MRD 728 (NFT Feature Catalog)

Summary of Requirement

MRD-728: The Ground System shall produce a catalog of up to 300 NFT features consisting of the following for each feature:

1. A position defined in Asteroid Center Fixed (ACF) coordinates,

2. A 2-D array of displacement (heights) relative to a reference plane above the asteroid surface to represent the shape,

3. A 2-D array of relative albedo values to capture variations in how light reflects off the asteroid surface.

Note: Relative albedo is the average of the relative surface reflectance at the given grid point computed from all images in which the grid point is visible.

Rationale: This requirement ensures the production of a catalog with an adequate number of sufficiently defined features for NFT to perform its functions of Checkpoint navigation state estimate, the TAG navigation state estimate and the time of touch estimate.

MRD-730: The Ground System shall produce a displacement and relative albedo array for each NFT catalog feature with sufficient fidelity to allow NFT to successfully correlate the feature.

Rationale: This requirement ensures correlation performance for each catalog feature is sufficient for NFT to meet requirements for the Checkpoint navigation state estimate, the TAG navigation state estimate and the time of touch estimate.

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 Altimetry Working group (AltWG), science operations (SPOC), navigation (FDS), and mission operations (MSA) teams, are conducting a set of tests to verify the adequacy of these products to meet the navigation requirements of NFT. In these tests, the NFT processes the DTMs using the same software that will be used for the mission and evaluates the results according to their ability to pass the flight criteria. OLA products are the primary approach for meeting the NFT requirements, including MRD-728 and 730. Verification will be completed before launch. Since there are several approaches that can be used to meet the requirements, pre-launch verification is a high probability.

Status (7 June 2016):

DTMs generated with error-free OLA data pass the NFT correlation criteria.

OLA DTMs with OLA range uncertainties pass the NFT correlation criteria except for some high-resolution features that occur after the Checkpoint.

DTMs with SPC processing had feature heights that had unacceptable deviations.

A few test DTMs that combine SPC processing and OLA data meet the NFT correlation criteria in cases where neither OLA nor SPC processing alone met the criteria.

Some test DTMs with additional OLA sampling meet the NFT correlation criteria when neither OLA nor SPC processing alone met the requirement.

OLA DTMs with spacecraft trajectory and pointing errors are in preparation.

DTMs with SPC processing using modified parameters or adjustments based on OLA data appear to be satisfactory and are being prepared for testing.

DTMs with albedo variations are being prepared for testing.

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. Figure 1 illustrates all of the data required by the AltWG to meet its requirements, including those in MRD-732 and 734.

