MRD-146 (2.12.3) Produce four light curves of detected satellites by measuring the time variation in their irradiance 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.

Summary of Requirement:

MRD-146 consists of the results from light curve photometry observations of detected satellites of Bennu. Observations will consist of 140 MapCam images taken with a cadence of v-b-v-w-v-x-v and repeat. This results in 80 v images, 20 b, 20 w images, and 20 x images. These observations will be scheduled for a time when the viewing geometry allows high S/N photometry of the satellite.

Data Products Required:

Inputs consist of the following data:

OCAMS MapCam b,v,w,x L1/L2 FITS data taken specifically for the natural satellite light curve data product (ocams_image_level2rad specification)

- the L1 OCAMS data is sufficient to produce accurate photometry

- at this time, I am unsure if the L2 rad cal OCAMS data will be useable for producing accurate photometry. A decision to use L2 rad cal OCAMS data is dependent on a better understanding of how that data will be produce. More will be known after a future OCAMS calibration meeting.

MapCam Radiometric Calibration data (including zeropoint measurements in all filters) based on observation of one or more ECAS standard stars

Relevant data product:

Satellite light curves (MRD-146)

·Temporal satellite lightcurves (lightcurves in MJD vs magnitude space with errors)

o b filter: Variation of the flux from a satellite over time in the OCAMS MapCam b filter

o v filter: Variation of the flux from a satellite over time in the OCAMS MapCam v filter

o w filter: Variation of the flux from a satellite phased to the rotation period of a satellite in the OCAMS MapCam w filter o x filter: Variation of the flux from a satellite phased to the rotation period of a satellite in the OCAMS MapCam x filter

Phased satellite lightcurves (lightcurves phased to the rotation period, rotation phase vs magnitude space with errors)

o b filter: variation of the flux from a satellite phased to the rotation period of a satellite in the OCAMS MapCam b filter

o v filter: Variation of the flux from a satellite phased to the rotation period of a satellite in the OCAMS MapCam v filter

o w filter: Variation of the flux from a satellite phased to the rotation period of a satellite in the OCAMS MapCam w filter

o x filter: Variation of the flux from a satellite phased to the rotation period of a satellite in the OCAMS MapCam x filter

Rotation period: A single real number describing the length of time for a satellite to rotate once around its polar axis and one or two real numbers describing the error estimate in the rotation period

Process Overview

If any satellites are detected, aperture photometry will be conducted on a time-series of MapCam images. Since there is great uncertainty in the rotation period of the satellites (it could range from days to tens of seconds) the following cadence will be used: (20 v images) – (20 b images) – (20 v images) – (20 w images) – (20 v images) – (20 x images) – (20 v images). A Fourier series fit will be made to the satellite temporal lightcurve to determine the rotation period. A chi-squared analysis will be conducted on the Fourier results to identify the best period. Manual inspection of the phased lightcurves will also be conducted to ensure that the resulting period is valid. It is possible that these observations may need to be repeated if the above cadence is not sufficient for determining the rotation period.

The final AAWG Bennu Lightcurve Asteroid Astronomy product will consist of a rotation period and a phased lightcurve in all 4 MapCam filters.

Ability/Availability of the System to Generate Sufficient Observations:

The OCAMS test STR 110 represents the best simulation available on the ground for the OCAMS spectral ratio imaging campaigns that are planned for the mission to Bennu. It simulated the detectability of the water hydration absorption as measured by MapCam's W filter relative to the V and X filters. STR110 successfully demonstrated MapCam's ability to identify a 2% absorption difference in the W (vs. V and X) band with a high degree of confidence (~95%). See Section 4 of OREX-DOC-05.01-00466_OCAMS Supplementary Calibrations for more details.

Minimum Success Criteria:

This requirement is 'best effort' since a discovered satellite may not be bright enough to conduct sufficiently high SNR photometry to determine a phase function.

Dependencies per Mission Phase:

Approach and later phases:

MRD-146 is dependent on the acquisition of OCAMS MapCam data for the light curves. If MapCam is not available, PolyCam can be used to conduct the light curves, though only in the panchromatic filter so color information would be lost.

If the satellite is too faint for high S/N photometry with MapCam and ECAS filters, we could forgo the color information but still get rotational lightcurve and a rotation period using MapCam with a panchromatic filter or PolyCam with its panchromatic filter. The panchromatic filter will transmit more light to the detector than the ECAS color filters. PolyCam will also collect more light than MapCam due to its larger aperture.

Approach phase is limited in duration. As this requirement involves the production of long-term science data, the satellite lightcurves can be obtained during any mission phase when the observing circumstances allow the observation of the satellite.

