MRD-148 (2.12.5) For detected satellites, determine their average ECAS b-v color index, v-x color index, and the depth of the 0.7-µm adsorption feature

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 color ratio data product (L2 ocams__image_level2rad specification)

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

Data Products

b-v index, v-x index, and 0.7-µm color ratios of satellites (MRD-148)

ECAS color indices (ratios)

o OCAMS MapCam b'-v filters index - Relative color ratio between the OCAMS MapCam b' and v filters

o OCAMS MapCam v-x filters index - Relative color ratio between the OCAMS MapCam v and x filter

o OCAMS MapCam 0.7-micron feature index - Depth of the 0.7-micron feature as measured by the ratio between the OCAMS MapCam w filter and the slope between the v and x filters

Ability/Availability of the System to Generate Sufficient Observations:

This requirement 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 and color ratio photometry

- light curve photometry may be possible with PolyCam or MapCam (+ panchromatic filter) which would produce a light curve but not ECAS color light curves resulting in the loss of color ratio measurements

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 photometric color indices.

Dependencies per Mission Phase:

MRD-148 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 index 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. This would result in not being able to produce data products meeting MRD-148

Adequacy of the DRM:

The data to fulfill this requirement will be taken as a contingency in the case that a natural satellite is detected.

Data Products per Mission Phase:

Approach phase:

If one or more satellites are detected, then the following contingency plan to acquire satellite photometry will be conducted.

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 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, on order of many hours to days. If they are not tidally locked, then their rotation periods could be anything (most probably > 19 seconds).

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 because it is the reference filter. More frequent sampling at v will allow the other colors to be measured relative to v 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/or Orbit phases of the Encounter.

Total number of MapCam images is 140 images per satellite.

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

Availability of Input Data Products

In order to plan the color photometry observations, we require an ephemeris for OSIRIS-REx, Bennu and any satellites containing, at a minimum, the Sun-satellite distance, the S/C-satellite distance, Sun-S/C-satellite phase angle and apparent positions of Bennu and satellites on the sky in Right Ascension and Declination (J2000). In addition to satellite ephemerides, we will also require satellite orbits from the Radio Science Working Group. This data will be used to determine a time when the Photometry observations can be made. Constraints on when the observations can be made are: satellites are sufficiently bright to produce S/N of 30 photometry in all 4 MapCam filters (< 50000 km range to Bennu), satellites are not occulted by Bennu or affected by scattered light from Bennu.

· OCAMS MapCam Images with the following corrections (Photometric, Geometric, Dark, Bias, Flat Field, Bad Pixel, Cosmic Ray)

· Predict SPICE kernels (SPK, SP, PcK, CK, FK, IK)

· Satellite orbits and ephemerides

Overview of Processing:

The Asteroid Astronomy Working Group will deliver a measurement of the Eight Color Asteroid Survey (ECAS) colors of any detected satellites of Bennu. ECAS is a set of broadband visible to near-IR wavelength filters optimized for the identification of spectral features on asteroids. The filters are also optimized for taxonomic classification of asteroids. The OSIRIS-REx MapCam instrument will be equipped with 4 of the 8 ECAS filters (ECAS-like b' @ 0.470 um, ECAS v @ 0.545 um, ECAS w @ 0.705 um, and ECAS x @ 0.86 um). The blue filter, b', is not the standard ECAS b, it is shifted from 437 nm to 470 nm to accommodate the camera performance in the blue.

During the Approach phase, satellite surveys will be conducted to detect any satellites larger than 10cm in diameter within 20km of Bennu. Larger satellites (1m or larger) will be searched for within the Hill Sphere of

Bennu (~35km). In the case that no satellites of Bennu are detected ECAS color observations cannot be made. If more than one satellite is detected, colors will be determined for all satellites. The ECAS color photometry will be disk-integrated due to the expected small diameters of any detected satellites. The photometry data products will be based on OCAMS MapCam images taken during the Encounter phases through the 4 MapCam color filters (b'vwx).

