited to problems that could jeopardize the safety of the spacecraft.

The SPOC operations engineer completes implementation of all of the OCAMS OpNav sequences and delivers science and OpNav ATFs and instrument Virtual Machine Language (VML) sequences to MSA on Wednesday of E–2. The MSA then integrates the science ATLs and sequences into the master background sequence and delivers an integrated Predicted Events File (PEF) on Thursday of E–2. If there are TAGCAMS OpNav images in the request, the MSA builds those sequences before PEF integration. The OpNav team conducts a review of the integrated PEF focusing on details of the TAGCAMS implementation, since the SPOC has already performed a comprehensive review of OCAMS OpNav implementation prior to delivery of the OpNav Checklist. On Monday of E–1, FDS completes their review of the integrated PEF and if necessary a recommendation for emergency re-build is provided. This is communicated to the Flight Operations Manager (FOM) who contacts and notifies all elements, and then the Mission Operations Manager (MOM) puts out a team-wide message of the necessity of the re-build. During this same timeframe, the predicted attitude file is available for review. FDS completes their review of the OpNav implementation and provides sign-off to the MSA. The SPOC and MSA also review the sequence and test products; OpNav team relies on other reviewers to identify any issues with flight rule violations, sequence collisions, slew completion times, etc.

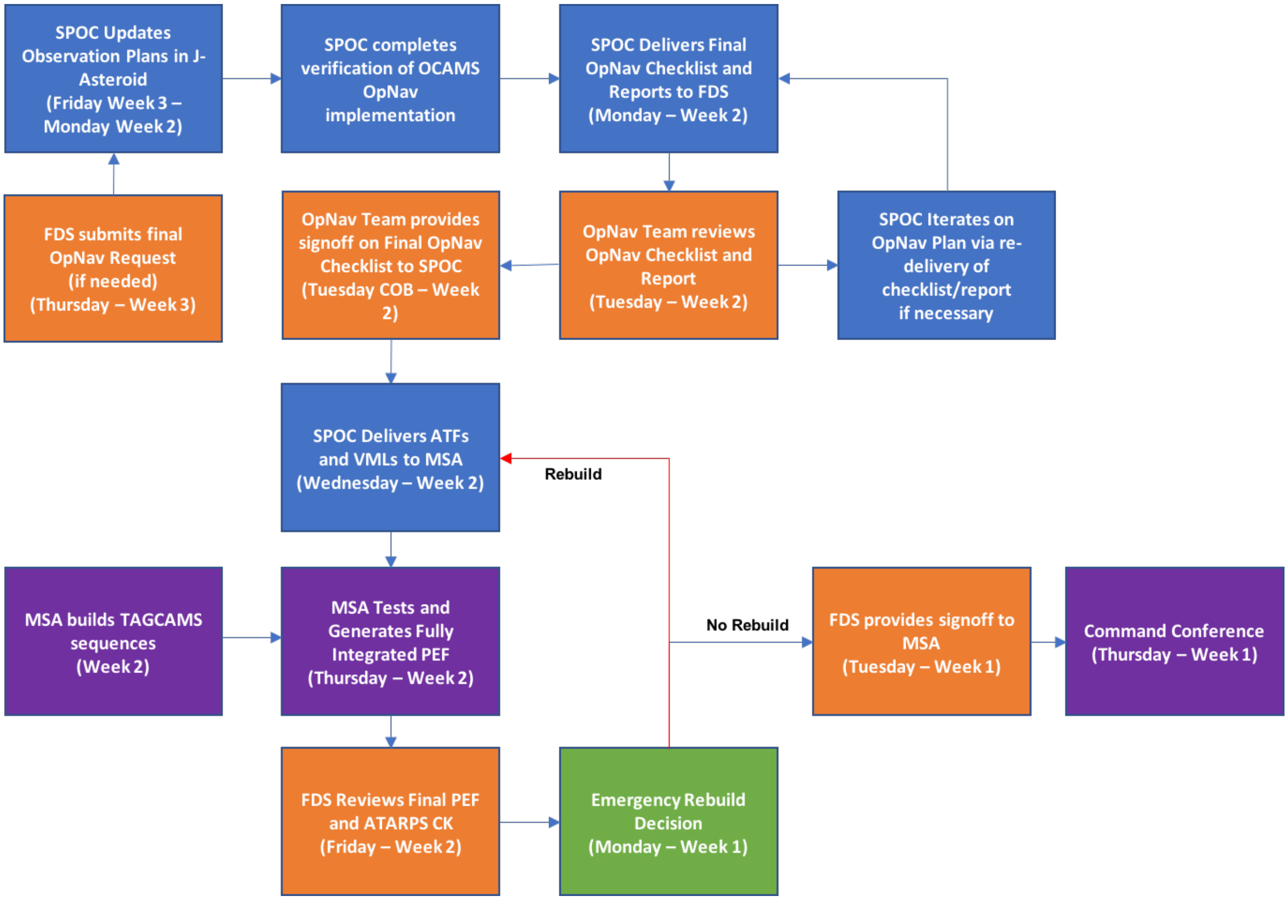

Figure 8. Implementation phase of the planning cycle (OpNav focus).

B. FDS Review of PEF and predicted attitude

The integrated PEF contains all the spacecraft commands for the week-long command sequence. A Python tool is used to extract relevant OpNav image commanding from the PEF and compare it against the expected images in the OpNav Checklist. The tool compares the commanded OpNav image times against the requested epoch bounds, and flags if any images fall outside the window. It also checks the TAGCAMS commanding against the requested block parameters. This KinetX tool enables a quick-turnaround review of the PEF so that any issues can be identified as early as possible before the deadline for the emergency rebuild decision.

The week-long integrated sequence is also run through an attitude simulator, which outputs a time history of the spacecraft attitude profile for evaluation by the ground teams. The FPS setup file from the review of the OpNav Reports is updated to include the predicted attitude kernel and the latest predicted trajectory. The OpNav analyst can then step through each OpNav target in the OpNav Reports and visualize any differences in the OpNav pointing between the plan and the final predicted attitude.

