Analysis of Projection Effects in OSIRIS-REx Spectral Mapping Methods: Recommended Protocols for Facet-Based Mapping

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Abstract We searched for an optimized protocol for mapping observations from a point spectrometer onto a shape model composed of triangular facets, in the context of NASA's asteroid sample return mission, OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer). Our study was conducted before the spacecraft arrived at the mission target asteroid (101955) Bennu, and we used observational sequence plans of the OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS). We explored six methods of mapping data to shape model facets, using three spatial resolutions. We attempted to boost map fidelity by increasing the observational coverage of the surface. We find that increasing shape model resolution improves mapping quality. However, once the shape model’s mean facet edge length is smaller than two-fifths of the diameter of the instrument’s field of view (FOV), the increase in quality tapers off. The six mapping methods can be broken into two categories: facets that (1) select or (2) combine (average) data from observations. The quality differences between similar averaging methods (clipped average, weighted average, etc.) are insignificant. Selecting the nearest observation to a facet best preserves an enclosed outcrop’s shape and signal, but averaging spots are more conservative against errors in photometric modeling. A completely enclosed outcrop border expands into the surrounding region by 0.8–1.5 radii of the instrument’s FOV. Regions smaller than the instrument’s FOV are present in resulting maps; however, their signal strength is reduced as a function of their size relative to the instrument FOV.

1. Introduction

NASA launched the OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer) spacecraft on September 8, 2016. OSIRIS-REx rendezvoused with its target, near-Earth asteroid (101955) Bennu, in December 2018. Having completed global and regional surveys of the asteroid in 2019, OSIRIS-REx will collect a sample in 2020 and return it to Earth in 2023 (Lauretta et al., 2017). Bennu is of particular interest because it is thought to contain primitive solar system materials, and, as such, it may contain some of the building blocks of life: organic molecules. In addition, Bennu is a potentially hazardous asteroid, with a non-zero probability of impacting Earth (Lauretta et al., 2015). Spectral mapping in the context of the OSIRIS-REx mission entails registering data from the onboard spectrometers to the surface of Bennu. The OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS) (Reuter et al., 2017) and OSIRIS-REx Thermal Emission Spectrometer (OTES) (Christensen et al., 2018) are point spectrometers in which everything within the field of view (FOV, or “spot”) is integrated. We focus on OVIRS for this study, but our findings are extendable to OTES because it is also a point spectrometer. To map the OVIRS FOVs to the surface of Bennu, we use a shape model. The shape model is a three-dimensional (3D) closed-volume approximate representation of the asteroid, composed of many small triangular facets (Gaskell et al., 2008). The orientations, sizes, and shapes of the facets as an ensemble define the shape of the asteroid, as shown in Figure 1. The mapping process assigns values obtained from the spot observations to the facets of the shape model (Figure 1).
Similar spacecraft missions to planetary bodies carrying spectrometers have used other mapping techniques than we present here. For example, the VIRTIS, VIR, and M3 spectrometers (Capaccioni et al., 2015; De Sanctis et al., 2012; Pieters et al., 2009, respectively) from the Rosetta, Dawn, and Chandrayaan missions (Goswami & Annadurai, 2009; Russell & Raymond, 2011; Taylor et al., 2017) are all imaging spectrometers. For these missions, the location of each pixel of the instrument observation can be projected to their target surfaces, as each data acquisition corresponds to multi-pixels. Thus, the mapping method of those missions differ from that of OSIRIS-REx.

Spectral mapping accuracy is limited by several potential sources of error, including pointing knowledge uncertainties, spacecraft location uncertainties, shape modeling uncertainties, and observation timing errors. In this paper, we do not attempt to account for positional errors in the mapping process. Instead, we investigate potential sources of error originating from “projection effects.” We define projection effects as the uncertainties stemming from the mapping process itself—the mapping process being the assignment (or projection) of circular spectrometer fields-of-view (i.e., boresight footprints or spots) to the facets of a triangularly tessellated shape model.

Our spectral mapping routine presents several choices to the scientist, and, a priori, there is no theory available to dictate the “right” answers. For example, which of the available shape model spatial resolutions is appropriate for use with the spectrometer data? When multiple spectrometer spots cover a facet of the shape model, which observation(s) should be used? As with imaging super-resolution, can multiple global sets of spectrometer observations be combined to enhance the spatial resolution of the spectral maps? Given all these choices, what is the smallest outcrop (enclosed and distinct mineralogy from a homogeneous surrounding region) that can be detected with spectral mapping?

We use simulated OVIRS data to address these questions, as our study was performed before the spacecraft encounter. Using actual OSIRIS-REx spacecraft flight plans and OVIRS observation plans, we simulate OVIRS data of Bennu to assess the effects of projection. We study three different shape model spatial resolutions to determine which works best, given the planned OVIRS spot size. In addition to determining which shape model resolution creates the best spectral data product, we are also interested in optimizing file size and computation time. For the OVIRS observation campaigns that we simulate, the typical OVIRS FOV diameter on the surface of the asteroid is between 14 and 20 m. We compare the efficacy of six different algorithms, or procedures that are repeated for each facet, in assigning data from the spots to the shape model. We test the hypothesis that combining observations from three dayside global surveys produces maps of higher spatial resolution than those produced using one global survey.

2. Materials and Methods

Figure 2 shows a flowchart of the experimental steps. We use spectral data from Donaldson Hanna et al. (2017) to create the “truth maps.” Truth maps are artificial data constructions of an ideal surface we create to study the mapping process. They are realistic spectral data values.
with latitude and longitude coordinates. We use these values and coordinates to simulate the spectrometer observing the “truth” maps as a proxy to simulate the spacecraft observing the asteroid. Their creation is necessary since we are simulating the mapping process prior to the OSIRIS-REx and Bennu rendezvous. We call them “truth” since they are used as our ground comparison after simulating the mapping process.

