Approach Phase Plan Narrative

OSIRIS-REx DOCUMENT

10/06/2017

Rev-9C

1 APPROACH

1.1 Purpose

The purpose of this document is to describe the nominal observation plan for the Approach Phase of the mission. It is intended to provide enough information for the science teams and instruments teams to ensure that the plan is consistent with the instrument capabilities and that it meets the observation constraints, or where it does not, the plan is nevertheless acceptable. Engineering details sufficient to determine if the plan fits within the spacecraft capabilities and available mission resources are provided here and in the Mission Plan Workbook.

The science plan described in this document does not include contingency observations that may be needed in the event of detection of a natural satellite or a dust/gas plume. Contingency plans for dust plume and natural satellite detection are described in the following documents: OSIRIS-REx-PLAN-0056 – Detection of a Natural Satellite Contingency Plan and OSIRIS-REx-PLAN-0057 – Detection of a Dust Plume Contingency Plan.

1.2 MRD Overview

The Mission Requirements Document (MRD) Rev K includes nine requirements that drive science observations taken during the Approach phase and/or science data products that are produced during Approach. Approach is the first time OSIRIS-REx will attempt to optically acquire Bennu beginning from approximately 2 million km away. Approach provides opportunities to view and characterize Bennu as a point source and as the range between OSIRIS-REx and Bennu decreases, Approach provides opportunities to collect imagery with high enough spatial resolution to begin deriving the first shape model and coordinate system and characterizing the Bennu spin state. MRD-157 describes the requirement to observe Bennu and determine its astronomical and photometric properties. MRD-159 and MRD-544 further describe the requirements to characterize the rotationally resolved spectral and thermal characteristics of Bennu. Observations collected during Approach contribute to fulfillment of MRD-678, which requires the generation of a 75cm shape model of Bennu. Using the imagery that is acquired to generate the 75cm shape model, the prime meridian for a Bennu body-fixed coordinate system is also defined during Approach, fulfilling MRD-125. Although not delivered until later, the observations in Approach will also contribute to fulfilling MRD-124, MRD-127, MRD-128, and MRD-129. Ultimately, Approach data will be used to follow-up on ground-based observations of Bennu and will also be compared to the Design Reference Asteroid.

In addition to observing and characterizing Bennu itself, Approach observations will be used to search the space immediately surrounding Bennu for dust/gas plumes and natural satellites (i.e., within the Hill sphere). Successful completion of MRD-142 and MRD-158 involve searching for and pointing to the surface origin of dust/gas plumes originating from Bennu by analyzing imagery, the point spread function, and phase function of Bennu. MRD-144 defines the requirement to search for natural satellites. In the event that natural satellites are positively identified, MRD-146, MRD-147, MRD-148, and MRD-196 describe the requirements for characterizing the light-curve, spectral, and color of the satellites as well as their orbital properties. The data that are collected in the course of meeting MRD-142, MRD-157, and MRD-144 are important for scientific as well as operational purposes.

A schematic of the Approach timeline for the observations is given in Figure 1.2.1

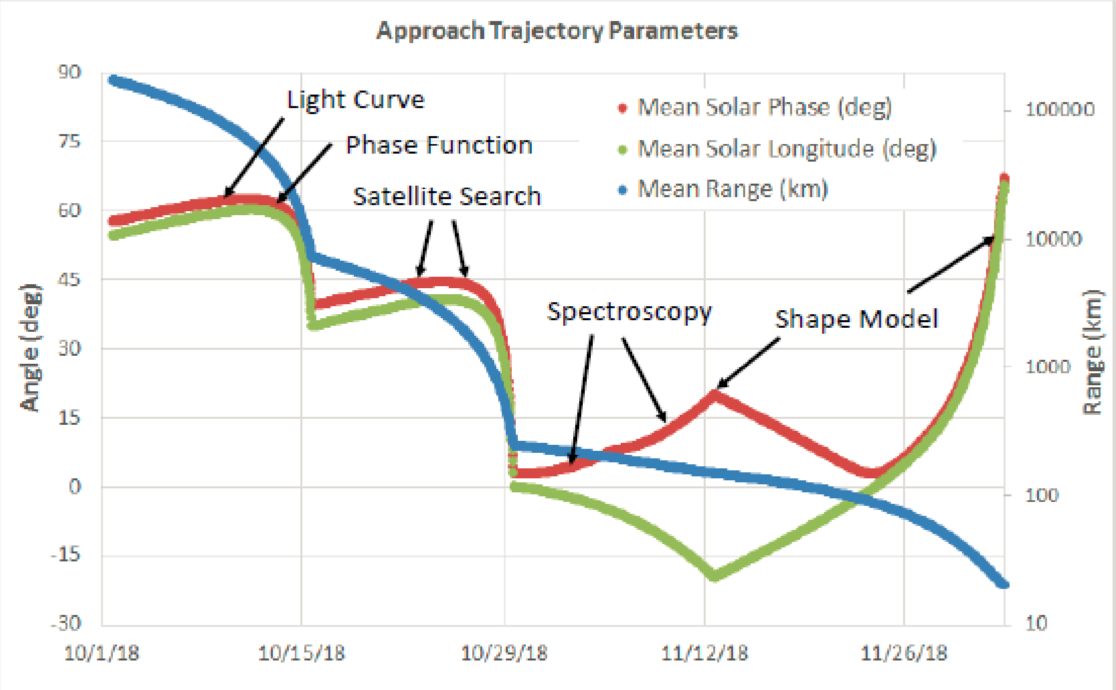


Figure 1.2.1 Timeline of the various observations made during approach. Two plume search observations on 9/11 and 12, and one phase function observation on 9/27 are not shown.

1.3 Inputs

Observation Constraints Spreadsheet:
UA-OPS-4.0-1001_Observation Constraints_Rev 2.0

SPK:
orx_170125_210304_170301_refod015_v1.bsp

The trajectory state error (TSE) files contain the expected navigation uncertainties and are listed below. They will be available on SPOC flight and currently are in the following location on the FOB /orxfob/DocumentLibrary/FDS/TSE/Mission_Plan_RevA/Approach/:

orx_tse_180806_181203_pre-AAM-1_v6.txt
orx_tse_180813_181203_pre-AAM-1_v6.txt
orx_tse_180820_181203_pre-AAM-1_v6.txt
orx_tse_180827_181203_pre-AAM-1_v6.txt
orx_tse_180903_181203_pre-AAM-1_v6.txt
orx_tse_180910_181203_pre-AAM-1_v6.txt
orx_tse_180917_181203_pre-AAM-1_v6.txt
orx_tse_180924_181203_pre-AAM-1_v6.txt
orx_tse_181001_181203_pre-AAM-2_v6.txt
orx_tse_181003_181203_pre-AAM-2_v6.txt
orx_tse_181008_181203_pre-AAM-2_v6.txt
orx_tse_181017_181203_pre-AAM-3_v6.txt
orx_tse_181019_181203_pre-AAM-3_v6.txt
orx_tse_181024_181203_pre-AAM-3_v6.txt
orx_tse_181026_181203_pre-AAM-3_v6.txt
orx_tse_181031_181203_pre-AAM-4_v6.txt
orx_tse_181102_181203_pre-AAM-4_v6.txt
orx_tse_181107_181203_pre-AAM-4_v6.txt
orx_tse_181109_181203_pre-AAM-4_v6.txt
orx_tse_181114_181203_pre-NPF_v6.txt
orx_tse_181116_181203_pre-NPF_v6.txt
orx_tse_181121_181203_post-NPF_v6.txt
orx_tse_181123_181203_post-NPF_v6.txt
orx_tse_181128_181203_post-NPF_v6.txt
orx_tse_181130_181203_post-NPF_v6.txt

The Approach Mission Plan Rev A trajectory dispersions from Monte Carlo analysis were provided by email on February 10, 2017 and are stored on ODOCS: OSIRIS-REx Mission Operations System 7.0\Science Operations Planning Group (NON-US persons access)\Supporting Material\Approach\

Other kernels used for J-Asteroid planning:

LSK = naif0012.tls
PCK = pck00010.tpc
PCK = bennu_v10.tpc
SPK = de424.bsp
SPK = bennu_refdrmc_v1.bsp
FK = orx_v07.tf
IK = orx_navcam_v01.ti
IK = orx_ocams_v06.ti
IK = orx_ola_v00.ti
IK = orx_otes_v00.ti
IK = orx_ovirs_v00.ti
IK = orx_rexis_v00.ti
IK = orx_struct_v00.ti

DSK = RQ36mod.oct12.bds
SCLK = ORX_SCLKSCET.00015.tsc

1.4 Dust Plume Search

Requirement:

MRD-142: OSIRIS-REx shall search for dust and gas plumes originating from the asteroid surface, and characterize their source regions and column densities.