The disk-integrated Photometry Science of the satellites of Bennu will be characterized throughout the Encounter. The disks of any detected satellites are not expected to be resolved or will only be poorly resolved due to the small expected size and distance of the satellites. As a result, disk-integrated photometry will be used to obtain color indices. The resulting color indices will be directly compared against the results obtained for the surface of Bennu.

The final APWG Photometry products will consist of 3 color indices (b'-v, v-x and the depth of the 0.7 micron feature measured via the v, w and x filters). Aperture photometry of satellites will be conducted. The color indices are a ratio between photometry taken in two filters. Solar color will be subtracted from each index.

The following formula from Vilas (1994) will be used to determine the presence and depth of the 0.7 micron feature:

(Rw – ((Rx- Rv) * 0.4984)) / Rv Eq. (1)

where Rv, Rw and Rx are the relative reflectances of the v, w and x filters, respectively. A formula result greater than 0.99 indicates the existence of the 0.7 micron feature. The value 0.4984 in the Vilas (1994) formula is unitless. It is derived from the location of the center bandpass of the I filter relative to the v and x filters. Specifically the difference in the v and w bandpasses is 0.4984 times the difference of the v and x bandpasses.

Absolute photometry will be determined for each bandpass by comparison with MapCam standard star observations.

Corrected MapCam data will be extracted from the SPOC Database. Photometry will be measured within an aperture centered on satellites. 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. 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 satellites 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 dark current will be monitored to ensure the cameras did not experience any anomalies during the course of the lightcurve observations. Most of the above tasks will have already been completed for this task as part of the reductions for MRD-146 (production of satellite lightcurves). MRD-148 builds on the results from MRD-146.

The four-color lightcurves will be compared and differenced in order to produce the 3 color indices. Plotting the color indices against the rotational phase of the satellite(s) will create a longitudinal spectral map of the surface.

Time-frame for Data Processing

Automated and manual inspection of data (identify the position of satellites and background stars, identify focus problems, identify cosmic ray interference with Bennu or background stars, identify interference between satellites and background stars, identify off-nominal detector bias levels) [estimated time: activity completed as part of MRD-146]

Photometric reduction of satellites and reference stars (aperture photometry of satellites and reference stars) [estimated time: activity completed as part of MRD-146]

Verification of OCAMS MapCam photometric calibrations (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) [estimated time: activity completed as part of MRD-146]

Determination of rotation period (conduct Fourier analysis on satellite photometry to determine rotation period(s)) [estimated time: activity completed as part of MRD-146]

Production and inspection of phased lightcurves (manual inspection of phased lightcurves, this step and the one above will be done in parallel) [estimated time: activity completed as part of MRD-146]

Determination of color indices (b'-v, v-x and depth of 0.7 micron feature indices by comparing the difference between measured magnitudes in the relevant filters) [estimated time: 20 hours]

Production of color indices lightcurves (lightcurves allow the detection of color differences at various asteroid longitudes) [estimated time: 20 hours]

Color photometry data products will be released 1 week (5 business days or 40 work hours) after downlink of the last downloaded images.

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.

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. ALC

can also be used to determine the color ratio by measuring the photometric offset in astronomical magnitudes between each light curve.

The following data products will be produced:

- one containing color index photometry measurements for all detected satellites
- one containing color index parameters for all detected satellites

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.

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.

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

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.

Existing or Potential Liens:

This requirement needs to be defined as '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 and color ratio photometry

- light curve photometry may be possible with PolyCam or MapCam (+ panchromatic filter) which would produce a light curve but not ECAS color light curves resulting in the loss of color ratio measurements

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

External Interfaces:

None.

b-v index, v-x index, and 0.7-µm color ratios of satellites (MRD-148)

Data Product Overview
One sentence executive description of product

Asteroid color index data product is a measure of the color differences between the following filter bands: b-v, v-x, 0.7-micron feature.