Because the maps are idealized values, we ignore physical, non-compositional effects on spectral remote sensing such as surface roughness, porosity, and shadows. Their effects on remote sensing comprise an interesting field of study; however, in this experiment, we are only concerned with the mapping of observations. The truth map used in the study is shown in Figure 3.

SPICE kernels, pointing information, and the truth maps are inputs to an IDL procedure called generate_test_data.pro. This procedure uses the geometry of the spacecraft observations of the asteroid surface (or truth map), which is stored in SPICE kernels, to assign spectral data values from the truth map to each OVIRS observation. These SPICE kernels are ephemerides that include positions and orientations of the Earth, the Sun, Bennu, and the OSIRIS-REx spacecraft, as well as the instruments on board (Acton, 1996; Acton et al., 2018). In short, the program generate_test_data.pro uses the mission observation planning SPICE kernels to find where the OVIRS observations intersect the truth map (Figure 3), then integrates each spot over the map and reports data values for each observation. The program Getspots written by Hari Nari at Johns Hopkins University Applied Physics Laboratory uses SPICE kernels and the shape model to provide a list of which spots cover which facets, including the percent overlap of each spot to each facet.

After running generate_test_data.pro, we have created data values for each OVIRS spot, and, after Getspots, we know which facets are covered by which spots. Next, we take the output data files from each preceding program and use them as the two input files to our MatLab mapping program, makeMaps.m. This program distributes the data values to the facets of the shape model. makeMaps.m is the official OSIRIS-REx spectral mapping software and is available in Ferrone et al. (2019). The program creates a map data product: an ancillary file that is associated with the specific shape model used. Each ancillary file is in FITS format, and each shape model is in OBJ format. An example output map is shown in Figure 4. Ancillary files contain one science value (and its associated uncertainty) per facet. When they contain real (not simulated) data,
these ancillary files are used and exchanged as maps of Bennu by mission
scientists and engineers across all elements of the OSIRIS-REx project.

After we have created our truth map (artificial data product), simulated
observations of the truth map, and mapped the simulated observations to
our shape model, we are ready for analyses. To conduct the analyses, we
interpolate ancillary FITS files of simulated data onto a latitude and lon-
gitude grid. We then compare this latitude-longitude map product with
the truth map. We have created our own metrics for quantifying the dif-
ferences between our truth worlds and the map data products. The met-
rics we developed measure changes in outcrop data values and changes
in the shapes of outcrop regions after mapping. These metrics are de-
scribed in Section 3. The rest of this section describes, in more detail, the
data products and their preparation for the study.

2.1. Truth Maps

In this section, we describe the role of truth maps in the study, why we
create them, and the significance of each component of the maps.

The truth map (Figure 3) is an artificial map that we create to understand
the projection effects of the OSIRIS-REx spectral mapping procedures.
In this experiment there are “initial” maps and “resultant” maps (before
and after). Truth maps are the initial maps that serve as the starting point.
The truth maps provide us with simulated spectral contrasts, at known
latitude and longitude positions, and these are viewed through the eyes
of the spectrometer. After we simulate observing the truth map, we map
those observations to obtain our resultant map. After we obtain our re-
sultant maps, we can compare the locations, spatial dimensions, and in-
tensities of mapped quantities against our truth maps. The truth maps have a resolution of 0.5° per grid
element, and as such exist on a 3,601 x 7,201 latitude by longitude grid.

Any scalar quantity can be mapped. In the context of this small body spectroscopy mapping, these quan-
tities could be: intensity of reflectance or emissivity at a specific wavelength or wavenumber, bolometric
bond albedo, spectral continuum slope, feature band depth, band width, or band minimum position (in
wavelength or wavenumber space). Since we conduct this study in the context of the OSIRIS-REx mission,
the quantities we have mapped are reflectance values of the spectra of two different mineral mixture sets
at 2.256 µm. These mineral mixture sets are carbonaceous chondrites, which are considered to be the best
analog for the composition of Bennu (Clark et al., 2011). These analog meteorites and mineral mixtures are
well-characterized in Donaldson Hanna et al. (2017). From their study, we used “Tony,” which is a mix of
anhydrous minerals with abundances consistent with type 3 carbonaceous chondrites. The second spectral
sample taken from their study is “Glenn,” which is a code name for a Murchison sample. We have chosen
this wavelength to optimize spectral contrast. That is, their difference (numerically) is well above the de-
tection limit of the OVIRS spectrometer (~2% of total signal), even though we ignore the uncertainty of the
instrument detection limit. Because we employ values that are well above the lower bound of double point
precision we expect that computational errors are negligible for this study.

We create truth maps composed of simple circular and rectangular outcrops embedded in a homogeneous
background. We define each outcrop to be an isolated encircled signal that is in contrast with the homoge-
neous background. We choose simple shapes to easily quantify their distortions. The simplicity of our truth
maps serve to highlight the effects of our method of assigning observations to facets. The spectrometer
averages everything in its FOV, and assigns a single value to all enclosed facets of the shape model. Of in-
terest are the outcrops that are smaller than the OVIRS FOV. We note that each simulated outcrop is spaced
sufficiently far apart from the others such that signals are not mixed between two outcrops by the mapping
process.