Observation Constraints:

Range to Bennu: 1M km

Area being observed: MapCam - 35000 km around Bennu, PolyCam – 7000 km around Bennu

Apparent Magnitude: >11.9

Signal to Noise Ratio: >5

Observation Plan:

A sequence of images centered on Bennu will be obtained using the OCAMS PolyCam and MapCam imagers. The image sequence will be median co-added on the motion of Bennu to produce a map of the dust near Bennu. Dust will exhibit itself as diffuse features either around Bennu, trailing Bennu in the anti-solar direction, or trailing Bennu along its orbit. Mapping the spatial extent and brightness of the dust will allow an estimate of the size distribution of the dust and the time of its release to be determined. These techniques commonly have been used to detect gas and dust plume activity for active comets.

PolyCam dust plume search images will be obtained on a nominal date of 2018-Sep-11 when Bennu will be at a range of 1.05M km and phase angle of 43°. The MapCam images will be obtained on the following date (2018-Sep-12) when Bennu will be at a range of 1.00M km and phase angle of 44°. On these dates, PolyCam will image a region of Bennu's orbit extending 7300 km leading and trailing Bennu. MapCam will image a region along Bennu's orbit that extends 35,000 km leading and trailing Bennu. Bennu will be V magnitude ~12.0 on these dates. This brightness will allow Bennu to be detected at a S/N of 10 in a 10-second MapCam exposure. It will be close to S/N = 100 in a 10-second PolyCam exposure. The brightness of Bennu is sufficient to allow the images to be 'stacked and tracked' on the position of Bennu to produce a median averaged image for each imager.

The September 11 and 12 dates were chosen because Bennu's apparent position in J2000 celestial coordinates places it in a part of the Milky Way that is relatively less dense in stars. From the beginning of Approach to the time of AAM2 (Oct 15), Bennu will be traversing a very dense part of the Milky Way as seen from the spacecraft. Although none of these dates are optimal, the September 11-12 dates are the best available that also maximize the region of space around Bennu that will be searched for dust. These observations can be obtained during the period of 2018-Sep-1 and 2018-Sep-12. On earlier dates, Bennu will be too faint to co-add in MapCam images. On later dates, the region along the orbit within a single FOV is too small to detect dust released more than days before the observations.

Note, that scattered light may compromise the sensitivity of these observations. An attempt to clock the spacecraft attitude in such a way as to minimize scattered light may be required. The details of these attitude adjustments are pending the conclusion of the OCAMS scattered light analysis which is being conducted during Outbound Cruise and involves ground modeling and in-flight calibration activities. It is possible that the s/c attitude to minimize scattered light conflicts with the requirement to keep the s/c in the Operational Safe Zone (OSZ). The scattered light 'flat field' observations described in the plans below will help mitigate any scattered light in the case that the s/c attitude allows significant scattered light.

Optimal Dates*: 2018-Sep-11 and 12

Possible Dates*: 2018-Sep-1 to Sep-12

*based on the expected dispersions from the nominal trajectory

Plan for September 11, 2018:

Conduct an 8x8 point and stare mosaic with a 93% image overlap along and across track. The center between fields will be only 0.85 mrad apart resulting in slews of 7.8 to 18.8 seconds with most being around 9.3 seconds with the fast slew parameters (ω = 5.00 mrad/sec, α = 0.0582 mrad/sec^2). With a 180 second settle time, the entire 64 field mosaic can be conducted in 3h 32m.

A single 10 second PolyCam image will be taken at each field for a total of 64 images.

Calibrations:

Ten 10-second dark PolyCam exposures will be obtained as soon as possible both before and after the dust survey images are obtained.

OCAMS contingency calibration plan to minimize or eliminate scattered light: After the dust survey images are completed, the PolyCam boresight will be pointed to a position one PolyCam FOV away from Bennu. A 3x3 point and stare mosaic grid will be conducted with a 90% FOV along and across field overlap. Single 10-second exposure will be conducted at each target for a total of 9 images. These fields will be median combined relative to the detector coordinates to produce a "flat field" image to be used to remove any signal from scattered light. With 180 second settle times, this activity will take 25 minutes. Since these observations are not sensitive to spacecraft jitter, one can even argue that the extra jitter would actually help remove the stars in the median combined flat field, no settle time is required. In the case of zero settle time, the flat field activity would take 6-7 minutes.

Plan for September 12, 2018:

Conduct an 8x8 point and stare mosaic with a 98% image overlap along and across track. The center between fields will only be 1.36 mrads apart resulting in slews of 9.8 to 23.8 seconds with most being around 11.7 seconds with the fast slew parameters ($\omega = 5.00$ mrad/sec, $\alpha = 0.0582$ mrad/sec^2). With a 180-second settle time, the entire 64 field mosaic can be conducted in 3h 34m.

A single 10-second MapCam image will be taken at each field for a total of 64 images.

Calibrations:

Ten 10-second dark MapCam exposures will be obtained as soon as possible both before and after the dust survey images are obtained.

OCAMS contingency calibration plan to minimize or eliminate scattered light: After the dust survey images are completed, the MapCam boresight will be pointed to a position one MapCam FOV away from Bennu. A 3x3 point and stare mosaic grid will be conducted with a 90% FOV along and across field overlap. Single 10-second exposure will be conducted at each target for a total of 9 images. These fields will be median combined relative to the detector coordinates to produce a “flat field” image to be used to remove any signal from scattered light. With 180 second settle times, this activity will take 25 minutes. Since these observations are not sensitive to spacecraft jitter, one can even argue that the extra jitter would actually help remove the stars in the median combined flat field, no settle time is required. In the case of zero settle time, the flat field activity would take 6-7 minutes.

Data Products:

The science data product associated with MRD-142 is a Dust Plume Image (AP-18). AP-18 is a FITS file produced by the Astronomy Working Group (APWG) using OCAMS instrument data. AP-18 is delivered during Approach and is used for operational purposes and is an input to the Science Value map.

The observations will also be used for Asteroid Phase Function products.

1.5 Bennu Light Curve

Requirements:

MRD-157 Produce four light curves of Bennu by measuring the variation in its irradiance over two rotation periods to within ≤ 3% relative brightness in four distinct wavelength regions that can be compared with observations of one or more recognized ECAS standard stars in the b, v, w, and x ECAS filters

Observation Constraints:

Range to Bennu: 50,000 – 6,000 km

MapCam filters: b, v, w, x

Number of images: 576 images per rotation

Rotational sampling frequency: every ~1˚ (v-filter), every ~5˚ (b, w, & x-filters)

Apparent Magnitude: ~9

Signal to Noise Ratio: ~33

Phase Angle Range: 0 - 70˚

Observation Plan:

Bennu will be continuously observed over a full rotation period on two dates (~4.5 hrs per date, ~9.0 hrs total). The two rotation periods do not need to be consecutive and a higher precision rotation period determination is possible if the two rotation periods are separated by 1-2 days. It is recommended that Bennu be observed during two Bennu rotations with each rotation observed on separate consecutive dates. One v filter image will be taken every ~1-degree of asteroid longitude (1 images per ~43 sec). ECAS b, w, and x filter images will be interspersed between the v images in the following cadence: v – v – v – v – w – x – b – repeat.

Timing of these observations is constrained to a period when the phase angle is not changing (or is changing very slowly). On 2018-Oct-11 and 12, the nominal phase angle only varies from 62.4 to 62.2 degrees. The 1-sigma Monte Carlo trajectory dispersions show phase angles of 60 to 64 degrees are possible. The brightness of Bennu (V=6.0 to 6.5) allows S/N >100 to be obtained in 10 second MapCam exposures for all filters except for the ECAS b filter (S/N>30, or 3% relative photometry). Observations taken Oct-13 and Oct-14 will also fulfill the above constraints though the Oct-11/12 dates are optimal.

