coaligned on a pivot platform. Both cameras are equipped with identical 1024 × 1024 format charge-coupled devices (CCDs) featuring 14-μm pixels and can deliver images with a pixel dynamic intensity range of 12 bits. Unlike the wide-angle camera (WAC), the narrow-angle camera (NAC) possesses a single filter only (700–800 nm). The NAC, featuring a compact off-axis optical system, suffers from geometrical distortions. Laboratory data from the ground as well as inflight stellar calibration data have been used to determine a geometric distortion map (F.S. Turner, personal communication, 2009), which has been utilized for this analysis. Indeed, once calibrated, CCD cameras are considered geometrically more stable than the Mariner 10 vidicon cameras and better suited for the photogrammetric measurement techniques central to this paper.

2.2. Images and mosaics

Image mosaics are obtained by scans of the pivot platform in combination with changes in the orientation of the spacecraft. This powerful capability was used to acquire several contiguous image mosaics during MESSENGER's first Mercury flyby (M1) on 14 January 2008 (Solomon et al., 2008). The digital terrain model (DTM) mosaic was produced from 208 NAC stereo images, which formed three sub-mosaics (H1, H2, and D1; Table 1).

The viewing geometry and the stereo conditions during the flybys were far from optimum, which aggravated DTM production. The basin was located near the planetary limb, and viewing (emission) angles near the northeastern margin of the basin were typically larger than 60°. Stereo angles were also small, differed substantially (8–14°) among respective image pairs, and were lowest (8°) for areas near the equator.

3. Stereo processing

The stereo processing follows algorithms and software realizations that have been used extensively on previous planetary image data sets (Albertz et al., 2005; Scholten et al., 2005; Heipke et al., 2007; Gwinner et al., 2009, 2010). However, adaptations of the software were required to account for MESSENGER camera parameters and image data formats. Also, software elements had to be combined in shell scripts. The processing had several stages, as described in the following.

3.1. Pointing data correction

The navigation data correction was carried out using bundle block adjustment techniques. This type of least-squares analysis produces solutions for spacecraft position and camera pointing for each image on the basis of large numbers of tie-point measurements. For the tie points, ground coordinates are computed in the process (Zhang et al., 1996). The a priori errors for angles were 450 μrad; errors in the spacecraft positions were assumed to be small (50 m).

Table 1
NAC sub-mosaics used to produce the DTM.

Mosaic	Time	No. of images	Resolution (m/pixel)
H1	$E + 15$ min	4 × 17	120–170
H2	$E + 27$ min	9 × 11	230–310
D1	$E + 50$ min	11 × 9	470–570

E (time of closest approach): 19:04 UTC, 14 January 2008. Time refers to first image taken.

First, the images were subjected to automatic image matching with a coarse matching grid to collect tie points. Only those tie points that were matched on at least three images were selected. In total, 21,975 line/sample coordinates were collected from the 208 images, representing 6475 ground points. Next, a starting model was derived. Three-dimensional Cartesian body-centered surface coordinates (x, y, z) of the tie points were computed from the nominal navigation data. While the horizontal coordinates were computed from classical ray intersections, the radius was kept fixed.

Next, full three-dimensional coordinates were derived by bundle block adjustment, beginning the iterations with the starting model. The inversion required solving the equations of observation for more than 24,500 unknowns (i.e., three spacecraft position components and three pointing angles for each image as well as three coordinates for each point). The adjustment converged after four iterations. Root mean square intersection errors were reduced from 10 km originally to 220 m. The intersection errors were visually inspected to verify that the model was free of stresses and topography bias. The high quality of the starting model prevented the iterations of the bundle block adjustment from converging erroneously on a local minimum of the residual field. Small errors in the starting model were found not to affect the outcome of the adjustment.

3.2. Image matching

Images were pre-rectified using the pointing data from the bundle block adjustment and subjected to automated image matching. A total of 241 individual matching runs were carried out on double- or triple-overlapping images. The pre-rectification step allowed searches for tie points to be limited to small areas. Hence, point misidentifications and gaps were reduced to a minimum.

3.3. Assembly of the DTM

Ray intersections of all matched points were computed to derive surface coordinates of object points. This process resulted in a total of 150 million object points. The object points were then interpolated to form a contiguous DTM grid at a size of 12.8 million pixels and a spatial resolution of 1000 m. While this spatial resolution is typically chosen to match the effective resolution of the model (a factor of three larger than the resolution of the images, according to a rule of thumb), a comparably small spatial resolution was chosen to avoid the loss of detail. No adjustments for absolute height or trend were applied. Though some erroneous height trend cannot be ruled out, gross errors in long-wavelength topography of the model are not likely, owing to the large number of concatenated images that are involved.

The DTM covers 12% of Mercury, or 8.8×10^6 km^2 (Fig. 1). Heights of the DTM are given with respect to a reference sphere of radius 2440 km. For further discussion, the portion of the object points that contained Caloris were extracted and projected separately onto a stereographic map (Fig. 2) centered on Caloris (30°N, 165°E). A variety of DTM representations were prepared, including the raw DTM (grey scale, Fig. 2), as well as shaded-relief maps color-coded by height (see Fig. 1 for an example). Selected height profiles were also computed for Caloris (Fig. 3) and areas of interest (Figs. 4–6).

The DTM has 8 km of total relief. The highest point within Caloris (2.5 km above the Mercury reference radius) is represented by an unnamed isolated peak (42.6°N, 149.9°E, Fig. 4). The lowest point within Caloris, and indeed of the DTM (5 km below the reference radius), is within the crater Atget in the southern basin floor (25.6°N, 166.4°E). At 100 km in diameter Atget is the largest crater within the Caloris basin (Fig. 5).