Figure 4. An output map from simulating OVIRS observations of the
truth map in Figure 3. This map uses our moderate-resolution shape
model with 49,000 facets, and the nearest distance algorithm for selecting
the closest spot when assigning data to each facet. One can immediately
notice intermediate values (yellow, green, light blue) transitioning from
outcrop to background that are absent from the truth map. In fact, the
outcrops that are smaller than the OVIRS spot have been completely
“degraded.” This happens when the spectrometer integrates everything
within the spot because the OVIRS point spectrometer cannot distinguish
sub-FOV outcrops from the surroundings. In addition, upon close
inspection one can see the discrete jaggedness of the outcrop borders
arising from the shape model facets. FOV, field of view; OVIRS, OSIRIS-
REx Visible and InfraRed Spectrometer.
Because the values we map are idealized and without uncertainties, we constrain the uncertainty spatially. Each outcrop’s size is expressed as a ratio of the outcrop’s diameter to the diameter of the OVIRS spot. The source of the error is that not all OVIRS spots are the same size, since the diameter and shape of each spot depend on the relative orientations of the instrument, spacecraft, and asteroid.

To calculate the ratio of an outcrop’s size relative to the size of the OVIRS spot, we first project the spot onto a plane tangent to a sphere. The sphere has a radius equal to the asteroid’s radius at the intersection point with the OVIRS’ center boresight vector. If the boresight vector is not perpendicular to the tangent plane, an ellipse is projected onto the plane; if it is perpendicular, the spot is a circle. We use the radius of Bennu at each boresight-to-body intersection to convert the OVIRS spot major and minor axes to radians. The radians are in the coordinate system of Bennu. We then average the major and minor axes of all observations to find the mean diameter and one standard deviation to report the error.

We report the error as one standard deviation of the size of all spots that fall between −10° and +10° latitude. We limit to this range since we have placed all outcrop on the equator. Consequently, the mean diameter of the spot on the equator in Bennu coordinates is \( \theta = 0.076 \pm 0.006 \) rad, or equivalently \( 20 \pm 2 \) m on the surface. The x-axes of the plots in the results section are reported in terms of the ratio of the outcrop’s diameter to the diameter of the OVIRS spot:

\[
\phi_x = \frac{\phi_m}{\theta} \pm \delta\phi
\]

(1)

where \( \phi_m \) represents the diameters of the outcrops of the truth map in radians, \( \theta \) is the diameter of the OVIRS FOV, \( \delta\phi \) is the error in the values of the x-axis, and \( \delta\theta \) is one standard deviation of the diameters of the OVIRS FOVs on Bennu.

We have chosen to express our spatial units as the ratio of the outcrop’s diameter to the OVIRS spot size in order to emphasize the dependence of projection effects on the spot size of the spectrometer. When the ratio is 2, the very center of the resultant map’s outcrop should be free of any signal from outside of the outcrop. Equally as interesting is the ratio value of 1. This occurs when the outcrop’s diameter is equal to that of the OVIRS diameter. This value is a spatial lower limit in that any outcrop smaller than this, OVIRS will not be able to totally isolate the signal from the local surrounding.

We do not include the truth map that corresponds to the resultant map in Figure 10. Despite this, we do show the original dimensions of the outcrops with black borders. To express the size of the outcrop reported for Figures 6 and 7, we compute the ratio of the outcrop latitude width to the OVIRS spot diameter. When the outcrop width is twice that of the OVIRS diameter, no signal from the outside should be mixed in with the mapped outcrop signal. When the width of the outcrop is equal to or less than the OVIRS spot diameter, the spectrometer will observe (and mix in) signal from the surrounding region.

2.2. Simulating OVIRS Observations

To simulate OVIRS observations we use a truth map, SPICE kernels, simulated observations, and the program generate_test_data.pro (see the flow chart in Figure 2). This step simulates what OVIRS sees when observing the truth world, and provides us with the simulated observations that we will map onto the shape model.

In this study, we use SPICE kernels for the equatorial observing stations in the Detailed Survey phase of the OSIRIS-REx mission (see Lauretta et al., 2017). At these stations, the spacecraft parks at the equator and conducts north and south slews throughout an entire rotation to observe the asteroid’s surface globally. We use only the dayside stations—10:00 a.m., 12:30 p.m., and 3:00 p.m. The different local solar time positions are necessary for constraining the photometric phase function (Zou et al., 2021).

The IDL procedure we have written uses SPICE kernels to determine the viewing and illumination conditions for each OVIRS observation of the surface of our truth world. The program integrates the truth map’s surface values under each OVIRS spot. Then, each spot is associated with one spectrum.
To simulate the optical culmination of light, the software randomly projects 10,000 vectors through the OVIRS field of view toward the surface of the asteroid shape model, where all vectors have equal probability of landing anywhere within the field of view. Each vector takes the surface value at the surface intersection point. All 10,000 vectors are then averaged together, and that value is assigned to the entire observation. In this way, we fairly approximate what OVIRS will "see" when observing our truth map. The actual OVIRS instrument observes more energy at the center of the field of view than the periphery and observes more than 96% of its signal within 2 milli radians of the boresight vector, or the total 12.57 micro-steradian solid angle FOV (Reuter et al., 2017). Our model assumes all the energy is observed within two milli radians of the boresight, and that the sampling is linear. We assume that any differences between model integrations and real integrations are negligible compared with other sources of error endemic to our mapping methods. We assume the detection efficiency is linear and finite to two milli radians for computational robustness.

2.3. Shape Models

The shape model used in the study, which was performed before the OSIRIS-REx rendezvous with Bennu, was constructed using radar observations by Nolan et al. (2013). The shape model resolution is defined by the mean facet edge length. The facets are not equilateral triangles, and not all facets are the same size. The mean facet edge length is the average length between every vertex of a facet for every facet in the shape model. We adapt the radar shape model to three different resolutions that have mean facet edge lengths of 1,278, 628, and 314 cm and facet counts of 12 k, 49 k, and 198 k, respectively, where k is one thousand. Some phases of the mission will use a high-resolution shape model with a mean facet length of 75 cm. However, we did not use this shape model resolution in this study owing to the correspondingly large computation times and output data sizes of the spectral maps. This is discussed further in Section 4.2.