These data will also be used to support the Asteroid Phase Function data product.

Optimal Dates*: 2018-Oct-11 and 12

Possible Dates*: 2018-Oct-11 to Oct-14

*based on the expected dispersions from the nominal trajectory

Plan for each date (October 11 and 12):

Observation type to be used is nadir point for 4.5-hours (4.3 hour rotation period plus 0.2 hours of overlap).

Total number of MapCam images is 376 images in v (1 image per ~1° of rotation), 75 images in b (1 image per ~5° of rotation), 75 images in w (1 image per ~5° of rotation), 75 images in x (1 image per ~5° of rotation) and 20 dark images for a total of 621 images.

Cadence of filter images: v – v – v – v – w – x – b – repeat.

Calibrations:

Ten 10-second dark MapCam exposures will be obtained as soon as possible both before and after the light curve images are obtained.

Data Products:

There are three science data products associated with MRD-157: Bennu Photometry (AP-4), Temporal and Phased Light Curve Parameters (AP-12), and Light Curve Parameters (AP-13). All three products are ASCII tables to be produced by the Astronomy Working Group (APWG) using Approach OCAMS instrument data and are inputs MRD-158 science data products. These products are delivered during Approach.

The observations will also be used for Asteroid Phase Function products.

Operational Considerations:

The observation type and cadence of images are identical for both dates of the Bennu Light Curve observations.

1.6 Bennu Phase Function

Requirements:

MRD-158: Produce four phase functions of Bennu by measuring the variation in its irradiance over a minimum of ten degrees change in phase angle, to within ≤ 3% relative brightness in four distinct wavelength regions that can be compared with observations of one or more recognized ECAS standard stars in the b, v, w, and x ECAS filters.

There is an outstanding lien that is addressed in this plan.

> *Lien-APWG-2 - The DRM Rev C plan to obtain phase function photometry was scheduled for a time when the phase angle was rapidly changing. At the time the lien was written, these observations were not possible due to their proximity to the AAM3 maneuver (no science observations within ~24 hours of the maneuver). As a result, only the Bennu light-curve observations were available for disk-integrated phase function photometry resulting in a range of phase angles observed of <1 degree and not the >10 degrees specified in MRD-158. Additional Bennu light-curve observations opportunities to increase the phase angle coverage during the Approach phase have been identified on ~~2018 August 25~~ at 30 degrees phase angle, ~~2018 September 7~~ at 40 degrees, ~~2018 September 20~~ at 50 degrees, ~~2018 October 24~~ at 54 degrees, ~~2018 November 1~~ at 0.5 degrees and ~~2018 November 8~~ at 2 degrees (note, the lined out dates are obsolete since they were based on the trajectory for DRM Rev C).These observations will fulfill MRD-158 by obtaining phase function photometry over a 62-deg span of phase angle (compared with the >10 degrees specified in MRD-158). A request has been made to the SOPG on behalf of the APWG and the Photometric Modeling WG to plan these additional Bennu observations which will also support MRD-149 and part of Lien-PhoMod-1.*

Although the observation dates and details of implementation for increased phase angle coverage have changed since the lien was written, this plan satisfies the request.

Observation Constraints:

MapCam filters: b, v, w, x

Rotational sampling frequency: every ~1˚ (v), every ~5˚ (b, w, & x-filters)

Apparent Magnitude: ~9

Signal to Noise Ratio: ~33

Range to Bennu for window 1: 200,000 – 400

Phase angle range: 0-50 (high as possible desired)

Change in phase over observation period: ~10˚ +/- 5˚

Range to Bennu for window 2: ~6,000

Phase angle range: 0-1˚

Range to Bennu for window 3: ~6,000

Phase angle range: 1-5˚

Observation Plan:

Disk-integrated Phase Function Photometry observations consist of different activities to ensure that the phase function of Bennu is properly determined at a number of phase angles. Full Rotation Phase Function observations will take place on two separate dates when the phase angle is between 52 and 55 degrees and again between 20 and 50 degrees. Daily Phase Function observations will take place when the spacecraft is targeting Bennu for OpNavs between Oct-02 and Nov-09. The combination of these observations (and the Bennu Light Curve observations) fulfill Lien-APWG-2 by providing rotationally resolved photometry in five filters at ~62, ~52 and ~32 degrees and non-rotationally resolved photometry in five filters for 39 points between phase angles of 0 and 62 degrees.

1. Full Rotation Phase Function observations

Bennu will be continuously observed over a full rotation period on two dates (~4.5 hrs per date, ~9.0 hrs total). The two rotation periods do not need to be consecutive and a higher precision rotation period determination is possible if the two rotation periods are separated by 1-2 days. It is recommended that Bennu be observed during two Bennu rotations with each rotation observed on separate consecutive dates. One v filter image will be taken every ~1-degree of asteroid longitude (1 images per ~43 sec). ECAS b, w, and x filter images will be interspersed between the v images in the following cadence: v – v – v – v – w – x – b – repeat.

Timing of these observations is constrained to periods when the phase angles are between 52 and 55 degrees and again when between 20 and 50 degrees based on 1-sigma dispersions to the nominal trajectory.

Optimal Dates*: 2018-Sep-27 and Oct-16

Possible Dates*: 2018-Sep-24 to Sep-29 and Oct-16 to Oct-20 *based on the expected dispersions from the nominal trajectory

Observation type to be used is nadir point for 4.5-hours (4.3-hour rotation period plus 0.2 hours of overlap).

Total number of MapCam images is 376 images in v (1 image per ~1° of rotation), 75 images in b (1 image per ~5° of rotation), 75 images in w (1 image per ~5° of rotation), 75 images in x (1 image per ~5° of rotation) and 20 dark images for a total of 621 images.

Cadence of filter images: v – v – v – v – w – x – b – repeat.

Calibrations:

Ten 10-second dark MapCam exposures will be obtained as soon as possible both before and after the phase function observations are obtained.

2. Daily Phase Function observations

These phase function observations will be taken on a daily basis and will use OpNav targeting of Bennu. The observations will begin on 2018-Oct-02 and continue through 2018-Nov-09. After the daily OpNav observations are complete, MapCam will be used to image Bennu with the following cadence of filters: single pan image – single b image – single v image – single w image – single x image. The exposure times will vary depending on the brightness of Bennu and will be set to provide a S/N of ~100. Based on the expected brightness of Bennu throughout the Approach phase, the exposure times will need to be changed once per week in order to ensure a SN of ~100 and prevent saturation of Bennu in the images. Individual images are to be obtained in succession as quickly as possible in order to minimize photometric variations due to the rotation of Bennu. The daily images will cover a phase angle range from 62 to nearly 0 degrees.

Total number of MapCam images per day is 1 image in panchromatic, 1 image in b, 1 image in v, 1 image in w, 1 image in x, and 4 dark images for a total of 9 images.

Calibrations:

Two dark MapCam exposures will be obtained as soon as possible both before and after the phase function observations are obtained.

Data Products:

There are three science data products associated with MRD-158: Phase Function Photometry and Models (AP-14), Phase Function Model Parameters (AP-15) and Bennu Point Spread Function (AP-19). All three of these products are ASCII tables produced by the Astronomy Working Group (APWG), derived from Approach OCAMS instrument data and MRD-157 science data products. These products are all delivered during Approach and contribute to characterizing Bennu as a point source as well as aid in the identification of dust/gas plumes originating from Bennu’s surface.

