MRD 687 (Global 35cm DTM)

Summary of Requirements

MRD-687: The Ground System shall, for > 80% of the asteroid surface, produce a set of DTMs at < 0.35 m in ground sample distance (sample resolution).

Note: Ground sample distance is defined as the sample spacing of the surface in m/pix.

Rationale: Ground sample distance of DTMs should be comparable to navigation imager(s) ground sample distance (m/px) for relevant mission phases.

MRD-689: The Ground System shall, for > 80% of the asteroid surface, produce a set of DTMs with post-fit residual RMS < 0.18 m (1-sigma) for each maplet.

Note: Post-fit residual of a maplet is defined as the (pixel, line) difference between predicted model and observed images of the maplet.

Rationale: The RMS post-fit residual from the DTM geometry solution should be less than 0.5 DTM pixels (1-sigma). Landmarks consist of an image spanning multiple pixels. Errors in the correlation of an OpNav image to a landmark will be introduced if there are distortions in the features of the landmark, or relative shifts in the positions of adjacent landmarks. This requirement bounds the allowable distortion of features across the landmark, or variations in the relative position shifts of nearby landmarks, which factors into the FDS landmark centerfinding error budget through errors in the correlation of OpNav images with a landmark.

Note: Verifying this requirement in flight assumes use of images for shape modeling that have a better ground sample distance than the maplets (i.e., Mapcam or Polycam imaging) as well as use of overlapping OLA data.

MRD-691: The Ground System shall, for > 80% of the asteroid surface, produce a set of DTMs with a 3D RMS accuracy < 0.75 m (1-sigma).

Note: Accuracy is defined as the absolute uncertainty of a point with respect to the origin of the asteroid centered fixed frame.

Rationale: Global accuracy of the delivered landmark centers factors into the FDS landmark-tracking error budget.

Note: Accuracy will be verified in flight through analysis and with OLA data.

MRD-693: The Ground System shall provide the global 35cm DTM product to FDS within 14 days of downlink of all Detailed Survey "Baseball Diamond" OCAMS and OLA data.

Rationale: 14 days ensures the global 35cm product is available early in Orbital B to demonstrate the predictive accuracy needed for Recon and TAG.

Verification Overview

The topographic maps or digital terrain maps (DTMs) produced to satisfy these requirements are generated using Stereo-Photoclinometry (SPC) processing of OCAMS image data or using range data obtained by the OSIRIS-REx Laser Altimeter (OLA). The Altimeter Working group (AltWG), in concert with science operations (SPOC), navigation (FDS), and mission operations (MSA) teams, conducted a set of tests to verify the spatial resolution, accuracy, and vertical precision of these products. These tests quantify the SPC, OLA, and processing performance by comparing the map products with truth models. In-flight measurements at Bennu will provide additional verification of vertical accuracy using shadow measurements from imaging data and using comparisons between the OLA and SPC terrain maps. The algorithms employed to produce the topographic maps have extensive heritage that includes analyses of data from Dawn, Hayabusa, and MESSENGER spacecraft.

Tests have verified that these requirements will be met, usually by each of the two methods, SPC and OLA. Table 1 contains a summary of the verified performance. Details, including liens and caveats are provided in the text.

Table 1. Tested performance.

MRD	Requirement	Test results
687	80% coverage, 35 cm GSD	100%, 35 cm (SPC); 30 cm (OLA)
689	Residual RMS < 18 cm	< 18 cm for >90% (SPC)
691	3D accuracy <75 cm	37 cm (SPC); 20 cm (OLA)
693	Deliver within 14 days	<11 days (SPC)

Data products required

SPC requires images from the OSIRIS-REx Camera Suite (OCAMS) with sufficient resolution and adequate variation of incidence and emission angles. OLA maps require altimeter measurements that encompass the sites. Additional required data include reconstructed NAIF SPICE spacecraft ephemeris kernels (SPK), attitude NAIF SPICE kernels (CKs) for the spacecraft and instrument pointing, instrument kernels (IK) for OLA and OCAMS, frames kernels (FK), and spacecraft clock kernel (SCLK). The spacecraft SPK should include the location of the spacecraft center of mass (COM). The initial shape model of Bennu is based on radar data from Arecibo measurements and will be updated based on processing of in-flight data. Since topography or "geopotential altitude" is defined relative to a geopotential surface, topography products require the mass of Bennu to compute the geoid. Figure 1 illustrates all of the data required by the AltWG to meet its requirements, including those in MRD 687, 689, 691, and 693.