Adequacy of the DRM:

The APWG satellite lightcurve observations are a contingency dependent on the discovery of a satellite(s). The resulting data products will be produced within 5 working days of data downlink and processing by the SPOC OCAMS pipeline.

Data Products per Mission Phase:

Mission Phase: Approach, Preliminary or Detailed Surveys or Orbital A or Orbital B

Assuming satellites are discovered, aperture photometry of satellites of Bennu will be conducted in all 4 MapCam color filters. A major uncertainty driving the cadence of observations will be the rotation period of the satellites. Lightcurve surveys of small asteroids find that over 80% of asteroids with diameters less than 100 m rotate with rotation periods less than 2 hours and as fast as 42 seconds (Hergenrother and Whiteley 2011). Though very few asteroids in the meter size range have been observed, studies of fireballs and their associated meteorites suggest rotation rates as fast as 19 seconds are possible (Brown et al. 2004). If the satellites are tidally locked then their rotation periods will be equal to their orbital periods, and will be on the order of many hours to days.

The rotation rate uncertainty complicates the determination of color indices. In order to properly measure the colors, brightness variations due to rotation must be corrected for. The following cadence of filtered observations is suggested in order to properly determine the colors of a satellite with unknown rotation rates: (20 v images) – (20 b images) – (20 v images) – (20 w images) – (20 v images) – (20 x images) – (20 v images). This results in a total of 140 images. This is a technique that is used to determine the colors of small fast rotating asteroids. In effect, a lightcurve is determined for the satellite in each of the colors. The reason the v filter is sequenced more often is in case the satellite is rotating at a much slower rate.

In order to obtain ECAS filter photometry of any detected satellites with a S/N of 30, the range to these satellites must be smaller than required for initial (panchromatic) detection. Depending on the size and orbits of the satellites, color photometry observations can be made during the Approach, Survey and Orbit phases of the Encounter.

Total number of MapCam images is 140 images.

Total data volume is 140 images x 2.1 MB = 294 MB = 0.29 GB (assuming no compression).

Availability of Input Data Products

MapCam data in support of measuring satellite lightcurves are contingent on the detection of any satellites around Bennu. Physical observations of any detected satellites are dependent on the brightness (a combination of size, albedo and phase function) and location of the satellites relative to Bennu and the S/C. Observations will be made during either the Approach, Preliminary Survey, Detailed Survey, and 2 Orbit phases. Data will be available after downlink. Due to the non-urgency of this data, data downlink may be delayed to accommodate more urgent observations.

Assuming satellites are discovered, scheduling of satellite lightcurve images are contingent on DRM changes driven by mission safety concerns.

Overview of Processing:

Corrected MapCam image data will be extracted from the SPOC Database. Photometry will be measured within an aperture centered on the satellite. The aperture will be 2 times the mean FWHM of the image. An annulus centered on each object that ranges from 5 to 7 times the FWHM of the image will be used to measure the background sky brightness. The resulting photometry will be used to produce lightcurves spanning 8.6 hours in all 4 MapCam filters.

Photometric calibration of the MapCam images will be based on standard star calibrations conducted prior to the encounter and throughout the Approach phase. These photometric calibrations will be used to determine the absolute brightness of the satellite in each image. In order to check for possible short- term variations in the performance of MapCam, no less than 4 photometric reference stars within each image field will be analyzed. If required the in-field standards will be used to determine corrections to the photometry. Also camera bias, temperature, and background brightness will be monitored to ensure the cameras did not experience any anomalies during the course of the lightcurve observations. Absolute photometric calibration of MapCam will be conducted throughout Cruise and the Encounter phases by observing solar analog stars and ECAS standard stars. If there are short-term variations in the performance of MapCam then photometric calibration images need to be conducted before and after the lightcurve observations. If MapCam's performance is stable on the order of months, then use of the nominal MapCam calibration observations will suffice.

The four-color lightcurves will be merged into a single lightcurve by determining the resulting color terms between the four filters. This step is also part of the Photometry Science. A Fourier series will be fit to the lightcurve in order to determine the rotation period. The rotation period will then be used to fold the lightcurve into a phased lightcurve.