In addition, these phase functions will contribute to achieving the accuracy and precision goals for the Global MapCam Photometric Model data products (IP-13) that are necessary to close out MRD-149a-c and build the global imaging mosaics. IP-13 includes 6 different photometric models: one for each MapCam filter (panchromatic, b, v, w, & x) and a PolyCam photometric model. The MapCam panchromatic photometric model is planned to be used in lieu of the PolyCam photometric model, as currently planned there is not enough phase angle coverage to provide a high-fidelity PolyCam photometric model. The PolyCam photometric model is therefore "best effort" and not required. The MapCam panchromatic photometric model is required and is planned to be used to photometrically correct global and local PolyCam image mosaics (IP-4 & IP-9). These photometrically corrected image mosaics will be used as the basemaps for viewing virtually all other acquired data. The MapCam color photometric models will be used to photometrically correct the global and local MapCam color-ratio and true-color maps (IP-20 & IP-21), which feed into the Science Value Maps. In addition, the MapCam x-band photometric model is of particular importance as it will be used to photometrically correct MapCam x-band image mosaics (IP-7 & IP-8) which in combination with the OVIRS Color Ratio Map (SA-43) will inform the Safety Map and ensure that the surface that will be observed with LIDAR to determine range to surface is within the range of reflectance values in which LIDAR is designed to operate. All IP-13 products are FITS files and will not be delivered until after Equatorial Stations as Equatorial Stations data is required to constrain the disk function.

Lien-PhoMod-1 is a lien on the DRM to provide the phase angle coverage of Bennu that is sufficient to predict the phase-angle dependency on surface brightness during a moderate phase-angle (30 to 70 degrees) TAG timeline. Currently, our modeling simulations of the DRM Rev-C show that insufficient data are obtained between 55 and 75 degrees phase angle, making predictions of surface brightness in this phase angle range uncertain. Hence, the plans described in this Approach Phase Plan address that concern and contributes to closing Lien-PhoMod-1.

1.7 Natural Satellite Search

Requirements:

MRD-144: OSIRIS-REx shall detect with > 95% confidence natural satellites > 10cm diameter with albedo > 0.03.

There is an outstanding lien that is partially addressed in this plan.

> *Lien-APWG-1: The Approach Phase is the only mission phase where these data can be acquired. To mitigate the risk of operational issues during this time period, a request has been made to the SOPG to conduct both search campaigns in their entirety over the course of three consecutive dates to reduce the risk of losing any single date's data due to spacecraft, instrument or environmental (Coronal Mass Ejections) issues.*

Although the plan for mitigating the risk of operational issues has changed since the lien was written, this plan partially satisfies the request.

Observation Constraints:

For MapCam:
1-m satellites:
36-km radius coverage area; Range < 4,000 km for phase angle < 50˚
36-km radius coverage area; Range < 4,700 km for phase angle < 40˚
36-km radius coverage area; Range < 5,700 km for phase angle < 30˚
36-km radius coverage area; Range < 6,800 km for phase angle < 20˚
36-km radius coverage area; Range < 8,200 km for phase angle < 10˚
36-km radius coverage area; Range < 10,000 km for phase angle < 0˚
Mosaics covering the required area are imaged 5 times in 5 hours
Image overlap = >5%

10-cm satellites:
20-km radius coverage area; Range < 400 km for phase angle < 50˚
20-km radius coverage area; Range < 480 km for phase angle < 40˚
20-km radius coverage area; Range < 570 km for phase angle < 30˚
20-km radius coverage area; Range < 680 km for phase angle < 20˚
20-km radius coverage area; Range < 820 km for phase angle < 10˚
20-km radius coverage area; Range < 1,000 km for phase angle < 0˚
Mosaics covering the required area are imaged 5 times in 5 hours
Image overlap = >5%

For PolyCam:
1-m satellites:
36-km radius coverage area; Range < 15,000 km for phase angle < 50˚
36-km radius coverage area; Range < 18,000 km for phase angle < 40˚
36-km radius coverage area; Range < 22,000 km for phase angle < 30˚
36-km radius coverage area; Range < 27,000 km for phase angle < 20˚
36-km radius coverage area; Range < 32,000 km for phase angle < 10˚
36-km radius coverage area; Range < 38,000 km for phase angle < 0˚
Mosaics covering the required area are imaged 5 times in 5 hours
Image overlap = >5%

10-cm satellites:
20-km radius coverage area; Range < 1,540 km for phase angle < 50˚
20-km radius coverage area; Range < 1,850 km for phase angle < 40˚
20-km radius coverage area; Range < 2,230 km for phase angle < 30˚
20-km radius coverage area; Range < 2,680 km for phase angle < 20˚
20-km radius coverage area; Range < 3,200 km for phase angle < 10˚
20-km radius coverage area; Range < 3,800 km for phase angle < 0˚
Mosaics covering the required area are imaged 5 times in 5 hours
Image overlap = >5%

Observation Plan:

The natural satellite search will use PolyCam to search for possible natural satellites orbiting Bennu. In DRM Rev C, MapCam was to be used for the natural satellite search. Radiometric analysis of Outbound Cruise OCAMS images show that MapCam can detect a visual magnitude (V) of 13.8 satellite in a 30-second exposure with a S/N of 2 and PolyCam can detect a V of 16.8 satellite in a 30-second exposure with a S/N of 2. Due to the enhanced sensitivity of PolyCam, the satellite search will be conducted with PolyCam. The search will be conducted prior to AAM3 on Oct. 24, 25, 27, and 28.

Initially the search is over an area of 36 km radius looking for 1-m or larger sized satellites; later, as we get closer and satellites get brighter, the search is looking for 10-cm sized satellites over an area of >16 km radius. Five sets of images are taken over a 5-hour period so that satellites can be detected by apparent motion relative to the star background. Images are taken on four days to permit long arc tracking of any possible identified satellites. As we approach Bennu, the PolyCam field of view (FOV) gets smaller in terms of area of the sky around Bennu. The mosaics are made with >5% image overlap, which exceeds the observation constraint. A 3-σ threshold is set on the targeting uncertainties. The observations are also based on the expected 2-sigma dispersions from the nominal trajectory.

The observation type used for the satellite searches is a point and stare mosaic with respect to the updated trajectory. We take six 10-second exposures at each field. The exposure durations are limited to no greater than 10-seconds to reduce random telegraph signal noise in the images. Co-addition of the six 10-second exposures allow the images to detect objects equal to or fainter than possible with a single 30-second exposure (resulting in a limiting magnitude of V = 16.7 or fainter). The slews use fast slew rates (ω = 5.00 mrad/sec, α = 0.0582 mrad/sec^2) and settle times of 180 seconds for slews from target to target.

An additional 'short' exposure of 1-second or less are taken before the search, after the search and in the Bennu-centered mosaic fields. These seven short exposures provide unsaturated images of Bennu and allow the relative offsets between Bennu and any satellites to be determined. In other words, we need to know where Bennu is during the search to determine the orbit of a satellite.

A summary of the plan:

- 1x1 point and stare mosaic centered on Bennu – single short exposure
- 3x3 point and stare mosaics repeated 5 times covering the region around Bennu – 6 10-sec exposures for each field, the center field of the mosaic will also contain an additional short exposure
- 1x1 point and stare mosaic centered on Bennu – single short exposure

Four observation days are proposed for the natural satellite search observations. The reason for different days is both to guard against losing a day due to a solar flare, coronal mass ejection, or some instrument or spacecraft issue, and also to allow for a longer arc to help determine the orbital parameters of any identified natural satellites. Obviously if we find any satellites, we need to determine their orbits with enough precision to ensure we can accommodate their being in the environment. The plan presented below will allow detection of 1-m satellites within 36 km of Bennu over 2 consecutive days (days 1 and 2) and the detection of 15-cm satellites within 20 km of Bennu on day 3 and 10-cm satellites within 16 km on day 4.

The search begins on 2018 Oct 24 with four days of observations looking for satellites down to 10 cm in size or smaller (Table 1.7.1). On Oct 24 and 25 a mosaic of 3x3 PolyCam FOVs can image the entire Hill Sphere of Bennu (36 km). Due to decreasing distance to Bennu, a 3x3 PolyCam mosaic on Oct 27 can only observe the region within 20 km of Bennu. A 3x3 PolyCam mosaic on Oct 28 can only observe the region within 16 km of Bennu. It is proposed that a 3x3 PolyCam mosaic be used on all four days of natural satellite search to simplify planning and implementation of the observations. This will result in a larger region around Bennu being searched on Oct 24 (day 1) when a smaller 2x2 PolyCam FOV would suffice to image the Hill Sphere.