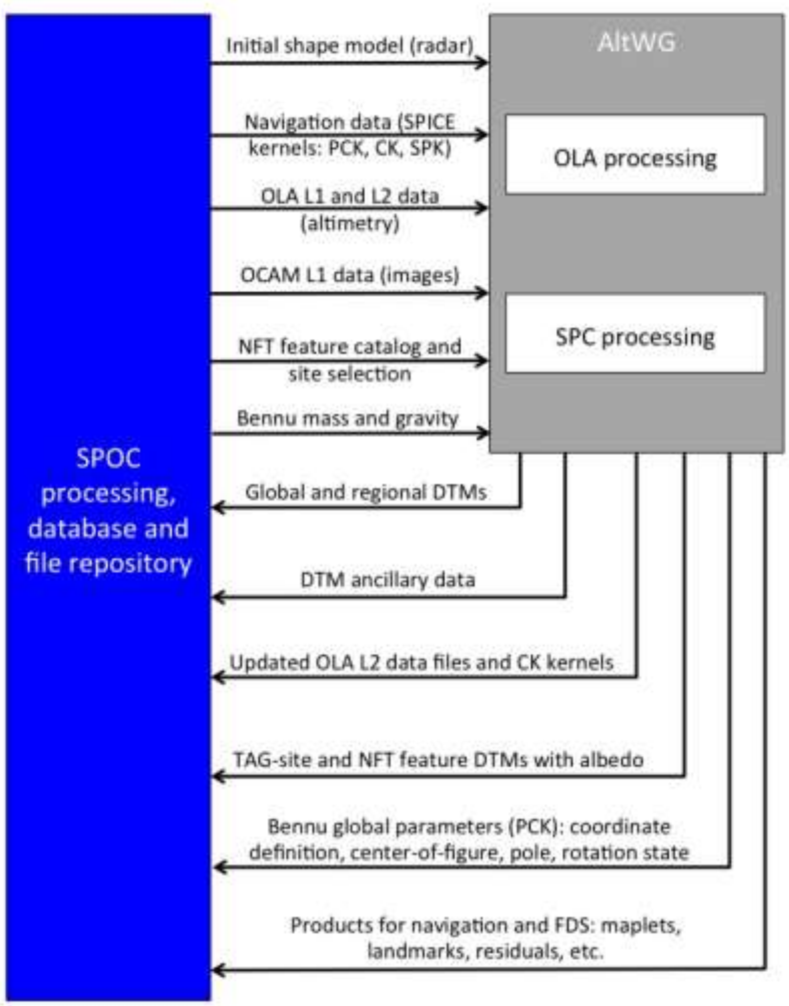

Figure 1. Data flow of the Altimetry Working Group that generates this required product.

The resulting outputs include:

OBJ shape file (ASCII) of each region.

SPC Maplets in the MAP format

Binary multi-layered FITS images with incorporated headers where DTM and all ancillary data produced are included (including topography).

NFT specific multi-layered FITS file (a subset of the full multi-layered FITS file with only surface height, albedo and data quality information)

ASCII or binary ancillary FITS tables where each number corresponds to a facet in the original OBJ file.

Detailed description of many of these products are listed in the ALTWG SIS (UA-SIS-9.4.4-307), OLA SIS (UA-SIS-9.4.4-302), and NFT SIS (UA-SIS-9.4.4-327).

Ability/Availability of the System to Generate Sufficient Observations

The OSIRIS-REx spacecraft, OCAMS, OLA, and mission were all designed and built to specifications that ensure the AltWG obtains the data necessary for the generation of the products required during the mission. The detailed observing plan was reviewed and then modified to provide images with the incidence and emission angles required for generating accurate maps using SPC processing.

Minimum Success Criteria

The minimum sample-return mission requires that the AltWG produce at least one topographic map that meets requirements MRD-687, 689, 691, and 693.

Dependencies per Mission Phase

Images from the approach, preliminary-survey, and detailed-survey phases are required to generate the SPC-derived topographic map that meets these requirements. The OLA map requires measurements from the detailed survey phase.

Adequacy of the Design Reference Mission (DRM)

Testing confirms that the stereo imaging and altimetry acquired by the current DRM Rev C is sufficient to produce SPC and OLA topographic maps with the accuracy and resolution required by MRD-678, 680, and 682.

The current plan provides the required global coverage with sufficient overlap between images and between individual OLA scans. The spacecraft observation geometry provides the incidence and emission angles to fulfill the SPC processing needs.

Data Products per Mission Phase

The SPC topographic maps to meet these requirements will be completed within 14 days from the time that all required data are available to the AltWG.