2.4. Spectral Maps

We use makeMaps.m to project the simulated OVIRS observations onto the 3D shape model. The software is an interactive spectral mapping tool written in MatLab. It allows the user to decide how to choose from or combine data values from overlapping spectrometer observations and assign them to the facets of the shape model. The program uses a sub-routine called GetSpots, written by Hari Nair of the Johns Hopkins University Applied Physics Laboratory, that assigns the spectral data to facets covered by the OVIRS spots, and returns the fractional coverage of each spot for each facet. To register the spectrometer FOVs to the facets of the shape model, GetSpots uses SPICE pointing information. In principle, makeMaps.m can create spectral maps using shape models of other astronomical bodies, and can be used with instruments and ephemerides of other spacecraft missions.

The program includes seven different algorithms to combine the overlapping spectral data: an average, a weighted average, a median, the nearest spot value, the highest quality spot (not used in this study), the most recent spot, and an average that allows a standard deviation cut-off (sigma clip). For all operations, the errors are mathematically propagated appropriately.

The average algorithm sums the spectra from each spot covering a facet, divides by the number of spots covering each facet, and assigns that value to the facet.

The weighted average algorithm averages the spectra from each spot but weights each value with respect to the fractional area of the spot covering the facet; the more coverage the more the spot value influences the assigned value.

The median algorithm lists all spots covering a facet and assigns the median value of the list to the facet. If there is an even number of spots in the list, the two central values are averaged.

The nearest distance algorithm assigns the spectral value from the spectrometer spot whose centroid is closest to the facet's centroid. An example is Figure 4.
The highest quality algorithm assigns the spectral value of the spot covering the facet whose ratio of signal to uncertainty is the largest. This algorithm was not analyzed in this study because our test data generation methods do not include sufficiently realistic observational noise sources.

The most recent algorithm uses the spectrum from the latest (in time) spot to cover the facet.

Lastly, the sigma clip algorithm calculates the standard deviation from the mean of the spectral values from all spots covering the facet, rejects the values outside \( n \) standard deviations of the mean, and averages the remaining values. The user may define the value for \( n \), but the default is set to 3.

### 2.5. Interpolation

After makeMaps.m creates our 3D maps, as in Figure 4, we use a nearest neighbor interpolation, MatLab's scatteredInterpolant.m, to project the 3D maps onto a finely gridded flat latitude and longitude space (MATLAB, 2019). We take this extra step in creating our map projections in order to retain the fidelity of the truth map. Since the shape model is discrete with triangular facets, the truth map cannot be replicated on the shape model. Comparison of projected maps with truth maps is best performed when both are represented by equivalent latitude-longitude grids. Because we take this step for the analytical purposes of this study, we also restrict our truth map “outcrops” to occur on the equator. This is to avoid introducing the cylindrical projection associated with transforming three dimensional coordinates to a two-dimensional grid. Our focus in this study is to constrain distortion solely from the mapping process.

The grid that we use has a resolution of 0.5° per grid element, and exists on a 3,601 × 7,201 latitude by longitude grid. This results in there being 530 and 132 grid points per facet for the shape models with 49 k and 196 k facets, respectively. This oversampling of grid points per facet reduces the likelihood that any strong additional projection effects will be added by this step.

### 3. Metrics

We created specific metrics to quantify the projection effects of our standard spectral map creation process. The smear metric measures the length of the outcrop extending beyond the originally defined region in the truth map. When the original truth map signal is spread out by the projection process, the highest value can also be reduced. The contrast reduction metric quantifies the decrease in the maximum signal in a projected map outcrop, relative to the original truth map. The retention metric sums the global signal of the interpolated map and compares it to that of the truth map.

#### 3.1. Smear

We measure the distortion or “smear” of our mapped quantities, and not the smear of the instrument FOV due to spacecraft motion (which is another commonly employment of the term smear). Smear is a measure of the distance over which the edge of a mineral-outcrop surface contrast spreads out when passed through the mapping process. We define it as the average length that the outcrop's border extends in the projected map beyond the original defined borders of the outcrop in the truth map.

Smear can be visualized as the distance from the black to the white outlines of the outcrops; radially in Figures 5, 8 and 9, and vertically in Figure 10. To calculate the smear length, first, we subtract the truth map in Figure 3 from Figures 8 and 9. Second, we find the farthest data points from the center of the outcrop with a non-zero value. Since the maps are idealized, and have the same homogeneous background, nonzero values locate where signal from the center of the outcrop has spread. We subtract the radius of the outcrop from the smeared distances. We do this for every data point surrounding the outcrop and report the error as one standard deviation of each outcrop.

A very similar process is conducted for Figure 10. The main difference is that these maps have errors associated with them, and, therefore, we must have a threshold determination of a smeared signal. Instead of searching for where the discrepancy is zero, we search for the largest radial distance from the outcrop's
boundary where the difference between the truth map and the data product is greater than the uncertainty in the map of the data product. We do this for the length of each outcrop and report the standard deviation as the error.

### 3.2. Contrast Reduction

This metric quantifies the fraction of a projected map’s facet value relative to the truth map value. We search for the facet with the highest value within an outcrop. We use the makeMaps.m 3D projected map for this metric (Figure 4), not the interpolated 2D map. Restricting the search to only include values within the original outcrop dimensions always returns the maximum facet value because the facets on the periphery have intermittent values between the outcrop and the surrounding background. Although we defined the

**Figure 5.** The three maps here compare the different algorithms of assigning spot data to the shape model’s facets. The white border surrounding each outcrop shows the smear (the spatial extent to which the signal has spread) from the truth map’s original border (shown in black). We omit the black borders of (c) to highlight the undesirable sinusoidal shaped artifact from the instrument’s north-south slewing pattern.
Figure 6. These plots show the reduction metric applied to various projected maps, where one curve corresponds to one projected map, and each data point corresponds to one outcrop. Our reduction metric captures the ratio of each outcrop’s highest value over its value in the truth map. For example, a reduction value of 90% means the facet with the highest value in an outcrop is 90% of the truth map’s, or 10% lower. Panel (a) compares the different algorithms while using the same shape model. Panel (b) compares different shape model resolutions using the average algorithm. Panel (c) demonstrates the use of more observations on the 49 k shape model. Panel (d) performs the same analysis as (c) but with simulated photometric corrections.

