THE TOPOGRAPHY OF LUNAR IMPACT BASINS AS DETERMINED FROM RECENTLY OBTAINED SPACECRAFT STEREO IMAGES

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ABSTRACT

We analyzed images obtained during the Galileo flyby in 1992 and by the Clementine orbiter in 1994 to derive Digital Terrain Models (DTM) of selected large lunar impact basins, in particular, the Humboldtianum basin, Mare Crisium, and parts of Mare Orientale. The Humboldtianum terrain model has a lateral resolution of 2 km/pixel and a height resolution of 500m. In the Orientale area we processed stereo images along a narrow strip cross-cutting the Rook and Cordillera Rings of the basin, and derived a terrain model with grid spacing of 200 m/pixel and height resolution of 50m. The new topographic data exceed the Clementine laser altimeter data in terms of resolution and noise level and will allow us to carry out morphological studies of the lunar impact basins in unprecedented detail.

1. INTRODUCTION

The large impact basins are important landmarks in lunar geology and morphology. The multiple rings associated with these basins represent the major lunar mountain ranges. The basin floors form deep regional depressions and often contain large volumes of volcanic deposits. However, the dynamics of formation of these basins and their evolution through lunar history has been an enigma, partially because information on their topography has been very poor. Previous studies of lunar topography included shadow-length measurements of mountain peaks (Jones, 1965), limb profiling (Watts, 1963; Appleby and Morrison, 1983), radar mapping from Earth (Zisk, 1972; Zisk et al., 1974), and analysis of Apollo Metric stereo images (Wu and Doyle, 1990; Cook et al., 1994) in the nearside equatorial regions.

Fortunately, our prospects to refine lunar topography have significantly improved in the past years. The Galileo and Clementine spacecraft encountered the Moon and obtained a wealth of digital stereo image data. These data provide the opportunity to derive Digital Terrain Models (DTMs) with high lateral resolutions using state-of-the-art photogrammetric methods of analysis. In addition, during the Clementine mission, for the first time ever, laser altimeter data were collected for studies of the global lunar shape.

In this paper we will describe the spacecraft image data, photogrammetric methods of analysis, and the properties of the resulting terrain models. Finally, models are compared with those from laser altimetry. We discuss the advantages and disadvantages of using either stereo images or laser altimetry for studies of lunar topography.

2. SPACECRAFT STEREO IMAGES

Galileo passed the Moon on December 7, 1992 at a distance of 110,000 km. Approximately 300 multi-look-angle images of the near-side northern lunar hemisphere were obtained by the SSI (Solid State Imaging) camera (Table 1) showing the Humboldtianum basin (82°E, 57°N) and Mare Crisium (58°E, 18°N) at image scales of approximately 1 km/pixel.

In contrast, the Clementine spacecraft orbited the Moon from February through May 1994, at altitudes ranging from 400 - 2940 km and gathered nearly 2 million images. Whilst the majority of the data were obtained with the cameras pointed towards nadir for global mapping, there were specific imaging sequences near the end of the mission during which the spacecraft was tilted to obtain stereo data (Cook et al., 1996). Excellent stereo coverage was obtained by the UVVIS camera (Table 1) near Mare Orientale, located on the western lunar limb (20°S, 89°W). Ground pixel sizes in the area were approximately 100-150 m/pixel.

Table 1: Cameras

	Galileo SSI	Clementine UVVIS
CCD chip size	800x800	384x288
focal length (mm)	1500	90
pix scale (px/mm)	65.617	43.478

Due to the large number of images involved, deriving terrain models of the entire Orientale Basin would have been a very time-consuming task. Instead, we selected a linear profile cross-cutting the Inner Rook, Outer Rook, and the Cordillera Rings near the eastern margin of the basin, along which we modelled topography. The input image data consist of 43 nadir-pointed images obtained from orbit 333 and a second set of 53 tilted images obtained a few hours later (orbits 334, and 338) under similar lighting conditions. Although multispectral data are available from the Clementine and Galileo cameras, only single-filter images, respectively, were used in the analysis.

