MRD 732 Sample Site DTM

Summary of Requirement

MRD-732: The Ground System shall, for a 3-sigma TAG delivery error ellipse around each of up to 2 (1 primary and 1 backup) sampling sites, produce a DTM with vertical RMS error < 0.14 m (1-sigma).

Rationale: NFT uses a coarse DEM representation of the TAG site to estimate time of touch. This DEM must have sufficient accuracy to ensure a good time of touch estimate within requirements.

MRD-734: The Ground System shall, for a 3-sigma TAG delivery error ellipse around each of up to 2 (1 primary and 1 backup) sampling sites, produce a DTM with vertical RMS error < 0.14 m when compared to each of the NFT features (1-sigma).

Rationale: NFT uses a coarse DEM representation of the TAG site to estimate time of touch. This DEM must be consistent with the NFT features to ensure a good time of touch estimate within requirements.

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), 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.

The SPC F6 test and the NFT thread test verified that these requirements will be met. Table 1 contains a summary of the results, and the detailed reports are in the references.

Table 1. Test results for OLA and SPC processing.

MRD	Requirement	Test results
732	<0.14 m vertical error	2.9 cm (baseline); 3.2 cm (backup)
734	<0.14 m vertical error compared to NFT features	11 cm (SPC-F6); 12 cm (OLA)

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 732 and 734.