Time-frame for Data Processing

Automated and manual inspection of data

- Identify the position of satellite and background stars
- Identify focus problems
- Identify cosmic ray interference with satellite or background stars
- Identify interference between satellite and background stars
- Identify off-nominal detector bias levels

· Estimated time: 4 hours

Photometric reduction of satellite and reference stars

- Aperture photometry of satellite and reference stars o Estimated time: 15 hours

Verification of OCAMS MapCam photometric calibrations

o Additional step to check that photometric characteristics of MapCam was stable for all images by comparing the flux from all non-saturated field stars with a S/N > 100)

o Estimated time: 1 hours

Determination of rotation period

o Conduct Fourier analysis on satellite photometry to determine its rotation period

o Estimated time: see below

Production and inspection of phased lightcurves

o Manual inspection of phased lightcurves, this step and the one above will be done in parallel

o Estimated time (total for both this step and the determination of the rotation period): 10 hours

Data products will be released to the project 1 week (5 business days or 40 hours) after data downlink.

The time estimates are based on serial processing. Some steps such as the inspection of data, photometric reduction and inspection of phased lightcurves could be done in parallel to reduce task duration. Estimates also assume no additional imaging is required to obtain the needed data.

Provenance of Algorithms, Software and Techniques:

One software packages/scripts will be used to produce the relevant data products for MRD-144.

1. IRAF (Image Reduction and Analysis Facility) is a freeware COTS package of reduction and analysis routines for the study of astronomical FITS data. IRAF has been the primary tool for the reduction of most

ground-based and space-based astronomical FITS data for ~30 years. IRAF will be used to measure brightness of a satellite using zeropoint magnitude inputs derived from MapCam star cluster and solar analog calibrations. Zeropoints will be derived for each filter.

2. ALC (Asteroid Light Curve) is a freeware Windows based software that is routinely used by the astronomical asteroid community to determine the rotation period and lightcurve parameters of asteroids. The following data products will be produced:

- one containing photometric lightcurve measurements for all detected satellites
- one containing lightcurve parameters (including rotation period) for all detected satellites

The software and processes have been tested on real images of faint rotating asteroids (an analog faint natural satellites of Bennu) taken with ground-based telescopes. Synthetic MapCam data was also produced using the SkyMaker COTS software package and run through IRAF and ALC successfully.

Expected/Simulated Data:

A document describing how the APWG test data was produced is linked below.

APWG Test Data Production.docx

Analysis & Verification Methods:

The software and processes have been tested on real images of faint rotating asteroids (an analog for Bennu) taken with ground-based telescopes. Synthetic MapCam data was also produced using the SkyMaker COTS software package and run through IRAF and ALC successfully.

Repository to the SPOC will be tested in an end-to-end data query, retrieval, analysis, and store thread test.

Image data visualization to occur in IRAF + SAOImage DS9. Lightcurve visualization to occur in ALC.

In-flight, photometry will be compared against 4 background ‘check’ stars to ensure that none of the photometric reference stars are variable. Camera bias, temperature, and background brightness will be monitored to ensure the cameras did not experience any anomalies during the course of the lightcurve observations.

Existing or Potential Liens:

This requirement really needs to be best effort for the following reasons:

- if many satellites are detected, we will not have the time to conduct photometric characterization of all of them

- a satellite may be bright enough to be discovered and followed astrometrically (S/N of 2 is detectable) but not bright enough to get sufficient S/N (10-100) for lightcurve photometry

- if the satellite is rotating at rapid rates on the order of seconds to minutes (very possible based on our knowledge of meter sized asteroids), sufficient S/N will not be possible for the short exposures (as short as sub-seconds) required to detect a light curve

- light curve photometry may be possible with PolyCam or MapCam (+ panchromatic filter) which would produce a light curve but not ECAS color light curves

SPOC Requirements:

SPOC support consists of:

- Access to relevant OCAMS MapCam L1/L2 FITS images
- Access to a computer (running Mac OS X and Windows [or Windows virtually on a Mac OS X machine)
- Access to relevant satellite search reduction programs delivered by APWG, including:
    - ALC (Asteroid Light Curve) (COTS)
    - IRAF (COTS)
- Ability to upload satellite light curve data products to SPOC Repository
- Notification of kernel, OCAMS calibration product updates

External Interfaces:

None.

OSIRIS-REx SPOC MRD Review

Carl Hergenrother
Asteroid Astronomy Working Group Lead
Astrometry and Photometry Working Group Lead

2016-Apr-15

Production of Synthetic MapCam data for APWG Testing

The program SkyMaker (by Astromatic.net) was used to produce synthetic MapCam image data to conduct tests of the Astrometry and Photometry Working Group (APWG) natural satellite search, dust plume search and lightcurve photometry software and algorithms. The data approximated the optical and electronic characteristic of the MapCam camera system.