Table 1.7.1 Observation parameters for natural satellite search.

Observation date and time	**10/24/18**	**10/25/18**	**10/27/18**	**10/28/18**
TSE file	10/19	10/19	10/19	10/24
Range (km)***	2700	2300	1400	960
Dimensions of mosaic	3x3	3x3	3x3	3x3
Phase angle (deg)***	37	38	37	34
Smallest detectable satellite (cm)**	33	27	15	9
Radius from Bennu imaged (km)	36	36	20	16
Number of images per field	6	6	6	6
Number of fields per mosaic	9	9	9	9
Number of mosaics per day	5	5	5	5
Number of images per day*	307	307	307	307

*Includes 30 dark images per day and 7 short exposures of Bennu to determine the position of Bennu relative to satellites.
**Size of smallest detectable satellite is valid for a limiting magnitude of V = 16.7 and satellite with an albedo of 0.03. Size is valid for the worst case 2-sigma dispersion of the Approach trajectory as contained in the Monte Carlo analysis.
***Ranges and phase angles are for the nominal trajectory.

Calibrations:

Ten 10-second and five 1-second dark PolyCam exposures will be obtained as soon as possible both before and after the natural satellite search images are obtained. Number of images per day as shown in Table 1.7.1 includes these calibrations.

Data Products

There are three science data products associated with MRD-144: Astrometry of Confirmed Satellites (AP-8), Photometry of Confirmed Satellites (AP-9), and Map of Region around Bennu with faint detectable satellites (AP-11). AP-8 and AP-9 are ASCII tables. AP-11 is a PNG file. All three science data products are produced and delivered during Approach using Approach OCAMS instrument data. In the event of positive satellite detection, they are inputs to the Radio Science Working Group (RSWG) science data product called Natural Satellite Ephemerides (RS-010).

Operational Considerations:
In order to image the volume of space within 36 km of Bennu on Oct. 24 and 25, within 20 km of Bennu on Oct 27, and within 16 km of Bennu on Oct 28, mosaics with dimensions of 2x2, 3x3, 3x3 and 3x3 are required for each respective date. To simplify operations, a mosaic of 3x3 will be utilized on all four dates. As a result, the same sequences can be used on all four dates.

Late updates (planning with respect to an updated trajectory) will be required using the TSE files as indicated in Table 1.7.1.

The nominal fast slews (ω = 5.00 mrad/sec, α = 0.0582 mrad/sec2) and 180 second settle time will be used for these observations.

1.8 Full-Disk Integrated Spectroscopy

Requirements:

MRD-159: OSIRIS-REx shall measure the integrated spectral properties of Bennu over one rotation period to detect spectral features listed in MRD-159 Table (Absorption Features of Key Mineralogical & Organic Molecules) with > 5% absorption depth.

MRS-544: OSIRIS-REx shall, for one Bennu rotation period, measure the integrated absolute flux of thermally emitted radiation with < 3% accuracy and derive the thermal inertia of Bennu.

Observation Constraints:

Along-track overlap of spectra: 50%

Rotational sampling: 10°

Solar local hour: afternoon (OTES only)

Signal/noise (SNR): >50 (OVIRS), > 320 (OTES)

Phase angle: 2-15° (OVIRS), 0-15° (OTES)

Range to Bennu: 125-500 km (OVIRS), 62.5-250 km (OTES)

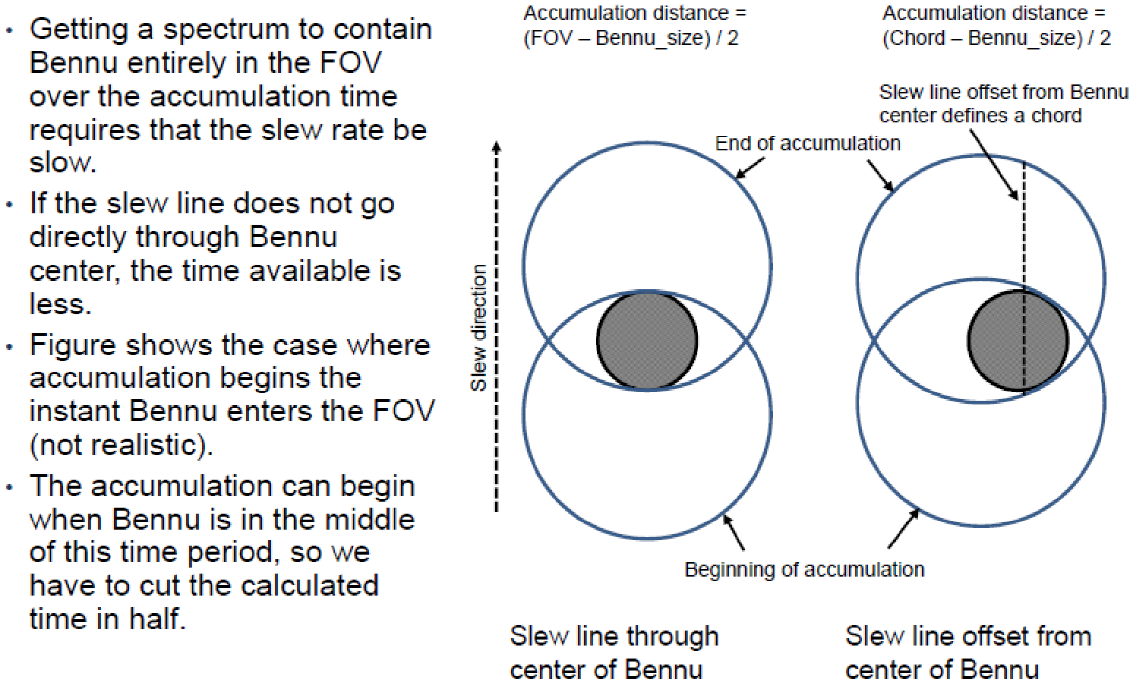
Observation Plan:

To get a full-disk integrated spectrum, it is necessary for the disk of Bennu to be fully in the FOV of the instruments for the integration time of the spectrum (0.91 sec for OVIRS; 2.0 sec for OTES). Because Bennu will not fill the instrument FOV, several spectra will need to be co-added to get adequate signal. The smaller Bennu is, the easier it is to keep it in the instrument FOV, but the more spectra will need to be co-added. To give some margin on the FOV, we use 3.6 mrad vs. 4.0 mrad for OVIRS and 6.5 mrad vs. 8.0 mrad for OTES. In some cases (for OTES) the targeting uncertainties are small enough that we can point at Bennu and have confidence that at the 2-σ level, Bennu will remain in the FOV. In the cases for OVIRS, we scan a very small area around Bennu but scan slowly enough that we can have confidence that at least several of the slews will pass over Bennu such that it will remain in the FOV for at least several full integration times. To help ensure that the slew rate is slow, we use a slower than normal slew acceleration rate of 0.0126 mrad/sec^2.The FOV of OTES is about twice that of OVIRS, so the early observations are optimized for OVIRS before Bennu becomes too large to fit in the OVIRS FOV. After that, the later observations are optimized for OTES. Both instruments will be operated in all of the observation activities.

Unlike most observations of Bennu, where we simply have to cover an area large enough to account for uncertainties in the location of Bennu relative to the spacecraft, here the situation is more complicated. In addition to covering the necessary area, we have to also ensure that Bennu is entirely within the FOV of the spectrometers, and that it stays in the FOV throughout an entire spectral accumulation interval. Because the FOV is not much larger than Bennu itself, when we scan the area of interest, we cannot slew at too rapid a rate, or the FOV may pass over Bennu before a full accumulation time.

In the cases for OVIRS, where we do have to scan, the scans take less time than the time it takes for Bennu to rotate 10° (430 seconds). After the scan is complete, we slew to the nominal location of Bennu with the presumption that there is some probability that Bennu will be in the FOV for the remainder of the 10° rotation. The scans are limited to six slew lines with two additional slews, at the beginning and end of the scans, to leave and return to the nominal Bennu location. Thus we need 8 slews for each of 36 observation sets for a total of 288 slews. We have a limit of 300 slews in the Absolute Target List (ATL) file, and thus we stay within this limit.