Figure 7. We report the y-axis in terms of the smearing distance, the distance from the black to white boundary, relative to the OVIRS spot diameter. For (a), we plot the x-axis the same as in Figure 6. In (b), we average together the smear for each outcrop and report one smear quantity for the map as a whole. For the x-axis in (b), we use the mean facet edge length divided by the mean OVIRS spot diameter. The horizontal error bars are the propagated standard deviation of the facet edge lengths and spot diameters. In comparing (b) to (a), we note that the mapping algorithm has a larger effect on smear than the shape model resolution. OVIRS, OSIRIS-REx Visible and InfraRed Spectrometer.
outcrops in this study to have a higher reflectance value than the surrounding background, in principle our methods could work for the opposite case. Contrast reduction is, thus, calculated as:

\[ R = 100 \times \frac{D_{\text{max}}}{T} \]  

where \( R \) is the contrast reduction, \( D \) is the maximum data value, and \( T \) is the spectral value of that region in the truth map. A value of 100% means that there is no reduction of the maximum contrast in the projected map relative to the truth map. A value less than 100% means that contrast reduction has occurred.

In most situations, we are able to search for and find the facets that are inside an outcrop. This search is conducted on the basis that the facet centroid is at a radial distance away from the outcrop center that is smaller than the outcrop radius. However, in the case of the 12 k shape model and the smallest outcrop used in the study, there are no facets that satisfy this condition. The outcrop is smaller than a facet and not near a facet centroid. When this happens, we calculate the contrast reduction using the facet whose centroid is closest to the center of the outcrop.

### 3.3. Retention

One of the most important questions about our mapping process is whether signal is created or destroyed. Neither would be desirable, so we devised this metric to perform a quick check that signal is retained. For the global signal, we sum all of the values of a discrepancy map—a map created from subtracting each grid point of a data product with the truth map (for example subtracting the truth map in Figure 3 from Figure 8). A positive value would indicate that signal is created, and a negative value would indicate signal is

![Figure 8](image-url). The two maps compare the effect of different shape model resolutions. Both maps use the average mapping algorithm. The zoomed images show the same outcrop for each map.
lost. We find that our spectral mapping procedures do not create or destroy signal. Thus, despite the smear and contrast reduction that we observe as projection effects, global signal is conserved.

4. Results

For the map shown in this section (Figures 5, 8, 9, and 10), the figure panels are ordered by quality, with the highest-quality map at the top.

4.1. Algorithms

Given the six algorithms that we considered for assigning spectral data to shape model facets, which works the best? These six algorithms can be broken down into two categories: combination and selection algorithms. When the spots that overlay a facet are assigned to the facet, all of the data can be statistically combined, or a single data value can be selected using a reasonable criterion. The selection algorithms are the median, nearest distance, and most recent, algorithms, and the combination algorithms are average, sigma clip, and weighted average.

We begin with visualizations of the maps from three of the six algorithms in Figure 5. We show the maps in order of highest quality to lowest, (a)-(c). Figure 5 shows that maps made from the (b) average algorithm smear more signal than maps made from the (a) nearest distance algorithm. This is shown with the outcrop's signal being more spread in (b). In addition to (b) having more smear than (a), the concentration of the original intensity of the signal of the outcrops before mapping is more well retained in (a), as shown with the darker red signal in the smaller outcrops, than panel (b).
The most recent algorithm is subject to the bias of the observation sequence, as shown in Figure 5c. For OSI-RIS-REx, the spacecraft observation sequence places the spacecraft at one local time of day and conducts north and south slews, while the asteroid completes a full rotation, to observe the entire surface (Lauretta et al., 2015). Therefore, while using the most recent algorithm to map, if the spacecraft conducts a north to south slew an entire longitudinal strip of facets systematically selects the southern-most spots. Likewise, when the spacecraft conducts the south to north slew, an entire longitudinal strip of facets systematically selects the northern-most spots. This results in a wave-like “sinusoidal” warping of mapped outcrops. Because of this artifact, we do not recommend the most recent algorithm due to the spacecraft’s north-south slewing patterns.

While applying our quantitative metrics, we’ve come across a striking result that the metrics are unable to parse any differences between the different averaging algorithms. In Figure 6a, we show plots of our reduction metric applied to each outcrop of six different map products. Each map uses the shape model with 49 k facets or mean facet edge length of 628 cm. The bottom curve in light blue is the weighted average mapping algorithm, and it covers the curves of sig-clip, median, and average—demonstrating that they are essentially indistinguishable. In fact, there are no obvious visual differences between these maps either. Given that they are not distinguishable from visual inspection, we have decided to show only maps made using the average algorithm in our figures (e.g. Figures 5b, 8, and 10a). This simplification allows us to explore the differences between the two most distinct algorithms: the nearest distance and averaging algorithms. All maps are available from the Ferrone et al. (2019) data repository.

**Figure 10.** These maps use a different truth map than shown in Figure 3. These maps are an extension of the experiment shown in Figure 9 in which now we add photometric modeling and photometric correction uncertainties.
In Figure 6a, the purple curve is the algorithm that assigns the most recent observation in time to each facet. In this plot, the purple curve essentially overlays the nearest distance algorithm, apart from the smallest outcrop. This metric, however, does not display the complete story in showing that nearest distance is superior to most recent. The metric does not capture the north south slewing bias as evident in visual inspection of the map in Figure 5c.