3. STEREO PROCESSING

For both, Galileo and Clementine, the photogrammetric processing was carried out using similar methods (Oberst et al., 1996). First, the nominal spacecraft trajectory and camera pointing information supplied by the Galileo and Clementine flight projects were adjusted using hand-picked line/sample coordinates of conjugate points or ground control points (Zhang et al., 1996).

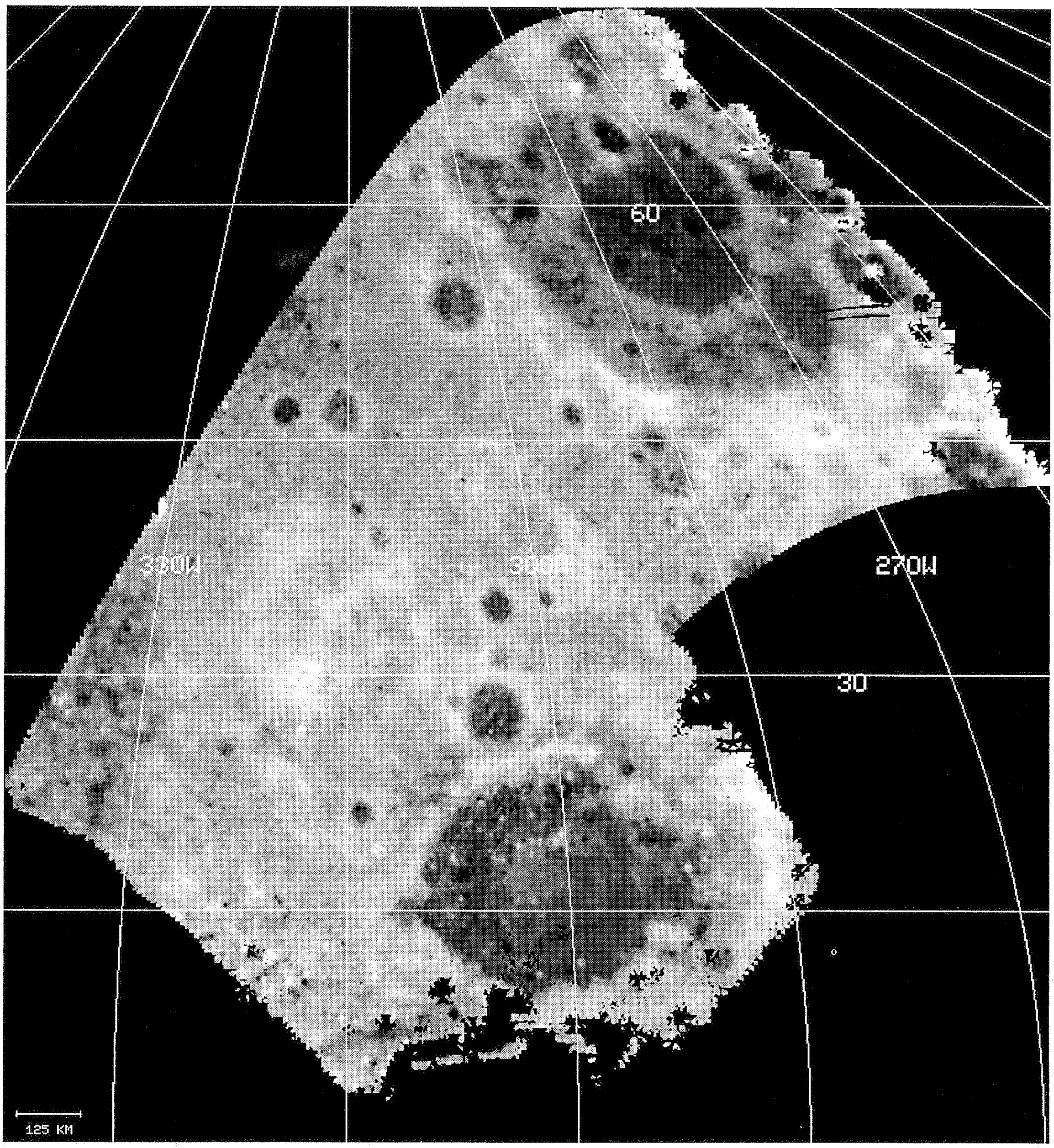

Fig. 1: Digital Terrain Model from Galileo stereo images showing of parts of the nearside northern hemisphere including the Humboldtianum Basin (82°E, 57°N) and Mare Crisium (58°E, 18°N). Heights vary from -4500 to +2000m. The DTM is represented in a sinusoidal map projection with 5 km/pixel scale. Note the gaps in the terrain data near the lunar limb and near the terminator, and in areas of high sun elevation angles, where the digital image matching failed.

In the case of Galileo, control points were used exclusively. The adjustment involved 49 images, 212 control points, and a total of 1004 individual image coordinate measurements. Control points were taken from the "Unified lunar control network" (Davies et al., 1994), which involves more than 1000 control points located mostly on the nearside hemisphere. In the case of Clementine, the adjustment involved 417 conjugate points and 1403 individual line/sample measurements in a total of 96 images. 6 control points from an earlier photogrammetric study of Clementine data (Oberst et al., 1996) were used to support the adjustment.

Next, we performed several parallel image matching runs involving one reference image and up to six target images, respectively, using an automatic area-based least- squares matching technique in image space (Ackermann, 1984; Oberst et al., 1996). The matched data were converted to object coordinates using the spacecraft position and camera pointing data determined in the bundle adjustment using ray intersection methods. Finally, the object coordinates were converted to line/sample coordinates in an appropriate map projection followed by interpolation to form a regular DTM grid. The DTMs are normally presented in a sinusoidal map projection.

4. RESULTS

Analysis of the Galileo images resulted in a terrain model covering much of the nearside northern hemisphere at 2000 m grid spacing and 500 m height resolution (see Fig. 1).