Prior to running skymaker, two input files needed to be modified. The first is the Skymaker list file. This file consists of a list of sources to be added to a synthetic image. These sources may be stellar (stars) or diffuse (galaxies). For all synthetic MapCam images created for APWG tests, the Vizier (http://vizier.u-strasbg.fr/viz-bin/VizieR) catalog service was used to obtain positions and brightnesses of real stars. The limiting magnitude for these tests was set to V magnitude 12.0 so the Tycho-2 star catalog was used (http://vizier.u-strasbg.fr/viz-bin/VizieR-3?-source=I/259/tyc2&-out.max=50&-out.form=HTML%20Table&-out.add=_r&-out.add=_RAJ,_DEJ&-sort=_r&-oc.form=sexa). The limiting magnitude is based on an OCAMS team produced model for the brightness of a Signal-to-Noise=10 point source achieved in a 10 second MapCam image with the Panchromatic filter. An Excel spreadsheet was created to convert the J2000 Right Ascension and Declination coordinates of each star to a MapCam image X,Y pixel coordinate.

For Natural Satellite search data, a number of satellites of different brightnesses (ranging from V magnitude 6.0 to 12.0) and rates of motion were added to the list file. The positions of the natural satellites were changed in such a way to mimic linear motion across the 5 natural satellite search images.

For the Bennu lightcurve photometry synthetic data, rather than create examples of all 576 images that will be used during the actual Bennu lightcurve observations, a subset of 36 images were created. This subset is sufficient to test the ability of the photometry reduction and lightcurve reduction software tools.

Below is a snippet from the skymaker list file containing the comment section of the file describing its use and format and a few lines of example star entries.

```
# This is a SkyMaker2 list file
# The format is:
# <code (100 = star, 200 = galaxy)> <x> <y> <magnitude> <...>
```

```
#
# Examples:
# A star at FITS coordinates (128.4,99.5) with magnitude 7.123 :
# 100 128.4 99.5 7.123
# A galaxy at FITS coordinates (102.0,180.7) with "total" magnitude 19.41,
# bulge-to-total ratio 0.42, bulge equivalent-radius 2.3 arcsec,
# projected bulge aspect ratio 0.8,
# bulge position angle 32.3 degrees (CCW, with respect to x axis),
# disk scale-length 4.0 arcsec, disk inclination (aspect ratio) 0.2, and
# disk position angle 31.3 degrees (CCW, with respect to x axis),
# 200 102.0 180.7 19.41 0.42 2.3 0.8 32.3 4.0 0.2 31.3
100     180.0000000     380.000000      6.000
100     500.0044221     510.7145021     7.338
…
100     6.562798566     10.34721999     11.959
```

For the dust plume search images, a diffuse feature approximating a Bennu-centric dust coma or trail was created and added to the skymaker list file. The following two lines (in blue below) were added to each of the dust plume synthetic images. The first line (starting with 100) creates a stellar Bennu of visual magnitude 10.8 (the expected brightness of Bennu during the Approach phase dust plume search observations in DRM Rev C). The second line (starting with 200) creates a highly elongated diffuse feature centered on the position of Bennu. The brightness of the feature is set to be faint enough that it is not detectable in single images requiring multiple co-added images to positively detect it.

Since Bennu and its associated dust is moving relative to the background stars, the X and Y coordinates of both should be placed on different pixels from image to image. The two lines below are an example of a Bennu and dust plume entry.

```
100     330.000000      330.0000000     10.80
200     330.000000      330.0000000     9.00 0.05 20 0.1 32.3 800.0 0.1 31.3
```