Figure 7a quantifies the smear of each outcrop for maps made from using the average algorithm and the nearest distance algorithm. They both use a single global survey station and the shape model with mean facet edge length of 628 cm, which are the maps in Figure 5.

An interesting result shown in Figure 7a is that an outcrop's smear is not a function of the outcrop's size. Rather, the smear is characterized by the mapping algorithm and the shape model resolution. For the 628 cm mean facet edge length shape model, the nearest distance map will smear 0.45 ± 0.05 OVIRS’ diameter while the average map will smear 0.65 ± 0.05, as shown in Table 1. The smaller mean smear of the nearest distance map to the average map shows that the nearest distance algorithm better retains the spatial distribution of an outcrop. However, smear is an inherent artifact in this method of mapping circular spectrometer spots to triangular facets of a shape model; in considering all map permutations, we have studied in this experiment, signal from one region will smear and mix with adjacent regions up to ~0.4–0.75 spot diameter, or roughly the size of the instrument's FOV radius (Table 2).

### 4.2. Shape Models

Given the spectrometer spot size and choices for the sizes of the shape model facets, which is the best to use for spectral mapping? At the start of this study, it was not clear to us whether facets of comparable size to the spectrometer spot would be the best mapping practice (under-sampling the spots), or whether a shape model with the smallest possible facet size (over-sampling the spots) would be best for mapping.

In Figure 8, one can see that the map using a finer-resolution shape model in panel (a) results in a smoother border than the coarser-resolution shape model map in panel (b). Panel (a) also shows better representation of the signal inside each outcrop.

Figure 7(b) shows our quantification of the smear of full global maps for each shape model resolution. We have defined the x-axis to be the ratio of the mean facet edge length to the OVIRS spot diameter. We calculated the mean facet edge length of each shape model using the facets that are between −10 and 10 latitude as well as from 0° to 180° longitude—where the outcrops are located. This figure demonstrates that as the facet size becomes larger, the smear becomes larger. The standard deviation also becomes larger which can be regarded as a metric for the "jaggedness." Clearly, larger facets do not result in maps that reproduce the dimensions of outcrops in the truth map as well as smaller facets.

Note that although the smear metric (in Figure 7b) shows that map fidelity is better with smaller facets, the improvement in quality due to facet size is less significant than improvement in quality due to choice of algorithm (as shown in Figure 7a). This is not to say that the quality difference is "insignificant," rather these results in tandem with those shown in Figure 6b indicate that finer facets improve map fidelity only up to a point. After this point, using smaller facets will no longer significantly improve results. In Figure 6b, the reduction curve of the 12 k shape model shows less reduction than the 49 k and 196 k shape models. The 49 k and 196 k shape model show nearly identical results, save for the smallest outcrop. In other words, the reduction metric shows there is no essential difference between the map created from the 49 k shape model and the 196 k shape model. This is consistent with the zoomed in

| Table 1 | The Smear of Average and Nearest Distance on the 49 k Shape Model Varying the Surface Coverage |
|---------|-------------------------------------------------|
| Smear on 49 k | Average | Nearest distance |
| 3 Global Surveys | 0.76 ± 0.05 | 0.43 ± 0.04 |
| Single Global Survey | 0.65 ± 0.05 | 0.45 ± 0.05 |

The units of smear is a fraction of the OVIRS FOV diameter. The average maps are shown in Figure 8, while the nearest distance maps are shown in Figure 9. The errors are the standard deviations of each outcrop’s smear summed in quadrature per map. FOV, field of view; OVIRS, OSIRIS-REx Visible and InfraRed Spectrometer.

| Table 2 | The Computation Time Here is Based on a 2015 MacBook Pro With a 2.9 GHz Intel Core i5 Processor, With a DDR3 RAM of 8 GB and Transfer Rate of 1867 MHz |
|---------|-------------------------------------------------|
| Facet count | 12 k | 49 k | 196 k |
| Mean Facet Edge Length | 1278 cm | 628 cm | 314 cm |
| Getspots File Size | 3.3 MB | 13.3 MB | 53.6 MB |
| Map File Size | 305 kB | 1.2 MB | 4.7 MB |
| Computation Time of Getspots | ~8 min | ~30 min | ~2 h |

Getspots is C code that has been compiled and is run as a unix executable.
outcrops of Figures 8a and 8b where the fine shape model in panel (a) retains some of the peak reflectance values while panel (b) does not.

Another interesting aspect of the spectral maps, apart from map fidelity, is the computation time and file size involved in creating these maps. In the context of the OSIRIS-REx mission, considering the number of global survey stations, instruments, different map-able quantities, and other factors, the possible permutations provide a large number of maps. We must create the Getspots files, which coordinate the observations to the facets of the shape model, as well as the data mapped to each facet. This needs to be done once for each instrument, and each survey, and each shape model. These factors further the importance in considering convenience and map exchangeability. Table 2 shows some file sizes and typical computation times for the maps and Getspots files for each shape model. Notice that when the mean facet edge length decreases by a factor of two: the facet count, Getspots file size, map data product file size, and computation time increase by a factor of four.

Considering that the file sizes of the 49 k shape model are smaller by a factor of 4 than the 196 k shape model, and considering that we have demonstrated that there is no significant change in quality, we recommend this shape model for creating spectral maps with OVIRS. However, it would not be unreasonable to use the 196 k shape model. The ~2 h computation times for the Getspots files are not quick yet they are also not unreasonable. Once a Getspots file is made, the observations are registered to a specific shape model and that Getspots file does not need to be computed again in order to map quantities derived subsequently from those observations. However, halving the shape model resolution again to facets of ~150 cm in size would bring the computation time to 8 h. Using the finest shape model resolution planned for the mission of ~75 cm could take up to 16 h. This seems unnecessarily cumbersome given the diminishing returns on map fidelity.

