Dawn DTMs Using Stereo Photogrammetry

The text of this document is heavily cribbed from the following two documents, both of which do a more complete job of describing the technique than is provided here. This document is provided for those who might not have easy access to the published literature.

Preusker, F., J. Oberst, J. Head, T. Watters, M. Robinson, M. Zuber, S. Solomon, Stereo topographic models of Mercury after three MESSENGER flybys. Planet. Space Sci. (2011). DOI:10.1016/j.pss.2011.07.005

Raymond, C.A., R. Jaumann, A. Nathues, H. Sierks, T. Roatsch, F. Preusker, F. Scholten, R.W. Gaskell, L. Jorda, H.-U. Keller, M.T. Zuber, D.E. Smith, N. Mastrodemos, and S. Mottola, The Dawn topography investigation. Space Sci. Rev. 163, 487 (2011).
DOI: 10.1007/s11214-011-9863-z

Dawn mission is equipped with two identical framing cameras (FC1 & FC2) [SIERKSETAL2011] with 1024 x 1024-pixel charge-coupled device (CCD) sensors, each of which have one clear filter and seven band pass filters. At both Vesta and Ceres, only the FC2 was used to acquire science images while the FC1 was held in reserve. Clear filter images taken during Ceres HAMO were used to produce a global digital terrain model (DTM) of the illuminated part of Ceres [PREUSKERETAL2016]. Dawn orbited Ceres during in 6 cycles between August 16 and October 23, 2015 at the HAMO altitude of ~1475 km. A cycle is a single complete mapping of surface at a fixed attitude (nadir or off-nadir). Individual images at the HAMO altitude have a spatial resolution of approximately 135m per pixel. The framing camera acquired about 2350 clear filter images [PREUSKERETAL2016] during the HAMO phase. The images were taken with different viewing angles and similar illumination conditions by slewing the spacecraft to various off-nadir attitudes in each mapping cycle. During HAMO, there were effectively two nadir mappings (Cycles 1 and 5) and four off-nadir mappings at angles specifically selected to provide the conditions required for stereo analysis [POLANSKEYETAL2016].

At Vesta there were two HAMO science phases, both at ~700 km altitude. During the first HAMO (HAMO-1: September 29 – November 1, 2011) Dawn acquired approximately ~2,675 clear filter images with an average image scale of about 63 m/pixel [PREUSKERETAL2011]. At this time, Vesta was in southern summer and most of the northern hemisphere above 35-40 degrees north latitude was poorly illuminated. HAMO-1 consisted of six cycles with the first and last at Vesta center pointing and the other four cycles at various off-nadir angles [POLANSKEYETAL2012]. After completing its low altitude mapping (LAMO) Dawn was allowed to have a second HAMO (HAMO-2) mapping before departing Vesta for Ceres. In HAMO-2 (June 15 – July 24, 2012) Dawn was able to acquire an additional ~2,825 clear filter images with an average image scale of about 65 m/pixel [PREUSKERETAL2014]. HAMO-2 also included six cycles with nadir and off-nadir geometries similar to those used during HAMO-1 [POLANSKEYETAL2012]. HAMO-2 occurred near the Vesta equinox providing much improved lighting conditions in the northern hemisphere. Combining the two data sets, Dawn was able to map nearly 95% of the Vesta surface.

The photogrammetric stereo analysis is based on algorithms and software realizations used extensively on previous planetary image data sets [GEISEETAL1998; GEISEETAL2006; GWINNERETAL2009; GWINNERETAL2010]. The processing involves several stages and includes pointing corrections made with photogrammetric block-adjustment techniques, multi-image matching, and the generation of DTMs and orthoimage mosaics [PREUSKERETAL2011].

The photogrammetric DTM generation process chain (Figure 1) is embedded in an iterative procedure [RAYMONDETAL2011]. Beginning with the nominal spacecraft position and camera pointing data provided by the NASA Navigation and Ancillary Information Facility (NAIF) as Dawn project SPICE kernels, image footprint information is generated to identify areas of stereo overlap between images. A coarse-to-fine iteration includes photogrammetric block adjustment in order to improve the initial spacecraft/position, pointing direction, and the alignment of the FC camera frame to the Dawn spacecraft frame. Subsequently, intermediate DTMs are calculated and serve as input for pre-rectification within the respective iteration. When iterations for all stereo models of a global image dataset have yielded full-resolution tie point coordinates, an overall photogrammetric adjustment of the entire global block is used to derive the final orientation, which is used for the calculation of the entire global object point dataset and the final stereo DTM interpolation [PREUSKERETAL2011]. The ground coordinates and the orientation of each image are considered as unknowns. Systematic offsets of the spacecraft trajectory from nominal are attributed to errors in the asteroid planetary constants since these are not well known for either Vesta or Ceres. As a result of the block adjustment, an improved set of planetary constants, orbit, and spacecraft pointing data are generated which are then used in all further processing.