Once these products are verified by FDS, a final sign-off is provided to the MSA with enough time margin to perform an accelerated rebuild if any issues are identified that could put the spacecraft or mission in jeopardy.

V. Conclusion

The concept of operations developed for the OSIRIS-REx OpNav planning process defines responsibilities, interfaces, and schedules across multiple ground system elements. The small size of asteroid Bennu, coupled with the challenging series of orbital and hyperbolic trajectories flown during the scientific observation campaign, meant that a large range of observing conditions and other challenges had to be taken into account by the planning teams. To ensure mission-critical navigation image data are successfully acquired, plans are developed through a waterfall of planning cycles over the course of 3 months prior to onboard plan execution. During the initial strategic planning for a mission phase, detailed analysis is performed by the OpNav team to conceptualize the ConOps for image data collection. The OpNav Narrative is included along with other strategic planning documents for the key ground segment stakeholders to review and provide feedback. The detailed science and OpNav plans are defined in the tactical planning cycle, which spans 8 to 3 weeks before execution of the week-long science sequence onboard the spacecraft. During the tactical cycle, the initial OpNav request is submitted and the OpNav imaging and science plans are developed in parallel. During this cycle, the draft OpNav plans are reviewed by FDS and updated if necessary before the implementation cycle begins. A rigorous schedule is followed by the planning teams during the implementation cycle to ensure all the necessary integration, testing, and reviewing can occur before the "go" for uplink. FDS is responsible for reviewing the final command products and predicted attitude data to provide concurrence on the plan, or trigger an emergency re-build if a spacecraft safety issue is identified. The development of the OpNav planning ConOps, including responsibilities, interfaces, timelines, and procedures, took extensive collaboration across mission elements and institutions. The process, which has been in place since the first OpNav images of Bennu were captured on 17 August 2018, has enabled a complicated and exhaustive global characterization of near-Earth asteroid Bennu to centimeter scales. The system continued to function like a well-oiled machine as the mission operations team worked through the onset of a global pandemic to successfully collect a sample from Bennu on October 20, 2020, and complete one final flyby of the touchdown site on April 7, 2021.

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