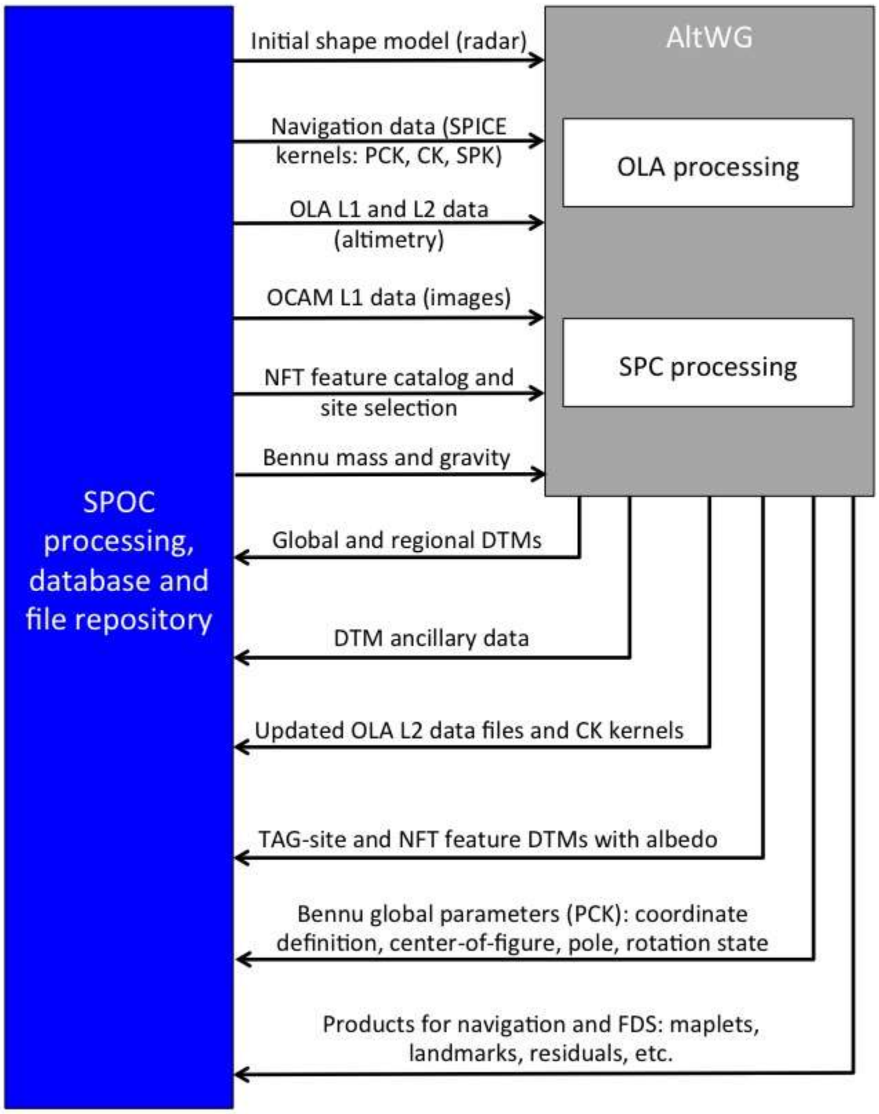

Figure 1. Data flow of the Altimetry Working Group that generates the required products.

The resulting outputs include (not all of these are required for TAG-site DTMs):

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.

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 Observation

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. Depending on the results of the NFT testing, additional images or altimetry measurements during Orbit B or the Recon phase may be required. If required, the changes are not expected to add to the mission timeline.

Minimum Success Criteria

The AltWG must produce these topographic and albedo maps to achieve the objectives of the OSIRIS-REx minimum mission: the digital terrain maps (DTMs) of the NFT features.

Dependencies per Mission Phase

The OLA derived DTMs require data from Orbit B. The SPC DTMs require data through the Detailed Survey mission phase and may be augmented with some Orbit-B data.

Adequacy of the Design Reference Mission (DRM)

DRM Rev C is adequate. Initial testing as described below showed some potential issues, however later testing confirmed that DRM Rev C is adequate.

Initial testing reveals that the stereo imaging acquired by the current DRM Rev C may need augmenting to produce SPC products with the required accuracy for NFT navigation. To achieve better illumination and viewing geometry, the Orbit-B phase of the mission would be modified to either change the existing orbits, to add orbits, or both.

For OLA products to meet the NFT requirements for the highest-resolution features, additional OLA measurements may be required. These additional OLA data can be acquired with additional data capture during the planned orbits; no change in the DRM is required.

Data Products per Mission Phase

The topography and albedo maps to meet the MRD-732 and 734 requirements will be generated following all required observations in Orbital phase B.

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 twopronged, 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

For MRD 728 and 730, the AltWG is providing relative albedo registered to the DTM. Albedo sources include one or more of the following: OLA reflectance, SPC ancillary data, and ISIS image analyses. The albedo data are registered to the DTM product using an interpolation between pixels.

If necessary, OLA data will be used to improve the accuracy of feature relief of SPC DTMs, which have suppressed heights when using the standard SPC processing.