Overview of Processing

Altimetry data processing is an iterative process that repeats the same processing steps several times to sequentially generate products of higher and higher fidelity. After each iteration, the products are evaluated with respect to the requirements and to the results of the previous iteration, stopping when requirements are met or when improvement is negligible. If new data are available, they are added to the processing for the next iteration. The AltWG efforts are two-pronged, one based on SPC processing of OCAMS images and a second based on OLA data. Usually, OLA processing requires only one or two iterations. The intermediate, lower-fidelity data products for both SPC and OLA will be produced in the same format as the final products. The next paragraphs describe the processing steps that produce each one of these products. The "ALT" label to map products refers to those generated from OLA data.

In one parallel effort, all the OCAMS images of the surface of Bennu are taken to incrementally build a shape model of the asteroid using SPC. SPC combines stereo techniques with photoclinometry to derive the tilt at each surface pixel of a given image. SPC uses stereo parallax to define the initial relationship between surface tilts and observed albedo. The tilts of a piece of asteroid surface imagined at multiple emission and incidence angles can then be refined via least squares to identify the tilts that best duplicate the input images. Once the surface tilts are obtained, the geometric height across each map is determined by integrating over the tilts. These individual terrain maps (called "MAPLETS") of the surface are then joined together to produce global shape models and regional digital terrain maps, taking additional advantage of stereo parallax. SPC also uses asteroid limb and terminator data to constrain the shape of the asteroid. Additional details on SPC processing are available in Gaskell et al., (2008) and Gaskell et al., (2011). The global shape model and the regional terrains maps are the primary SPC products. SPC also provides estimates of the center of figure, pole location, wobble and rotation state, and volume of Bennu.

The second parallel effort uses the OLA Level 2 data products to create a shape model. The process makes use of the University of Hawaii's School of Ocean and Oceanography (SOEST) Generic Mapping Tool (GMT). The locations of each OLA measurement in the asteroid body fixed frame are an "OLA point cloud" and are collected in a global or local grid generated over the surface. Then the GMT blockmedian, and the GMT sphrinterpolate or surface algorithms are used to generate an initial set of low-resolution surface maps by computing the median height of a grid and performing a spline fit. Local maps are produced by splitting OLA data into a suite of low-resolution local maps ("MAPOLAs"), which can then be combined using the same algorithms and processes employed to convert SPC MAPLETS to the global shape. The OLA data are adjusted to the global map using an iterative closest-approach algorithm, to minimize differences between the OLA point cloud and these surfaces. Each iteration produces a suite of slightly higher resolution maps. This process is repeated until additional adjustments yield no improvements in the resulting maps. With this final set of MAPOLAS, a global shape model and a suite of regional surfaces and tilt maps are produced. Combining OLA data with the SPC products generates the final, highest-fidelity version of these parameters.

The AltWG uses the surface terrain models to compute the height or geopotential topography at each OLA measurement and at the center of each facet of the shape, global, and site-specific maps. This definition of topography requires a reference geoid, which is an estimate of the local geopotential and provides the local acceleration due to gravity (Turcotte and Schubert, 1986). The shape model provides a volume over which to integrate to obtain the surface geopotential, acceleration due to gravity, and thus topography. We use a uniform density until the Radio Science Working Group (RSWG) finds that the gravity field measured by the OSIRIS-REx spacecraft indicates that Bennu's density is sufficiently heterogeneous to warrant a more-sophisticated density model.

The AltWG will generate initial products of topography, potential, gravity, and slope using this assumption of uniform gravity. The AltWG and the RSWG use the technique of Werner and Scheeres (1996) to compute the geoid and gravitational acceleration of an asteroid and can use an alternative algorithm that generates equivalent results but requires a factor of 2.5 less computing time (Cheng et al. 2002). Both algorithms can derive rotation rate and wobble. With either algorithm, the processing computes the scalar potential U at each facet center of a shape model, and the associated vector of acceleration due to gravity g. In the case where the measured gravity field shows a large discrepancy between the field produced by the shape of the asteroid, and measureable heterogeneity, the algorithm produced by the RSWG is used to compute the geopotential, the acceleration due to gravity and surface slopes correctly across the asteroid, and for individual OLA data.

Once a geoid is computed, the height or topography e as measured at each facet center x of a shape model or at each OLA return becomes $e = [U(x)-Uref]/|g|$ where Uref is a reference potential. Because of the important centrifugal effects due to the rotation of Bennu, we set Uref to the minimum potential at the surface rather than some other average value. To compute surface slope in degrees with respect to gravity, we use $\cos = n(x).g(x)/|n(x)||g(x)|$where n is the normal vector to each facet center x of a shape model produced by the AltWG.