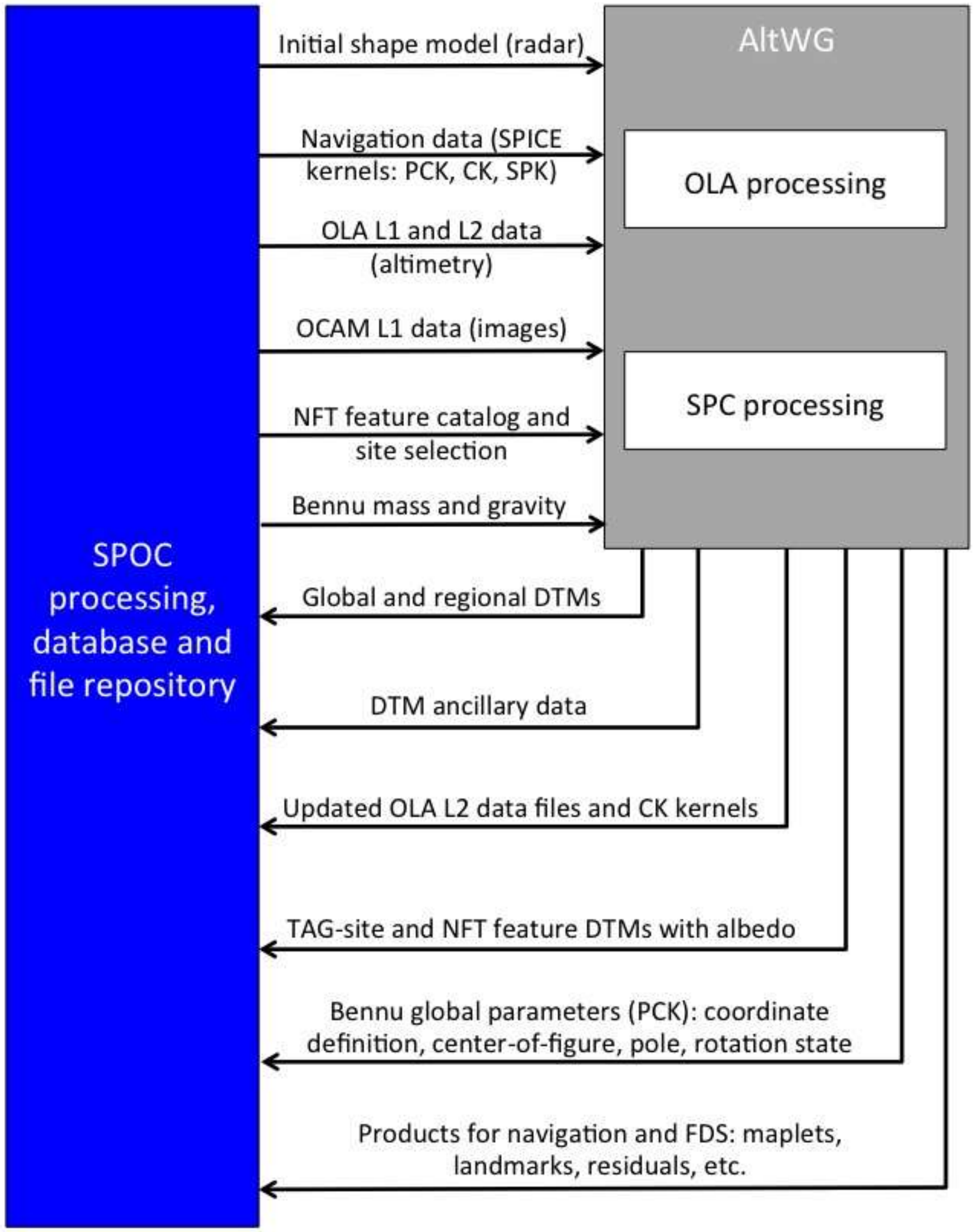

Figure 1. Data flow of the Altimetry Working Group that generates the required products.

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 was adequate.

Minimum Success Criteria

The AltWG must produce the TAG-site topographic maps to achieve the objectives of the OSIRIS-REx minimum mission.

Dependencies per Mission Phase

For OLA and SPC-derived products, the site-specific digital terrain maps will be produced are based on observations through the Orbit B mission phase. The ground sample distance (GSD) of images and OLA data from earlier phases of the mission is too large to produce the resolution required for these maps.

Adequacy of the Design Reference Mission (DRM)

To produce the 5-cm DTM used to verify these requirements, the AltWG created DTMs from OLA data and using SPC processing of images, both from the current DRM Rev C. The resulting SPC and OLA topographic maps have the accuracy required by MRD-732 and 734.

Data Products per Mission Phase

The topography maps to meet the these requirements will be generated after completion of Orbit-B phase, when the required OLA and OCAMS data are collected.

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 $e = [U(x)-U_{ref}]/|g|$ 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.