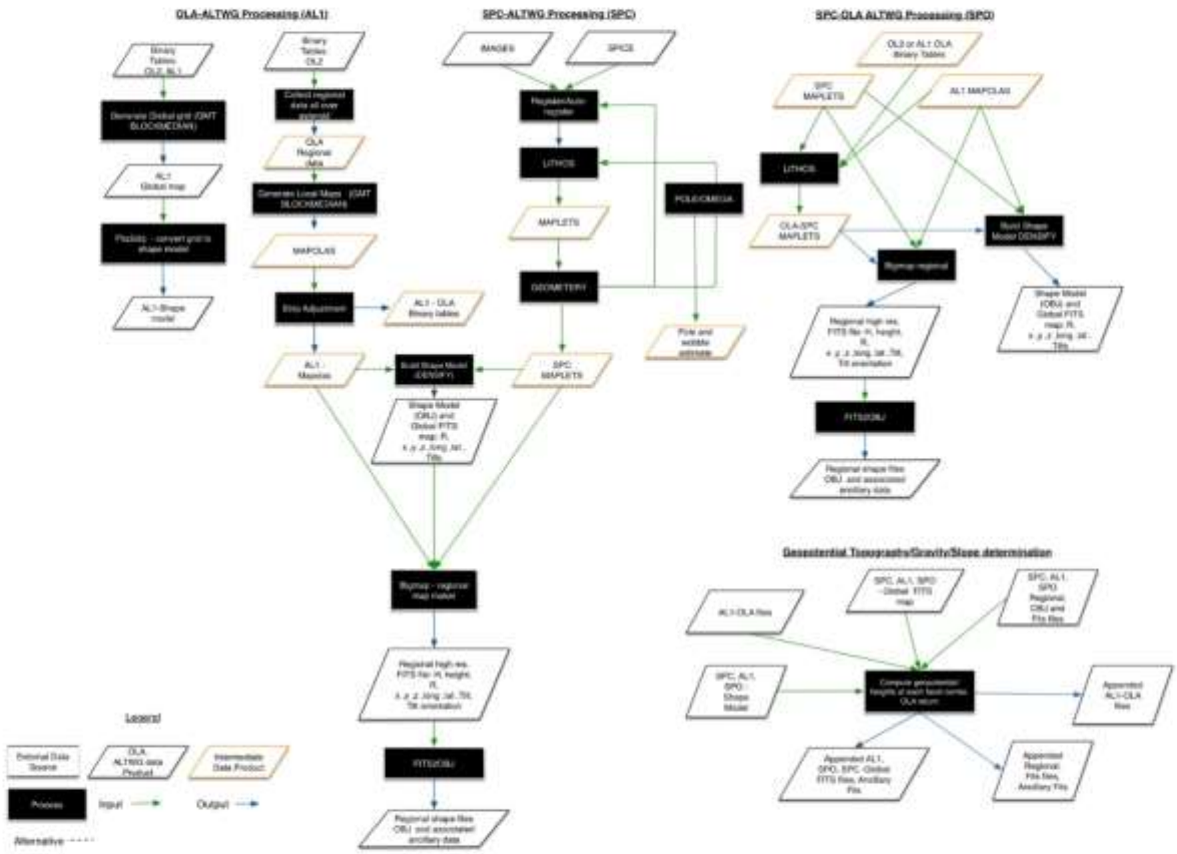

Figure 2: Flow chart showing the processing that produce global and regional maps from which are generated the MRD-115 site-specific maps.

Provenance of Algorithms, Software and Techniques

The configured 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 MRD-732 and 734 were produced during several tests and will be produced for additional tests, to be completed by launch. Initial tests with OLA data met NFT requirements, and a series of tests with increasing fidelity is underway.

Analysis & Verification Methods

Verification of AltWG DTMs for MRD-732 and 734 requires processing the DTMs through the NFT navigation pipeline. The adequacy of each DTM is quantified with a correlation score, which relates to the ability of the NFT software to locate the feature from the DTM. For the AltWG DTMs to meet NFT requirements, a minimum number of features must be identified.

SPC verification: 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. At a chosen sample site, images with <2cm GSD were generated from a shape model composed of a surface sampled at 5 cm globally, and under 1 cm within the chosen tag site. Current DRM Rev C orbits were used in imaging the surface of Bennu at the TAG site during the Detailed-Survey and Orbital-B phases.

The AltWG is investigating three improvements to SPC processing. 1) incorporating OLA data to improve DTM height accuracy, 2) adjusting parameters to reduce the smoothing that suppresses the height of smaller features, and 3) additional images. The current DRM Rev C imaging plan is not ideal for SPC, which performs best with a wide range of illumination and viewing angles. This deficiency may prevent the success of improvement number 2, and it may be that the addition of only a few images is insufficient. Collecting a full set of ideal-geometry-and-illumination images for SPC may require new orbits and an additional 60 days of viewing.

OLA verification: The OLA data used to generate the products that are being tested are based on the current, unmodified DRM Rev C. The higher-fidelity OLA verification tests use a simulated OLA data set that contains realistic errors. For each simulated OLA measurement, a weighted average is 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.

Existing or Potential Liens

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).

Lien-ALT-8 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. This lien can be closed from the AltWG perspective since there are no issues meeting requirements for hybrid TAG.

Lien-ALT-8: additional OLA measurements near Matchpoint. The small, high-resolution features that occur after Checkpoint may require additional OLA measurements in order to meet the NFT correlation requirement. If testing confirms that this approach is successful, then the additional measurements, which do not require a change in the DRM, must be added to the observing plan. It is also possible to collect data during the Recon phase, but this is not expected to be required.

Lien-ALT-9 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. This lien can be closed since SPC processing of DRM Rev C is adequate to navigate to checkpoint and with LIDAR TAG as prime and hybrid as the backup, there is no need to validate beyond checkpoint.

Lien-ALT-9: additional OCAMS images for SPC NFT. If SPC is required for NFT features, the Orbit-B orbits must be modified or augmented to improve the illumination and viewing geometry for SPC processing. This option would be implemented if testing fails to verify that OLA data can produce DTMs that meet NFT correlation requirements. This option would require a modification of the DRM.

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.

AltWG references

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