From Figure 7b, we generalize beyond OSIRIS-REx mapping with OVIRS by expressing the smear metric in terms of a “size ratio” of the mean facet edge length to the diameter of the instrument spot size. If we consider the 49 k facet shape model to be “sufficient” with a size ratio of ~0.37, then, rule of thumb, “better than 0.4” is sufficient to retain map fidelity. The OTES instrument, with a spot size twice that of OVIRS during mission phases when the two instruments are both observing, would have a size ratio to the 12 k shape model of ~0.35. Applying our new rule of thumb, we suggest that the 12 k facet shape model will be sufficient for mapping with OTES spectrometer data.

4.3. Combining Data

Even after we have enough observations to completely cover the surface, if we add more observations can we improve map fidelity? First, we begin by attempting to add all observations from three different observation sequences into one data set for mapping assuming that each observation is idealized and taken under the same photometric viewing conditions. In essence, the experiment isolates the mapping variable to be the number of observations to cover the surface. This tests if increasing the observation count will improve map fidelity. At the same time, we know that in the case of OSIRIS-REx mapping, the observing conditions are not the same, therefore, we also conduct a second test from modeling the effects from the different viewing conditions. We begin by displaying the idealized results (i.e. the same incidence, emission, and phase angles). The following section discusses results of combining observations without neglecting the effects observing conditions have on the data.

We complete this experiment in the context of OSIRIS-REx. In the Detailed Survey phase of the mission, there are three stations where the spacecraft maintains position with respect to Bennu, and observes the whole surface throughout one complete rotation of the asteroid. These campaigns have local solar times of 10:00 a.m., 12:30 p.m., and 3:00 p.m. (Lauretta et al., 2015). Effectively, we compare maps created from using 3× the number of observations necessary to obtain global coverage, Figure 9a to Figure 9b, respectively.

The comparison of the maps in Figure 9 show that sub-panel (a) has smoother borders and less smear than sub-panel (b). Figure 6c shows the reduction for each outcrop of these two maps. The yellow curve is three global surveys using the nearest distance algorithm, Figure 9a, and the purple uses nearest distance and one global survey (Figure 9b). We note that in these curves, yellow shows less reduction of signal for two
outcrops as the size of the outcrop decreases relative to the instrument diameter size. We note, especially, the drop in reduction from the third to the fourth smallest outcrops in the purple curve, where the yellow curve remains monotonic and increasing. We attribute the drop in signal to originate from the nearest spot not being directly over the outcrop, thus, increasing the outside regions signal’s weight in the net observation. The yellow curve has a higher contrast reduction mostly from chance. Since there are 3× the number of spots, the chance that a spot would directly cover the outcrop is higher, and, thus, that particular outcrop is less reduced and the contrast was better retained. The outcrop we speak of is shown in the zoomed-in regions of Figure 9.

The contrast reduction metric does not show improvement in map fidelity upon increasing the observation count for an Averaging algorithm. From inspection of the red and blue curves in Figure 6c, neither can definitively be stated as superior. In the case of averaging, a consequence of using more observations is that signal can be mixed between two regions. Since we are averaging all spots that cover a facet anyway, increasing the observation count does not change the contrast reduction in mapping.

The values in Table 1 report the smear for each map. The smear for a map is average smear for all outcrops. The error is found from adding the standard deviations of each outcrop’s smear in quadrature and dividing by the number of outcrops. We use the error again as a metric for the “jaggedness” of the border between the outcrop and the surrounding region. Smaller smear and error show higher map fidelity. Thus, from Table 1, the map created from using the nearest distance algorithm with three global surveys best reproduces the truth map.

Again, the smear metric (similar to contrast reduction) does not support the hypothesis that increasing the observation count for a map created using the average algorithm will improve fidelity. Table 1 shows that the smear is higher for three global surveys than a single global survey for the average algorithm. We attribute this to mixing between two regions. This larger mixing of the two regions while mapping expands the outcrop’s original dimensions. Despite the fact that smear is larger for a map created using the average algorithm with ~3× the number of observations, the error is smaller. This shows that even though the borders are more saturated and extended, they have a shape more consistent with the truth map. The weighted average, sig-clip, and median maps are shown in Ferrone et al. (2019).

4.4. Simulating Photometric Effects

While we have demonstrated in the previous section that increasing the observation count can improve map fidelity for the nearest distance algorithm, we have devised an experiment to see if we can enhance map resolution by increasing the observation count within the constraints of the OSIRIS-REx mission. During the Detailed Survey mission phase, the spacecraft parks at local solar time positions of 10:00 a.m., 3:00 p.m., and 12:30 p.m. while the asteroid rotates to observe the entire surface. Thus, in actual OSIRIS-REx conditions the data are largely constrained by the illumination and observation angles. Photometric models must be employed to correct the data as if each observation was viewed from the same orientation (Li et al., 2015).

To simulate photometric effects encountered by OSIRIS-REx, first we start with the laboratory spectra provided by Donaldson Hanna et al. (2017). We employ a photometric model derived by Li et al. (2007) for a comet nucleus to extrapolate how reflectance of the simulated observed spectra would change as a function of the viewing geometry. While extrapolating reflectance for each spectrum of each observation of the three global surveys, we add Gaussian zero mean noise to the data. Many photometric model would have been sufficient to simulate the effects of viewing geometry; we chose the model from Li et al. (2007). The observations were then blindly corrected. The methods in Zou et al. (2021) were used to choose the best photometric model in reversing these effects and correcting each observation to the same viewing geometry of the data provided from Donaldson Hanna et al. (2017). We then used these observations to create the maps shown in Figure 10.