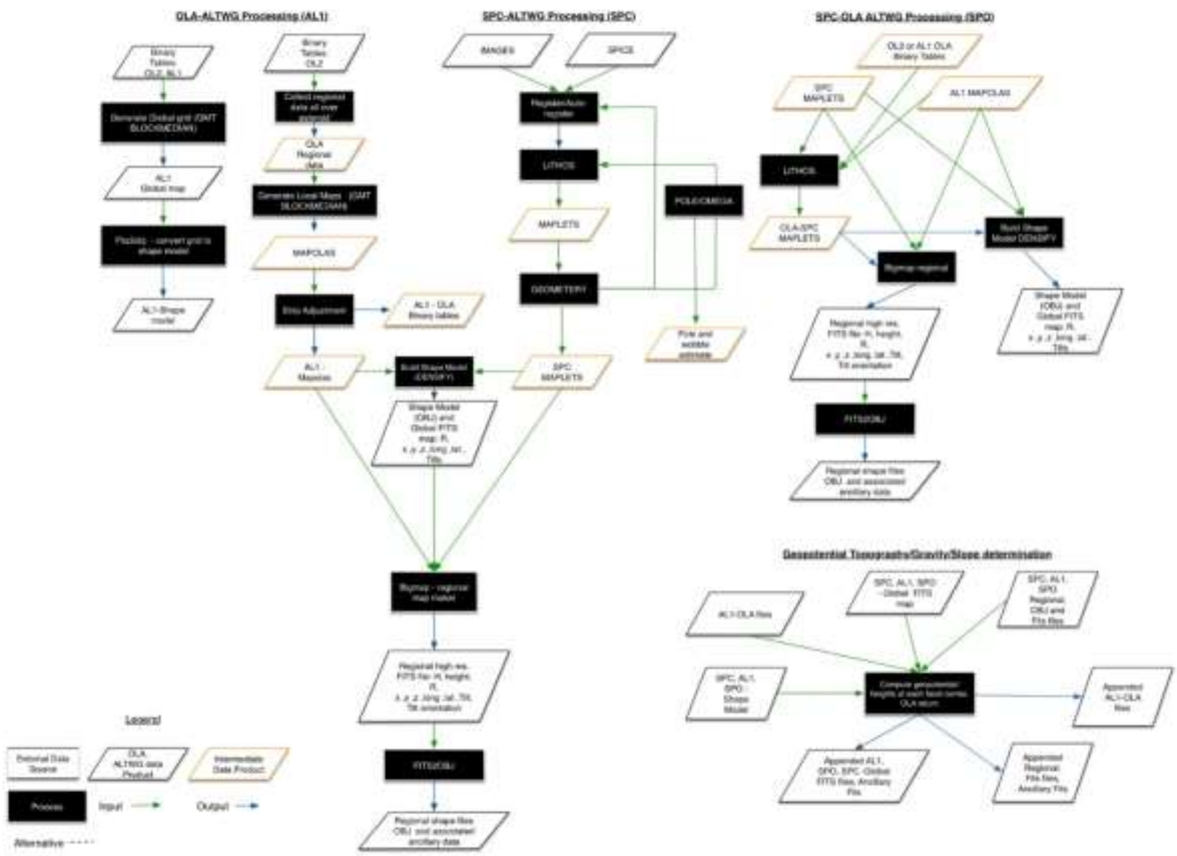

Figure 2: Flow chart showing the processing that produce global and regional maps from which are generated the MRD-115 site-specific maps.

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 the NFT thread test. The SPC F6 test also produced a TAG-site DTM that meets the requirements. The products were generated with 5 cm spatial resolution or GSD. Table 1 shows the accuracy of the products produced during the tests, and the referenced reports contain details of the processing and results. The simulated data contained realistic errors for OLA range measurements, spacecraft position, and pointing.

Analysis & Verification Methods

SPC verification (Test F6): The OCAMS test images used to generate the current DRM Rev C results for the SPC product were produced using the Bennu shape model 4. 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.

OLA verification (NFT thread test) The DTM is the product of OLA data collected during the Orbit-B phase of the mission. The DTM is an intermediate product that would be produced during the mission before the Recon phase. Recon data would improve the DTM and would be incorporated into the final TAG-site DTM and feature DTMs.The DTM has an average precision of 3.2 cm (1 sigma). The accuracy is <0.9 cm relative to the SPC global DTM (generated during F6), which has a formal uncertainty of 11 cm, which is the primary error source for the OLA DTM, which was registered to the F6 SPC DTM.

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 images and the OLA data both indicate that the final data products should have resolution that is better than the 5-cm requirement. In practice and with more than ten images, SPC can achieve a factor-of-two sub-pixel resolution, that is, the SPC product can have better resolution that the GSD of the images. With 2-cm images, there is ample margin. Similarly, the GSD of the OLA data will be at least a factor of two shorter than 5 cm over the required area.

Existing or Potential Liens

Lien-ALT-2 has closed with the completion of the F6 and NFT thread tests, which demonstrated that the AltWG products met the MRD requirements using data with realistic errors in spacecraft and pointing.

Lien-ALT-2: lien on subsequent testing. The completed SPC and OLA tests have so far assumed that there were no errors in either the spacecraft trajectory or the pointing data. Ongoing SPC and OLA thread tests are evaluating the effects of including spacecraft and trajectory uncertainties. Initial results of these tests show that spacecraft trajectory and pointing errors have negligible effects on final results as both sets of errors can be extracted during processing of the data sets. OLA tests will be complete in June 2016 and SPC tests will be completed after launch.

Lien-ALT-12 has closed with the results of the NFT thread test, which showed that the Orbit-B OLA data will produce a TAG-site DTM and NFT feature DTMs that meet the requirements. The NFT reports in the reference section (see below) contain additional details.

Lien-ALT-12: lien on completing NFT testing. Calculating the error between the TAG-site DTMs and NFT features (MRD-734) will be completed as part of the NFT testing. The testing that will be completed before launch includes the relevant portions of the ALT2 and ALT3 tests.

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.