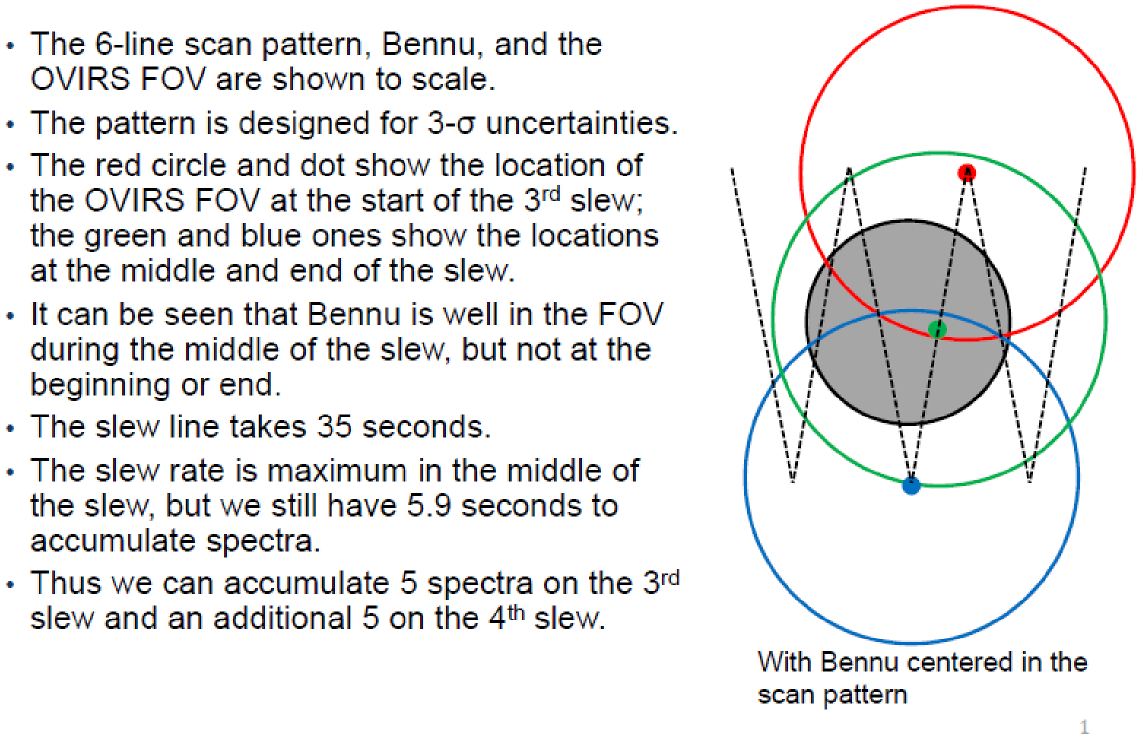
It is difficult to calculate with certainty the time that Bennu will be entirely within an instrument's FOV. If the slew line takes Bennu close to the center of the FOV, knowing the slew rate, it is easy to calculate the time Bennu will remain entirely in the FOV. Due to targeting uncertainties, however, Bennu may not pass through the center of the FOV but will be along some chord smaller than the FOV diameter. The more closely spaced are the slew lines, the more likely the chord will be close to the diameter of the FOV. This concept is illustrated in figure 1.8.1.



- Getting a spectrum to contain Bennu entirely in the FOV over the accumulation time requires that the slew rate be slow.
- If the slew line does not go directly through Bennu center, the time available is less.
- Figure shows the case where accumulation begins the instant Bennu enters the FOV (not realistic).
- The accumulation can begin when Bennu is in the middle of this time period, so we have to cut the calculated time in half.

Figure 1.8.1. Diagram showing the need to account for the slew line not going directly through the instrument FOV.

Normally when we scan an area for imaging, we use a raster scan where we image along one slew line and then at the end, we slew to the next line, which is generally spaced by 80% of the image size. With these point-source spectrometers, we do not need to take the time to transfer between scan lines, so we use a zig-zag pattern rather than an X-Y raster scan. An example of the scan pattern is shown in figure 1.8.2, where the scan sweeps from right to left over the nominal location of Bennu.



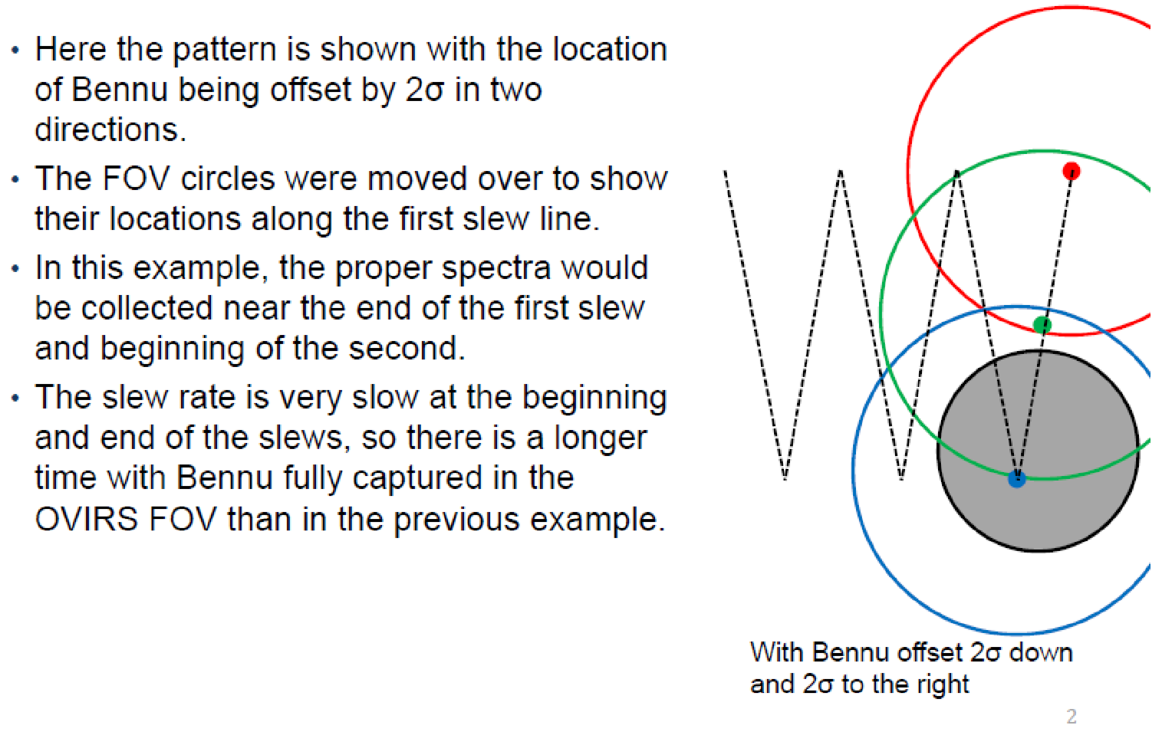
- The 6-line scan pattern, Bennu, and the OVIRS FOV are shown to scale.
- The pattern is designed for 3-σ uncertainties.
- The red circle and dot show the location of the OVIRS FOV at the start of the 3rd slew; the green and blue ones show the locations at the middle and end of the slew.
- It can be seen that Bennu is well in the FOV during the middle of the slew, but not at the beginning or end.
- The slew line takes 35 seconds.
- The slew rate is maximum in the middle of the slew, but we still have 5.9 seconds to accumulate spectra.
- Thus we can accumulate 5 spectra on the 3rd slew and an additional 5 on the 4th slew.

With Bennu centered in the scan pattern

1

Figure 1.8.2. Diagram showing the scan pattern planned for OVIRS on 11/02/2018.

Because the slews reach their maximum rate in the middle of the slews, the time available to get complete spectra is a minimum there. Figure 1.8.3 shows an example of the same scan pattern but considers the case where Bennu is located far from its expected position. In the former case Bennu is captured near the middle of the third and fourth slews, whereas in this case Bennu is captured toward the end of the first slew and beginning of the second.