We note that in Figure 10b, there is strong aliasing pattern from the north south slews of the spacecraft. We note the systematic differences in values from adjacent longitudinal strips. We believe this arises because the photometric correction, which is not perfect, systematically over/under corrects different survey stations when correcting to the standard viewing geometry. Since the observation sequences of the OVIIRS instrument are north-south slews, there is little longitudinal variation within one slew. Thus, entire slews of
one survey are systematically closer to a strip of facets than another survey’s slew. Thus, if creating a map using data from different phase angles, and there are uncorrected systematic differences between the data sets, then the nearest distance algorithm is more susceptible to artifacts than the average algorithms.

In Figure 6d, we see that even with modeled photometric effects we still follow the same trend in terms of which outcrop’s signal is reduced with size relative to the spectrometer’s diameter. We have chosen to use a truth map with rectangular outcrops for Figure 10 to better show the aliasing bias from different surveys. Despite the difference in representation, and the addition of photometric effects, the smearing and contrast reduction results have not changed. We express the x-axis of Figure 10d to be the ratio of the outcrop’s width (in latitude) to the outcrop’s diameter. The figure shows that when the width is twice the diameter of the instrument FOV, there should be no signal from the spot that reaches the center of the outcrop. The lower limit in which a perfectly placed observation may land and fall entirely within the outcrop is when the width is the same as the spot diameter. These two limits are shown with black vertical bars.

In Figure 10a, we note that averaging values to the facets of the shape model from different global surveys smooth over these systematic biases. We conclude that averaging observations together from different surveys may be a more conservative method while mapping to reduce potential artifacts from individual surveys and the differences between each survey.

Overall, we note that adding observations together from different surveys may enhance results while using the nearest distance algorithm if they may be combined without systematic differences. In cases when there are subtle radiometric differences between the data from different survey stations, the average algorithm may be effective to reduce the artifacts visible in any single global data set used alone.

5. Summary and Conclusion

We produced global spectral maps from simulated point spectrometer data in the context of the OSIRIS-REx mission. We simulated OVIRS observations of a simple artificial world with two “values” or mineralogies: a global background (surroundings) and distinct embedded outcrops of varying sizes. We explored the mapping process of assigning simulated data from the spectrometer spots onto the triangular facets of a shape model of Bennu at three different spatial resolutions. The primary mapping considerations are the facet size of the shape model, the size of the instrument’s spot, and the algorithm selected for assigning spectral data to each facet. We evaluated different choices using three main metrics: first, visual inspection; second, a smear metric that measures the distortion of an outcrop’s boundary with the surroundings; and third, the reduction in contrast of the outcrop’s “truth” peak value due to the mapping method selected.

We explored different algorithms for assigning the spectral data from the spot observations to the facets of the shape model. We find the differences between methods to be maximized when comparing maps made using an averaging algorithm versus the nearest distance algorithm. We tested three different averaging algorithms: an average, a weighted average by area coverage, and a sigma clipping method where data outside of three standard deviations are rejected and the average is recalculated. We find no meaningful differences in map quality among maps made with averaging algorithms.

The quality differences between maps that average data and maps that select data for facets are, however, substantial. The border of an outcrop from an average map smears up to ∼1.25 spot radii, and in the worst cases, ∼1.5 spot radii. In comparison, when using the nearest distance algorithm, outcrops smear up to only ∼0.8–1 instrument spot radii. We find that boundary smear depends on instrument spot size, and second, facet size. The smear is independent of the size of the outcrop.

We find that increasing shape model resolution increases map fidelity to a point. Once this limit is reached, decreasing the facet size becomes increasingly computationally expensive and improvements in fidelity diminish. We find that the optimum configuration is when the length of a facet is about 40% of the diameter of a spot. Maps created from facets larger than this will suffer from the coarseness of the shape model.

Contrasting outcrops that are smaller than the instrument’s projected spot size can be detected while mapping. The center facet of an outcrop that is larger than the spot diameter will be mapped without a reduction in value. A region whose smallest linear dimension is about two-fifths of the spectrometer’s diameter will
show signal reduction to about 30% of the original value. We would consider that outcrop to be detected only if the difference between that 30% reduction of signal and the signal of the local surroundings is above the detection limit of the instrument.

We tested whether map fidelity can be improved using three times more observations than required for global coverage. We compared maps using three simulated day-side global surveys and compare them with maps that use only a single simulated day-side global survey. While the values are idealized, we find that fidelity of maps created using three surveys is higher than for maps created using one survey. However, using an averaging algorithm in such an over-sampled case can "super-smear" an outcrop. The averaging of more data smears outcrop borders up to the worst-case scenario, about 1.5 spot radii.

Lastly, we simulated what happens when three global surveys from different observing conditions are photometrically corrected before being combined. We were unable to precisely map the data from different observing conditions, and each different global survey had some small yet systematic differences. When combining data from the three global survey stations and mapping with the nearest distance algorithm, we found the position-based selection method to impart a map bias, where a whole north-south slew from only one global survey is assigned to a vertical strip of facets, and an adjacent vertical strip of facets take the values from a different global survey. This resulted in vertical linear artifacts on the surface. This aliasing is undesirable and, thus, if the observations cannot be corrected to a sufficient precision where the differences between data sets are not smaller than the uncertainty in each individual observation, mapping with the nearest distance algorithm is not viable. On the other hand, the averaging algorithm seems to work well under these conditions, and such maps are advantageous over single survey average maps. Thus, if difficulties appear in mapping observations from different viewing conditions, using the average algorithm can be effective, and most likely, conservative.

Data Availability Statement

The data from this study are available in the Mendeley data repository (Ferrone et al., 2019; doi: https://data.mendeley.com/datasets/htjvrstdx6/2).

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