Overview
Data type (image, spectrum, data table, map format etc.)
data table

What does it measure at what scale
unresolved/point source

What observations are required to provide the input data needed to make the data product?
MapCam images taken through all 4 ECAS color filters

When in the DRM are the observations that make the data product scheduled to be taken?
during the Approach phase

How long does it take to produce the data product?
data obtained during multiple 4.5-hour science observation windows. reduction to be completed after the delivery of the last Bennu lightcurve photometry observation. A week of time is required to reduce, analyze and produce this data product.

Is this product used of sample site selection, science value, or long-term science?

long-term science

Data Product Structure and Organization
What is the structure of the data product (e.g. FITS file with 4 extensions)

ASCII

How is the product organized (e.g. one data set per mission phase, one file per Earth Day, etc.)

two files (one contains color index photometry and the other contains color indices at different rotational phases and phase angles

Data Format Descriptions
Header information (metadata) included with data product. For example:

ASCII table including the following: rotation phase, phase angle, b-v color index, b-v color index error, v-x color index, v-x color index error, 0.7-micron color index, 0.7-micron color index error

Detailed Description of data format. For example:

Table

Data Type

ASCII

Field name, Field Description, Field Length, Field Format

for color index photometry file:
ASCII table including the following for the lightcurve photometry file: year of mid-point of observation (UT), month of mid-point of observation (UT), decimal day of mid-point of observation (UT), exposure length, filter, photometric flux, apparent magnitude, absolute magnitude normalized distances of 1 AU between the Bennu and Sun and Bennu and spacecraft, rotation phase, lightcurve photometric correction, phase angle, OREx-Sun distance, OREx-Bennu distance

for color index parameter file:
rotation phase, phase angle (degrees), b-v color index (magnitudes), b-v color index error (magnitudes), v-x color index (magnitudes), v-x color index error (magnitudes), 0.7-micron color index (magnitudes), 0.7-micron color index error (magnitudes).

Example format (for color index photometry file):

```
2018 10 11.123456 100.000 b 123456 10.123 20.123 0.1234 -0.123 123.456 0.12345 123456.123
```

Fortran format (for color index photometry file):

```
I4,1X,I2,1X,F9.6,1X,F7.3,1X,A1,1X,I6,1X,F6.3,1X,F6.4,1X,F6.3,1X,F7.3,1X,F7.5
```

Example format (for color index parameter file):

```
0.1234 123.456 +0.123 0.123 +0.123 0.123 +0.012 0.012 -0.198 0.102
```

Fortran format (for color index parameter file):

```
F6.4,1X,F7.3,1X,F6.3,1X,F5.3,1X,F6.3,1X,F5.3,1X,F6.3,1X,F5.3
```

Data Product Generation
How and by whom is the product generated?

What are the input products needed to produce the product?

OCAMS MapCam L2 images of Bennu, MapCam photometric calibrations, s/c ephemeris position, Bennu ephemeris position, MapCam image filter, MapCam image exposure time, MapCam image exposure duration, Bennu lightcurve parameters

Are there format expectations for the input products?

Yes. MapCam image headers need to use the standard FITS header format. A list of FITS keywords and their meanings is required for reading these values into the photometry software.

What algorithms and/or calibration data is used to generate products?

Rotation Period Determination (ALG-AP-008) and Color Index Determination (ALG-AP-010) are used to produce this data product.

Are there format expectations for the inputs?
No

Has a specific Science Team Member been assigned to produce this product?
Yes, Carl Hergenrother.