- Here the pattern is shown with the location of Bennu being offset by 2σ in two directions.
- The FOV circles were moved over to show their locations along the first slew line.
- In this example, the proper spectra would be collected near the end of the first slew and beginning of the second.
- The slew rate is very slow at the beginning and end of the slews, so there is a longer time with Bennu fully captured in the OVIRS FOV than in the previous example.

With Bennu offset 2σ down and 2σ to the right

Figure 1.8.3. Diagram showing the scan pattern planned for OVIRS on 11/02/2018 with an assumed navigational offset of 2σ in both X and Y directions.

The characteristics of the data collection are shown in table 1.8.1. For the two OVIRS-optimized collection activities, the scan pattern is designed to accommodate 3-σ navigational uncertainties. We plan for this level of uncertainty because both activities are based on the same orbit determination (TSE file of 10/31); if the orbit determination is off by more than 3σ it will be off by that amount for both activities. In the case of the OTES-optimized activities, the FOV is large enough that both can be operated in a nadir-dwell mode without a scan pattern being needed at 2σ confidence.

In addition to collecting data with the spectrometers, we will collect a single PolyCam image at every 10 degrees of rotation. Doing so will help in calibrating any pointing offsets between the spectrometers and PolyCam. In addition, the images may be helpful in generating the shape model of Bennu as noted in the next section.

Table 1.8.1 Observation parameters for spectroscopy activities.

Optimized for	OVIRS	OVIRS	OTES	OTES
Observation date	11/2/2018	11/3/2018	11/5/2018	11/9/2018
TSE date	10/31/2018	10/31/2018	11/2/2018	11/7/2018
Solar Longitude (deg)	0.0	0.0	-5.6	-12.2
Sigma Solar Longtude (deg)	2.7	3.2	4.5	2.3
Phase angle (deg)	3.9	4.8	7.9	12.7
Sigma phase angle (deg)	2.1	2.5	3.9	2.3
Range (km)	224.5	217.2	198.3	169.3
Size of Bennu (mrad)	2.2	2.3	2.5	2.9
Fraction of full FOV (area)	30%	32%	15%	20%
Width to scan (mrad)	2.9	3.6	Operated in Nadir-Point mode. No scans necessary.	
Spacing between scan lines (mrad)	0.6	0.7		
Chord length at half scan-line spacing (mrad)	3.6	3.5		
Accumulation distance (mrad)	1.4	1.3		
Time to traverse this length at fastest slew rate (s)	6.50	5.37		
Minimum number of spectra that can be accumulated	12	8		
Rotation of Bennu during scan time (deg)	5.94	6.64		

All of the OVIRS constraints are met with this plan, but the phase angle does not exceed the >2° constraint at the 1-σ level. The observation constraint on afternoon local time observations of Bennu are not met, but the OTES team notes that the SNR constraint can be met with morning observations.

Discussion

The calculations above consider both pointing and navigation uncertainties without slewing. The precision with which the spacecraft can control the pointing during the first 15 to 20 seconds of a slew, which is the relevant timescale for these observations, is not well known. In calculating the time available with Bennu completely in the FOV of OVIRS, we assumed the slews are in a straight line as programmed, but we know the slew can wander a bit away from a straight line. If the wander is large enough, it could move Bennu into and out of the FOV as the slew proceeds. We are hopeful that after generating performance data during cruise (SOCR 17: Pointing stability and slew precision), we will have more confidence in the ability of this plan to generate the necessary data.

We show four days of data collection (two optimized for OVIRS and two optimized for OTES), which is more than what is needed to satisfy the science requirement. Having an additional day for each instrument is prudent since it would be very time consuming to return to this distance from Bennu to repeat the observations if they were missed for some reason.

Data Products

There are two science data products associated with MRD-159: OTES Rotationally Resolved Spot Mineral/Chemical Abundance (SA-23) and OVIRS Rotationally Resolved Mineral/Chemical Parameter Strength (SA-31). SA-23 is an HDF file and SA-31 is FITS file. Both data products are produced by the Spectral Analysis Working Group using

OVIRS and OTES instrument data collected during Approach. Both products are delivered during Approach.

There is one science data product associated with MRD-544: Rotationally Resolved Thermal Inertia (TA-008). TA-008 is a text file and will be produced by the Thermal Analysis Working Group (TAWG) using OTES instrument data collected during Approach. TA-008 can be delivered during Approach, but is a long-term science product that will mainly be used for ground-based follow-up activities and other long-term science projects.

Operational Considerations

As an operational simplification, we will plan both of the OVIRS-optimized activities with the same zig-zag scan pattern. The larger scan pattern of the 11/3 day will also work for 11/2 and provides additional margin against navigational uncertainties. On the other hand the larger scan pattern has a larger spacing between slew lines which makes the scan more susceptible to problems with slews wandering off the planned line. Depending on what is learned about slew accuracy during cruise (SOCR 17: Pointing stability and slew precision), we may have to re-visit trades between navigational uncertainty and slewing uncertainty.

The slew used is a slow slew with 1.35 mrad/s slew rate limit and 0.0126 mrad/s^2 acceleration though we never get close to reaching the maximum slew rate. Each OVIRS scan pattern takes about 270 sec, repeats every 430 sec (10° of rotation), and has 8 slews for a total of 288 slews with 36 repeats. Both of the OVIRS-optimized activities are planned with respect to an updated trajectory (10/31 TSE file), and they are designed around a 3σ targeting (combined navigation and pointing) uncertainty. The OTES-optimized days are planned as nadir point, using the TSE file dates as indicated in Table 1.8.1 for ephemeris updates. Ten PolyCam dark images are taken on each day's activity at a time TBD in addition to the one PolyCam image taken every 430 sec. The OVIRS accumulation time is 0.91 sec/spectrum, and for OTES it is 2.0 sec/spectrum.

An OVIRS solar calibration is scheduled to take place on 11/9 shortly after the Full-Disk Integrated Spectroscopy observations. This observation must be scheduled after the OVIRS science observations are complete. The observation times for all four activities are scheduled for 05:00 on the days indicated.

1.9 PolyCam Imaging for Shape Model

Requirements:

MRD-124: Shapemodel Center of Figure. OSIRIS-REx shall produce a > 1 million vector shape model.

MRD-125: OSIRIS-REx shall designate a prime meridian using a distinctive surface feature and define the coordinate system for Bennu.

MRD-127: OSIRIS-REx shall determine the rotation pole (right ascension, declination, and obliquity) of Bennu relative to J2000 to within 1° in each parameter.

MRD-128: OSIRIS-REx shall determine the amount of wobble in the rotation pole of Bennu to within 1°.

MRD-129: OSIRIS-REx shall measure the rotation period of Bennu to within 10 seconds.

MRD-678: The Ground System shall, for >80% of the asteroid surface, produce a set of DTMs at < 0.75 m in ground sample distance (sample resolution). Note: ground sample distance is defined as the sample spacing of the surface in m/pixel.

Observation Constraints:

Image Bennu every 20° of rotation (10° desired) with the following constraints

10:40 ± 0:30 local time and <3-m pixel size

12:00 ± 0:30 local time and <2-m pixel size

13:20 ± 0:30 local time and <1-m pixel size

14:40 ± 0:30 local time and <0.5-m pixel size

20% overlap between images and scan lines

Observation Plan:

Initially the range to Bennu is large enough that a single nadir-point PolyCam frame is sufficient to image Bennu within >3-σ navigational uncertainties. The observational plan is to point nadir and take 36 images, one at every 10° of rotation (430 seconds). The observation parameters are given in table 1.9.1 for the activities that can be accomplished with nadir pointing. In addition to the activities noted in the table, PolyCam images, taken every 10° of rotation to support the spectroscopy observations, (section 1.8) are also useful in developing the shape model of Bennu. These observations also give a longer arc of data (out to 11/25/2018) over which to assess the pole direction and rotation rate. These first data will provide the key information on the pole that will be supplied to the Flight Dynamics System (FDS).

The 11/12/2018 observation activity meets the 10:40 local time of day constraint, and the following ones are redundant and serve as backup. The last two observations bracket the 12:00 local time constraint, and the pixel-size constraints are also satisfied.

Table 1.9.1 Observation parameters for early PolyCam shape-model images.