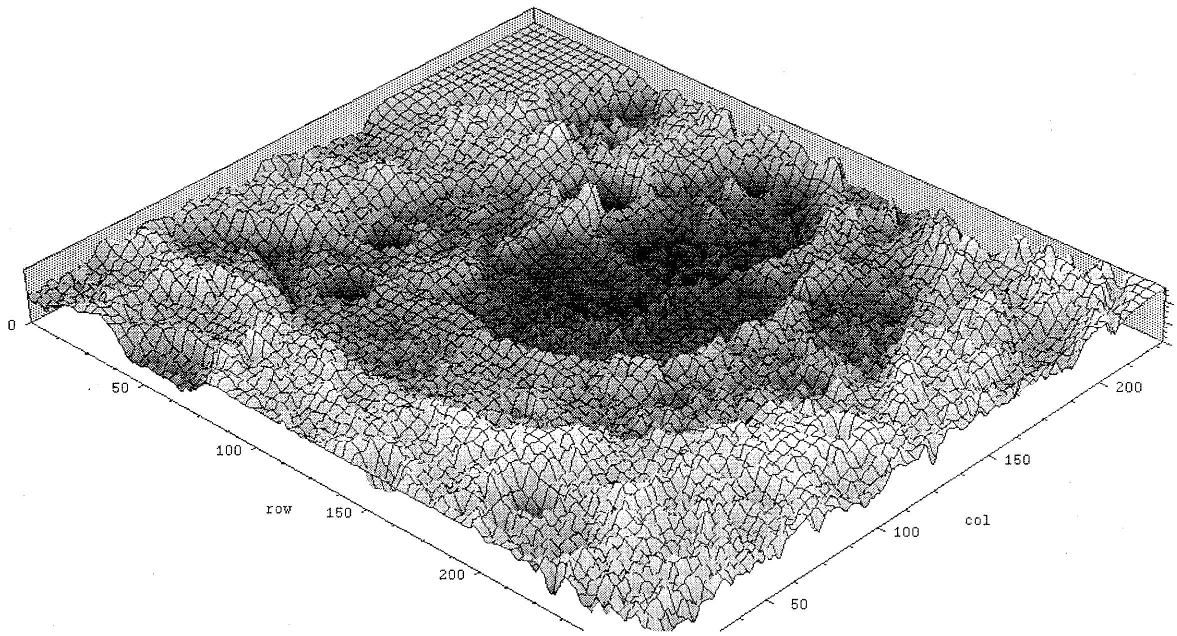

Fig. 2: Perspective view from the South of the lunar Humboldtianum basin showing a section of the terrain model from Fig.1. The inner and outer basin rings have diameters of approximately 270 and 500 km, respectively. True heights vary by as much as 6 km and are exaggerated in this view. Axes have arbitrary units.

Heights vary from -4500 m to +2000 m. The Humboldtianum basin displays a clear double-ring structure difficult to see in image data alone (Fig. 2). The basin has a depth of 6000 m below the lunar reference sphere (1737.4 km) and thus represents one of the most pronounced regional depressions on the Moon. In contrast, Mare Crisium exhibits voluminous basalt fillings. The terrain model indicates that the basin is slightly elliptical in shape, indicating, possibly, that the basin was formed by an oblique impact. Several large (>100 km-diameter) craters are visible in the terrain model.

The Clementine terrain model of Mare Orientale extends from 20°S–10°N to 88°W–90°W. It has a grid spacing of 200 m and a height resolution of better than 50m (Figs. 3, 4). Preliminary analysis of the terrain show a variety of surface features: depressions associated with lava ponds, isolated volcanic constructs, and steep slopes towards the center of Orientale up to 1500 m per 5000 m. Furthermore, a number of impact craters are included in the terrain model that show much morphologic detail for studies of depth, diameter, rim height and impact ejecta patterns.

5. COMPARISON WITH LASER ALTIMETER DATA

The Clementine laser altimeter obtained measurements of the slant range between the spacecraft and the lunar surface from spacecraft altitudes of 640 km or less (Nozette et al., 1994; Zuber et al., 1994). Laser pulses were emitted once every 0.6 second. 19% of the shot returns were detected and resulted in a total of 114,000 altitude measurements.