Will multiple versions of the product be generated?
No

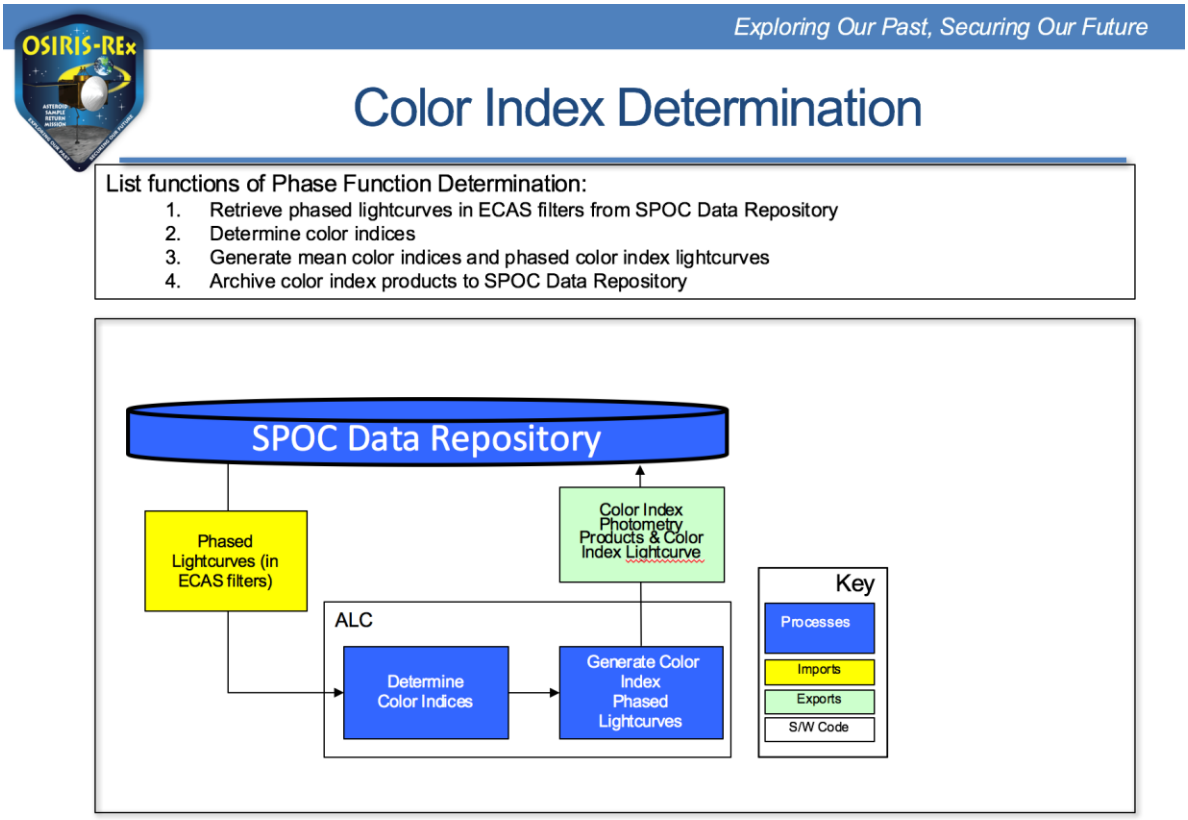
How will they differ?

On what cadence will they be delivered?
N/A

Data Product Validation
How will the product be vetted to ensure contents and format are correct?

Software to be tested on real ground-based color indices data of asteroids analogous to Bennu. Analogous asteroids will have “well determined” color indices parameters.

Data Flow
Update Data flow diagrams with more detailed based on current processing configuration.



Describe the sources, destinations, and transfer procedures for data products.

State the size of an individual data product and the total size of all the data products generated over the course of each mission phase. Can we have an estimate by Baseline?

Data products are relatively small ASCII text files (size < 1 MB)

State the time span covered by a product, if applicable, and the rate at which products are generated and delivered.

Data products to be delivered at the end of the Approach phase

Standards used to generate data product
Time (e.g. times are all converted to UTC)

UTC

Coordinate System

astronomical photometric system (b,v,w,x,monochrome v)

Data Storage Conventions (i.e. byte order, compression, machine dependence)

Product to be retrieved via WebQuery based on data product type (name) or date observation was made. For example, I do not foresee a request to download one photometric point but do foresee downloading all photometry taken on a single date.

Relevant ICD Data Products:

- Color Index Photometry Parameters (AP-16)
- Color Index Light Curve (AP-17)