Observation date	11/12/2018	11/13/2018	11/16/2018	11/19/2018	11/23/2018	11/25/2018
TSE file date	11/9/2018	11/9/2018	11/14/2018	11/16/2018	11/21/2018	11/23/2018
Solar Longitude (deg)	-19.1	-18.8	-13.8	-8.7	-1.1	3.4
Sigma Solar Longitude (deg)	0.4	0.3	0.3	0.4	0.7	1.0
Equivalent local time	10:43	10:44	11:04	11:25	11:55	12:13
Solar Latitude (deg)	0.0	0.1	0.6	1.2	2.4	3.3
Sigma Solar Latitude (deg)	0.4	0.3	0.4	0.5	0.8	1.1
Phase angle (deg)	19.1	18.8	13.8	8.8	2.6	4.7
Range (km)	151.8	147.4	134.9	119.7	95.0	80.6
PolyCam FOV (m)	2094	2034	1862	1652	1311	1113
PolyCam pixel size (m)	2.0	2.0	1.8	1.6	1.3	1.1
Total number of images	36	36	36	36	36	36

Later in Approach, the FOV of PolyCam is small enough that we will have to generate a mosaic of images to cover the area defined by the navigational uncertainties. The plans are all generated with the 20% image-overlap constraint and with a slew rate limit of 1.35 mrad/s. Unlike the point and stare observations used for the natural satellite search, here we take images during the slew with an X-Y raster scan. The 1.35 mrad/s slew rate is set by using a 10 msec exposure time and allowing for 1-pixel blurring. The area to image is covered with a raster scan consisting of long slews with imaging and short non-imaging slews being used to traverse between lines. Most of the scans accommodate navigational uncertainties at the 3-σ level or greater.

Table 1.9.2 Observation parameters for late PolyCam shape-model images.

Observation date	11/27/2018	11/29/2018	12/1/2018	12/2/2018
TSE file date	11/23/2018	11/23/2018	11/28/2018	11/28/2018
Solar Longitude (deg)	9.0	17.1	33.0	48.9
Sigma Solar Longitude (deg)	1.4	2.3	3.7	3.4
Equivalent local time	12:36	13:08	14:12	15:15
Sigma local time	0:05	0:09	0:14	0:13
Solar Latitude (deg)	4.7	7.2	12.4	16.8
Sigma Solar Latitude (deg)	1.6	2.4	3.2	2.4
Phase angle (deg)	10.2	18.6	35.3	51.7
Range (km)	65.0	48.4	31.2	23.8
PolyCam FOV (m)	897	668	430	328
PolyCam pixel size (m)	0.9	0.7	0.4	0.3
Number of scan lines	2	4	4	5
Number of images per line	2	4	4	6
Total number of images per mosaic	4	16	16	30
Number of mosaics	36	28	36	26
Total number of images	144	448	576	780

The activities on 11/29 and 12/1 address the 13:20 and 14:40 observation constraints including the pixel size; the others are redundant and serve as backup. The observation on 11/29 allows only 13° of rotation, which meets the 20° constraint but not the 10°

desire. The observation on 12/2 is planned for only 2σ uncertainties and 14° rotational resolution for operational considerations (see below).

Data Products:

There is a suite of products generated by the Altimetry Working Group (ALTWG) after the 75-cm shape model from SPC is defined. This suite of products will be used as an input for virtually all global map science data products. The 75-cm shape model is derived from OCAMS instrument data. Approach is the first time data are collected for the 75cm shape model from SPC, but these data alone do not close out the MRD. OCAMS instrument data are also collected for the 75cm shape model from SPC during Preliminary Survey. During Preliminary Survey, a preliminary version of the 75cm shape model is released to FDS, but the final version for global mapping is not released until Orbital A.

Operational Considerations:

The early PolyCam imaging is from a nadir point attitude with no slewing. The TSE file dates are the DCO dates assumed for the ephemeris update, upon which the decision to use nadir point for the 3-σ confidence limit was made. The later imaging activities need a scan pattern to account for the navigational uncertainties, and the date of the TSE files listed are the ones used in the analysis. In many cases an earlier TSE file can be used and still permit satisfying the observational constraints. The observation on 12/2 was originally planned assuming the 11/30 TSE file, but given the complexity of a late update with sun clocking, we decided to use the 11/28 TSE file. Doing so meant we had a substantially larger area to scan to account for the larger uncertainties. To make the plan close, we had to change from 3σ uncertainties to 2σ, which still required a larger scan area that that possible with the later TSE file. The scan time for this larger area was such that the rotational resolution had to increase from 10° to 14°.

All of the scan patterns are set up with Sun clocking. Originally we were thinking the late PolyCam imaging could be simplified from an operational standpoint by having the same scan pattern run on different days with just an offset to the time and the pointing, but with the Sun clocking, that does not appear to be possible.

All observations are planned to begin at 05:00 on the date specified. The slew used for the late PolyCam shape model imaging is the slow slew with 1.35 mrad/s slew rate limit and 0.0582 mrad/s^2 acceleration. Note that this differs from the slow slew used earlier in Approach and will therefore require a change to the slew configuration file. The images taken during the slews will be equally spaced in distance, not in time. Doing so leads to fewer images, but makes commanding more complicated. The J-Asteroid planning tool cannot generate plans with images equally spaced in time. Ten dark images are planned during each activity at times TBD.

1.10 OVIRS Spectra for Phase Function

Requirements:

MRD-149 (2.13.1) 149 For ≥80% of the asteroid surface, map the variation in spectral properties in regions where the albedo is ≥1% using photometrically corrected (to 30° phase angle) and normalized (at 1.3 µm) reflectance spectra over a wavelength span of at least 0.3 µm within the region 0.4 - 1.5 µm with 5% accuracy and 2% precision (Global MapCam Panchromatic Photometric Model, Global MapCam Color Photometric Models (4), Global OVIRS Photometric Model).

Observation Constraints:

Collect OVIRS data at phase angles between 55° and 75°.

Observation Plan:

On the last day of the PolyCam shape-model observation, we will also simultaneously collect OVIRS spectra. This opportunity is not optimum for OVIRS, but there are no other times in the mission when we can get OVIRS data at phase angles between 55° and 75°. The slew pattern is designed for coverage with the 13.8 mrad FOV of PolyCam with 20% overlap, which corresponds to spacing of the slew lines of 11.0 mrad. With the 4 mrad FOV of OVIRS, there will be a 7 mrad gore between the lines of OVIRS spectra. During this time the range to Bennu is about 24 km, which implies a 96-m size of the OVIRS FOV with 168-m gores. Thus there will be at least two OVIRS stripes across Bennu. Though there is not a requirement to collect OTES data, we will collect OTES data at the same time as a ride-along opportunity.

Operational Considerations

The OVIRS accumulation time is 1.21 sec/spectrum, and for OTES it is 2.0 sec/spectrum.

Data Products:

Approach provides the opportunity to begin constraining the phase function for MRD-149c, the OVIRS Photometric Models (SA-28). SA-28 includes a photometric model for each OVIRS wavelength. SA-28 is used to generate the Global OVIRS Color-Ratio Map (SA-43), which in combination with the Global x-band Image Mosaic (IP-7) will inform the Safety Map and ensure that the surface that will be observed with LIDAR to determine range to surface is within the range of reflectance values in which LIDAR is designed to operate. SA-28 will also be used to photometrically correct OVIRS spectra that feed the Bolo Bond Albedo Maps (SA-42 & SA-37) and the Mineral and Chemical Abundance Maps (SA-40 & SA-41) which ultimately feed the Science Value Maps. SA-28 will be delivered as a FITS file after Equatorial Stations as Equatorial Stations MapCam data is required to constrain the disk function.

1.11 Calibrations in Approach

Launch+24 month calibrations take place in the early part of Approach. The three days that were reserved in the DRM Rev C timeline for these activities are carrying forward to this revision of the Science Phase Plan:

8/23/2018: MapCam and TAGCAMS

8/29/2018: PolyCam, SamCam, OVIRS, OTES, OLA, REXIS

8/31/2018: OVIRS solar calibration

In addition, an OVIRS solar calibration is scheduled to take place on 11/9 shortly after the OVIRS Full-Disk Integrated Spectroscopy observations.