The second input file needed to create synthetic data is the skymaker configuration file (sky.conf). The file is set up to produce data that approximates the characteristics of MapCam imaging data.

```
# Default configuration file for SkyMaker 3.10.5
# EB 2014-10-10
#

#-------------------------------- Image ------------------------------------

IMAGE_NAME      sky.fits        # Name of the output frame
IMAGE_SIZE      1024,1024       # Width,[height] of the output frame
IMAGE_TYPE      SKY             # PUPIL_REAL,PUPIL_IMAGINARY,PUPIL_MODULUS,
                                # PUPIL_PHASE,PUPIL_MTF,PSF_MTF,PSF_FULLRES,
                                # PSF_FINALRES,SKY_NONOISE,SKY,GRID
                                # or GRID_NONOISE
```

```
GRID_SIZE       64              # Distance between objects in GRID mode
IMAGE_HEADER    INTERNAL        # File name or INTERNAL
LISTCOORD_TYPE  PIXEL           # Coordinates in input lists: PIXEL or WORLD

#-------------------------------- Detector ----------------------------------

GAIN            4.5             # gain (e-/ADU)
WELL_CAPACITY   65000           # full well capacity in e- (0 = infinite)
SATUR_LEVEL     65535           # saturation level (ADU)
READOUT_NOISE   7.5             # read-out noise (e-)
EXPOSURE_TIME   10.0            # total exposure time (s)
MAG_ZEROPOINT   14.0            # magnitude zero-point ("ADU per second")

#-------------------------------- Sampling ----------------------------------

PIXEL_SIZE      14              # pixel size in arcsec.
MICROSCAN_NSTEP 1               # number of microscanning steps (1=no mscan)

#---------------------------------- PSF -------------------------------------

PSF_TYPE        INTERNAL        # INTERNAL or FILE
PSF_NAME        psf.fits        # Name of the FITS image containing the PSF
PSFCENTER_TYPE  UPPERHALF       # UPPERHALF, LOWERHALF, HALF, CENTROID,
                                # CENTROID_COMMON or PEAK
SEEING_TYPE     LONG_EXPOSURE   # (NONE, LONG_EXPOSURE or SHORT_EXPOSURE)
SEEING_FWHM     30              # FWHM of seeing in arcsec (incl. motion)
AUREOLE_RADIUS  0               # Range covered by aureole (pix) 0=no aureole
AUREOLE_SB      16.0            # SB (mag/arcsec2) at 1' from a 0-mag star
PSF_OVERSAMP    5               # Oversampling factor / final resolution
PSF_MAPSIZE     1024            # PSF mask size (pixels): must be a power of 2
TRACKERROR_TYPE JITTER          # Tracking error model: NONE, DRIFT or JITTER
TRACKERROR_MAJ  10.0            # Tracking RMS error (major axis) (in arcsec)
TRACKERROR_MIN  10.0            # Tracking RMS error (minor axis) (in arcsec)
TRACKERROR_ANG  0.0             # Tracking angle (in deg, CC/horizontal)

#----------------------------- Pupil features -------------------------------

M1_DIAMETER     0.038           # Diameter of the primary mirror (in meters)
M2_DIAMETER     0.0             # Obstruction diam. from the 2nd mirror in m.
ARM_COUNT       0               # Number of spider arms (0 = none)
ARM_THICKNESS   0.0             # Thickness of the spider arms (in mm)
ARM_POSANGLE    0.0             # Position angle of the spider pattern / AXIS1
DEFOC_D80       0.0             # Defocusing d80% diameter (arcsec)
DEFOC_CENTER    0.5,0.5         # Relative center of PSF focus variations
SPHER_D80       0.0             # Spherical d80% diameter (arcsec)
SPHER_CENTER    0.5,0.5         # Center of PSF spherical aber. variations
COMAX_D80       0.0             # Coma along X d80% diameter (arcsec)
COMAY_D80       0.0             # Coma along Y d80% diameter (arcsec)
COMA_CENTER     0.5,0.5         # Center of PSF coma variations
AST00_D80       0.0             # 0 deg. astigmatism d80% diameter (arcsec)
AST45_D80       0.0             # 45 deg. astigmatism d80% diameter (arcsec)
AST_CENTER      0.5,0.5         # Center of PSF astigmatism variations
TRI00_D80       0.0             # 0 deg. triangular d80% diameter (arcsec)
```

```
TRI30_D80       0.0             # 30 deg. triangular d80% diameter (arcsec)
TRI_CENTER      0.5,0.5         # Center of PSF triangular aber. variations
QUA00_D80       0.0             # 0 deg. quadratic d80% diameter (arcsec)
QUA22_D80       0.0             # 22.5 deg. quadratic d80% diameter (arcsec)
QUA_CENTER      0.5,0.5         # Center of PSF quad. aber. variations

#-------------------------------- Signal ----------------------------------

WAVELENGTH      0.5             # average wavelength analysed (microns)
BACK_MAG        22.0            # background surface brightness (mag/arcsec2)

#----------------------------- Stellar field ------------------------------

STARCOUNT_ZP    0               # nb of stars /deg2 brighter than MAG_LIMITS
STARCOUNT_SLOPE 0.2             # slope of differential star counts (dexp/mag)
MAG_LIMITS      2.0,12.0        # stellar magnitude range allowed

#----------------------------- Random Seeds -------------------------------

SEED_MOTION     0               # rand. seed for PSF turbulent motion (0=time)
SEED_STARPOS    0               # random seed for star positions (0=time)

#----------------------------- Miscellaneous -------------------------------

VERBOSE_TYPE    NORMAL          # QUIET, NORMAL or FULL
NTHREADS        0               # Number of simultaneous threads for
                                # the SMP version of SkyMaker
```