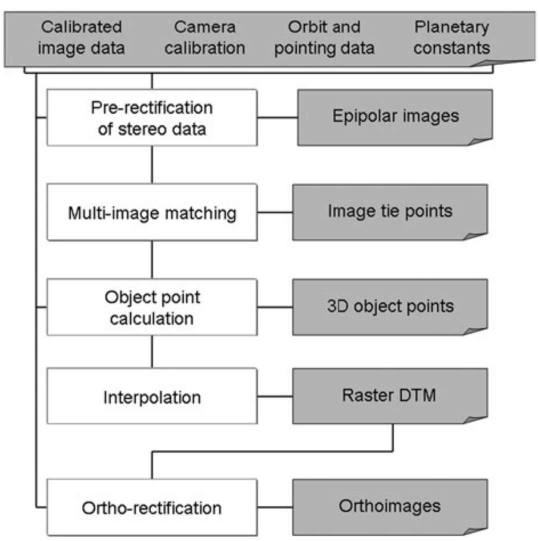

Figure 1 [Processing flow for DTM generation from stereo data. The top tier of the flow is a coarse-to-fine iteration photogrammetric block adjustments [from RAYMONDETAL2011].

Pre-rectification: Based on given orbit and pointing information the stereo observations are pre-rectified to a constant pixel scale in a common map projection. Thus, all stereo data sets are fitted to a common geometry. The images were pre-rectified on a reference sphere with a radius of 470 km (Ceres, Vesta = 255 km) by using the improved orientation data described above. The pre-rectification warrants that the search for tie points be limited to small areas [PREUSKERETAL2011]. Hence, point misidentifications and gaps are reduced to a minimum. The matching algorithm is an area-based image correlation to derive approximate values for the match-point coordinates, which are refined to sub-pixel accuracy by least-squares matching [PREUSKERETAL2011]. After the matching, the derived image coordinates (which refer to pre-rectified images) are transformed back to the geometry of the raw images, using the history files generated during the pre-rectification. The accuracy of this back-transformation is better than 0.1 pixel [SCHOLTENETAL2005].

Multi-image Matching: A multi-image matching technique is applied to the pre-rectified image data in order to derive conjugate points in each of the stereo observations [RAYMONDETAL2011]. The algorithm makes use of area-based correlation in image pyramids to derive approximate values for the image coordinates, which are refined to sub-pixel accuracy by least-squares matching [GWINNERETAL2009]. The correlation is done for each image as the reference image with all stereo partners, i.e. all overlapping images. A pyramidal approach using stepwise reduction of the correlation patch size yields moderate computation times and completeness even with large parallaxes [RAYMONDETAL2011]. After the multi-image matching process, the derived image coordinates of all stereo observations are transformed back to raw radiometrically corrected data geometry, using the history files generated during the pre-rectification. The accuracy of this back-transformation is better than one tenth of a pixel [SCHOLTENETAL2005].

Object Point Calculation: The lines of sight, defined by the image coordinate pair for each stereo observation, the geometric calibration, and the orientation data, are used for forward ray intersection. Least-squares adjustment is applied for this over-determined problem. The result is an object point and its relative accuracy defined in body-fixed Cartesian coordinates. The redundancy given by multi-stereo capability allows us to accept only those object points that are defined by at least three stereo observations. Thus, the influence of occasional gross matching errors, which cannot be avoided by simple two-image matching, is minimized.

Global DTM Interpolation: For the generation of a DTM with a regular grid in a given map projection, object points from single stereo models as well as from a set of stereo models can be used. For the derivation of global DTMs, typically a large set of different models is combined to one, as will be done for derivation of global Vesta and Ceres DTMs. The object points were first transformed from body-fixed Cartesian coordinates to Ceres (Vesta) geographic latitude/longitude/height and then transformed to chosen map projections (simple cylindrical equidistant for low latitude, stereographic projection for the high latitudes). A pixel scale of about 137m (60.0 pixel/degree) was chosen for the Ceres HAMO DTM and about 70m (64.0 pixel/degree) for Vesta HAMO. Object points located within a DTM pixel are averaged, and can optionally be combined by different filtering techniques with those within a chosen neighborhood [GWINNERETAL2010]. For regions that lack any object-point information, a gap-filling algorithm using DTM pyramids with reduced resolution is applied [PREUSKERETAL2011].

Ortho-rectification and Mosaicking: Each image can be ortho-rectified precisely using finally adjusted orientation data and shape as represented by the DTM [RAYMONDETAL2011]. The ortho-rectification consists of ray-tracing regular pixel positions of the input radiometrically-corrected pixel matrix with the DTM using interior camera calibration and exterior orientation data related to the respective pixel [SCHOLTENETAL2005]. For each grid point, a 3-D intersection point with the DTM is derived and transformed to the map projection of the output orthoimage (same standard projections as for the DTM). For each pixel within a mesh of these transformed grid points, an indirect resampling based on different selectable interpolation methods is performed within the radiometrically corrected input matrix in order to derive the final orthoimage grey value. Ortho-rectified images from different Dawn orbits need to be combined for mapping of target areas spread over multiple orbits. For this purpose, a radiometric mosaicking tool has been developed. It combines all input orthoimages by simply copying them to one common image mosaic, and also allows brightness adjustment. No geometrical adjustment is applied; the geometric relationship between the images to be mosaicked is considered to be fixed and is defined by each image's label information comprising nominal map projection parameters, scale, and the offset of its upper left pixel with respect to the projection center.

Quality Assessment of 3D Products: Detailed quantitative statements about the data quality, the accuracy of the entire data processing line, and the derived products require intensive studies and statistical analyses, since the geometrical conditions of each orbit may vary [SCHOLTENETAL2005]. Orbit maneuvers do not allow for a consistent quality of orientation data, but these did not occur during Vesta HAMO. At Ceres, after the failure of two of the four reaction wheels [POLANSKEYETAL2016], there were small spacecraft pointing actions, whose impact on the DTM quality is difficult to assess. The impact of variable local texture and varying illumination conditions are also difficult to include in an overall quality assessment.