Altitude profiles along orbits are available, as well as an interpolated 2°x2° global raster terrain model. However, due to high spacecraft altitude, there is no data for lunar latitudes higher than 75°N or 75°S. For this study, the global data set was reprojected to match the stereo terrain model in terms of map projection parameters and scale (Fig. 5). It is obvious that the resolution of the laser altimeter dataset is inferior to that of the terrain model from the stereo images. Furthermore, gaps in the dataset exist. Also, the laser altimeter data appears noisy in rugged terrain due to the difficulties in detecting reflected laser signals when these are scattered. In contrast, it is obvious that the stereo model is constrained by illumination and viewing conditions and becomes noisy near the lunar limb and the terminator.

6. SUMMARY AND DISCUSSION

The availability of digital image data and digital photogrammetric techniques has greatly improved our means to recover topographic information from spacecraft stereo image data. These datasets represent new and powerful tools for geologic studies of the large lunar impact basins.

The study emphasizes that imaging sequences have to be planned carefully in terms of viewing geometry and lighting conditions if photogrammetric analyses are to be carried out. Orbit, camera pointing and imaging sequences have to be planned with the goal of achieving good image base-to-height ratios. However, lighting conditions are also important. Unlike Earth, albedo varies very little on the lunar surface, and there is little texture in images that were obtained at high Sun angles, therefore. Hence, this suggests that imagery should be obtained at low Sun angles, so long as cast shadows are avoided. Cast shadows pose a particular problem on lunar imagery because of the lack of an atmosphere and little scattering of light. In addition, we experienced that it is important for possible stereo partner images to be obtained under similar lighting conditions, as otherwise the automatic matching will fail. In addition, either good control point-, good spacecraft trajectory and camera pointing data, or both are needed for photogrammetric analysis.