AltWG also provides several products of surface tilts. Tilts are a measure of surface shape that are independent of geopotential topography. Absolute tilt is important for evaluating the viability of potential TAG sites.

All the software and algorithms that produce the required products are tested and verified. Additional testing is planned to improve margins and evaluate contingencies. The SPC code is qualified and controlled at the class B level.

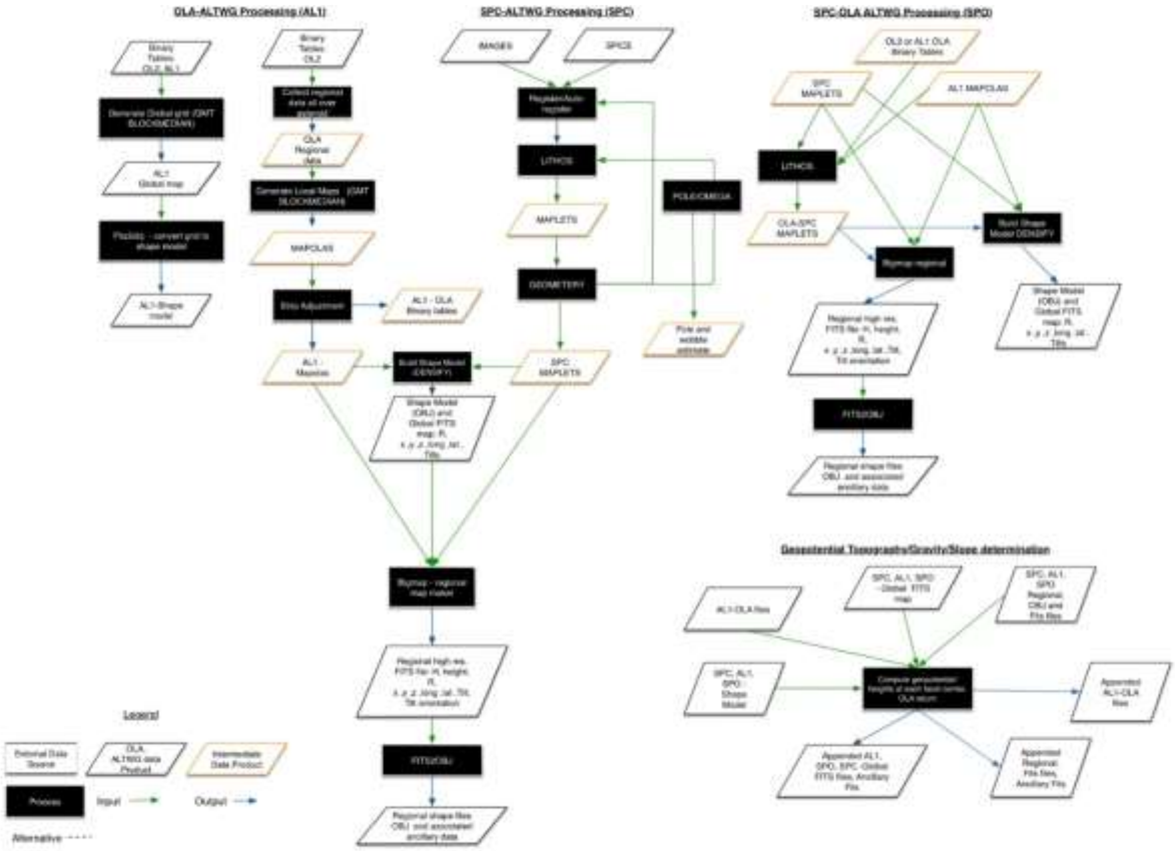

Figure 2: Flow chart showing the processing that produce global and regional maps from which are generated the required topographic maps.

Provenance of Algorithms, Software and Techniques

The SPC algorithms, software and techniques employed have recent heritage, including use in an operational settings: Dawn, Hayabusa, MESSENGER and LRO. The SPC software has been qualified as Class B by modularizing and documenting the code. Many of the software tools such as GMT are standard tools used in many missions including MGS (MOLA) and the NEAR-Shoemaker mission.

Expected Results/Simulated Data

SPC and OLA data products that would satisfy these requirements were produced during several tests, with F4 begin the highest-fidelity SPC test and ALT2 the highest-fidelity OLA test. F4 included spacecraft trajectory and pointing errors for the imaged processed by SPC, and the OLA data contained perturbations that simulated the errors in range measurements. Table 2 shows the results of the test. During F4, the required SPC products were generated in 11 days, including some unproductive time during a weekend. This time could be reduced by using additional processors. Initial tests of OLA processing showed that one person can generate the OLA products in one week.