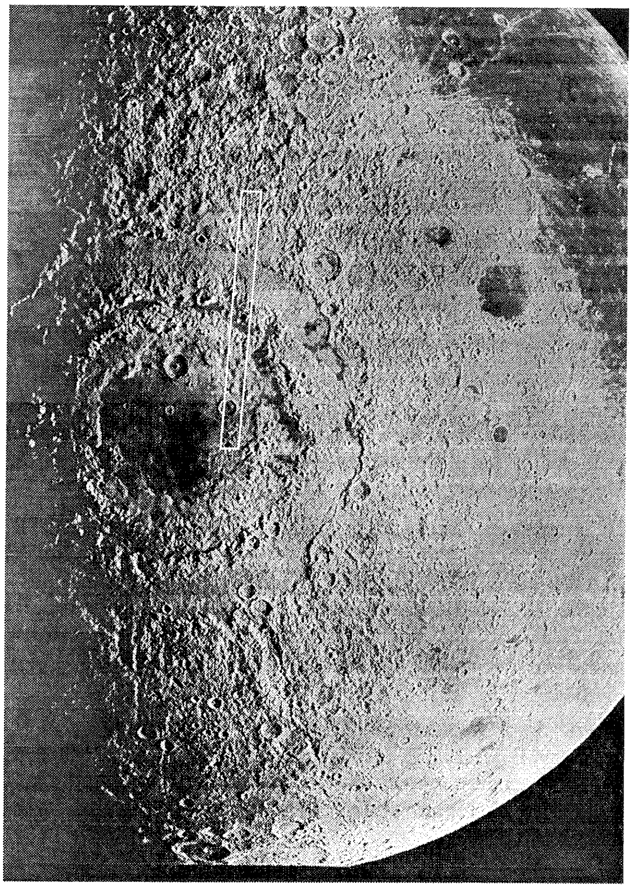

Fig. 3: The Moon's western hemisphere showing the 900-km diameter Orientale Basin and the area in which the terrain model from Clementine stereo images (Fig. 4) was derived.

From a comparison of stereo images and laser altimeter data (see. Fig. 1 and Fig. 4) it becomes clear that the stereo models are clearly superior to altimeter data sets in terms of lateral resolution and general noise level. The main advantage though of the laser altimeter is that it yields a near-global, relatively unbiased dataset of absolute heights. However, with todays availability of digital photogrammetric processing methods, a global DTM from stereo data could have been obtained easily, if mission scenario and imaging sequences for Clementine had been designed for optimum stereo coverage.

Finally, we experienced that the small sizes and large numbers of Clementine images pose quite a challenge to photogrammetric data processing. In spite of the availability of sophisticated automated methods of analysis, much operator-interaction, and much processing time are still required to derive large contiguous accurate terrain models. We therefore suggest that for future studies of lunar topography from space, metric cameras equipped with large pixel arrays or dedicated stereo cameras, such as those on the Mars '96 mission (Neukum et al., 1995), should be used.

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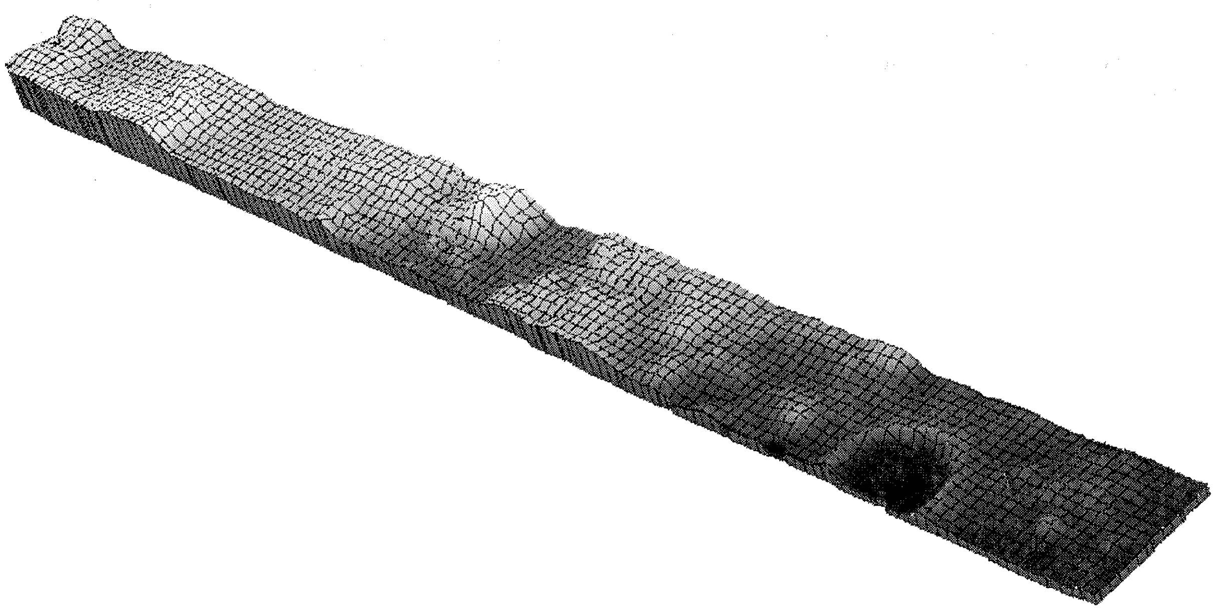

Fig.4: Perspective view of a DTM profile cross-cutting the Eastern Orientale Basin Rings (see Fig. 3). The grid spacing of this model is 200m (although not fully reproduced here). The width and length of the strip are 60 km and 600 km, respectively. Heights range from -3000 to +2000 m. Crater Kopff in the foreground has a diameter of approx. 36km.

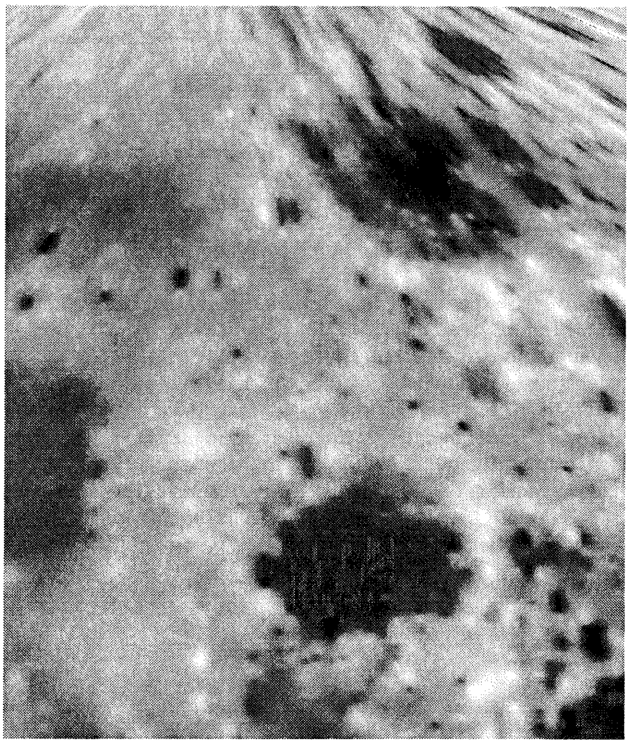

Fig. 5: A section of the global Digital Terrain Model derived from the Clementine laser altimeter data (Zuber et al., 1994) covering the same area on the Northern Nearside Hemisphere, as in Fig.1. Note the rather crude resolution as compared to the stereo model (see Fig. 1).

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