The following section, titled “Analysis & Verification Methods,” provides details of the tests.

Table 2. Performance of topography products produced in tests to verify MRD 687, 689, and 691.

Product	Accuracy	Coverage	RMS	Notes
SPC	37 cm	100%	<18 cm (92%)	F3, F4 tests
OLA	20 cm	96%	Pending	ALT2 tests; RMS will be in final test

Analysis & Verification Methods

SPC verification (Test F3, F4; see references): The OCAMS test images used to generate the current DRM Rev C results for the SPC product were produced using the enhanced Bennu shape model 3. Each OCAMS image was produced using the Goddard tool, Freespace. With this tool, several vectors from each camera pixel are shot at a truth model to derive the surface reflectance at each vector. The average of this reflectance for all the vectors in one pixel is used to compute the reflectance detected at one OCAMS pixel, after applying a model for the pixel response. The SPC processing first generates MAPLETS, which are then combined to build the shape model.

The F4 test includes errors in the spacecraft trajectory and pointing. These errors reflect the uncertainty in spacecraft performance and translate directly to registration errors in the images. The SPC processing solves for the true spacecraft parameters, finding that the errors degrade the final result only slightly.

OLA verification (Test ALT 2): The OLA data used to generate the products that were shown to verify these requirements were based on the current, unmodified DRM Rev C. The OLA verification test used a simulated OLA data set that contained realistic errors. For each simulated OLA measurement, a weighted average was used where 80% of the range comes from the distance between OLA and a truth model at the center of the OLA footprint, and 20% from four ranges computed around the edge of the footprint. This simulates the 1/e decay of the range pulse across an OLA footprint. The resulting range is then perturbed by OLA's required precision, +/-3cm at 700m. This provides margin on OLA's tested performance, which is approximately +/-1cm.

We also perform basic-principle analysis to verify that test results are consistent with expected performance. The GSD of the image pixels and the shot density of OLA data both indicate that the products should have resolution that is better than the 38-cm requirement.

Existing or Potential Liens

Lien-ALT-6 has closed based on the detailed timelines developed by the SPOC, AltWG, operations, and FDS teams.

Lien-ALT-6: lien on availability of SPICE data. MRD-684 requires that the global DTM be provided 14 days after all OCAMS and OLA data are downlinked, but processing cannot start until delivery of all required SPICE data, particularly the trajectory and pointing kernels.The actual elapsed time during F4 to perform SPC processing was 18 days, but that included seven days of lost time due to an error in the simulated data, a particular error that will not occur in flight.

Lien-ALT-5 has closed with completion of the SPC testing, which verifies that the SPC products meet the requirements of the 1-m global DTM. The OLA global DTM is not required to meet these requirements.

Lien-ALT-5: lien on final OLA testing. Both of the OLA tests assumed that there were no errors in either the spacecraft trajectory or the pointing data. Initial tests confirm that spacecraft and trajectory uncertainties, which are automatically corrected during processing, cause negligible effects in the final products. The final thread tests include both trajectory and pointing errors.

Lien-ALT-7 is closed. Project decision to go with LIDAR TAG as prime and hybrid as warm backup. NFT-only is considered a contingency navigation system and as such will not be validated or implemented any further than has already been done with the exception of having Bill lay out a possible plan for obtaining the extra imaging. This lien can be closed from the AltWG perspective since no issue meeting requirements for hybrid TAG.

Lien-ALT-7: testing to meet the MLN requirements for features near the Matchpoint. Testing to demonstrated that all NFT correlation requirements can be met, and the required modifications, if any. Lien-ALT-8 and Lien-ALT-9 are two approaches to meeting the requirement, but others can be analyzed if either of these two fail or are found to be impractical (not likely).

SPOC Requirements

For the AltWG to produce the required product, the SPOC must provide the data products, software, and hardware described in the SPOC-to-AltWG and OLA-to-SPOC ICDs. These requirements include numbers 1, 2, and 3, below. Number 4, remote access, is not a requirement but the SPOC is providing the service to facilitate data operations and analysis.

The image and altimetry data, SPICE kernels, and information such as the location of the candidate TAG sites.

Four computers with a capability similar to or better than the 2016 12-core MacPro.

A file-access and folder structure compatible with remote processing.

Remote access that facilitates off-site processing of AltWG software.

External Interfaces

VPN, GIT, and web-based interfaces as defined in the SPOC-to-AltWG and SPOC-to-OLA ICDs.

References

The link to the list of full citations for AltWG references is here.