Shape and Albedo from Shading with Planetary Flyby Images of Mercury and the Moon

Isabel Krüll[1,2] (isakruel@uni-bremen.de), Kay Wohlfarth[1], Moritz Tenthoff[1], Christian Wöhler[1], Valentina Galluzzi[3], Jack Wright[4], Johannes Benkhoff[4], Joe Zender[4]

[1] technische universität dortmund
[2] Universität Bremen
[3] iaps
[4] esa

Introduction

- **3D Surface reconstruction:** crucial for geomorphological analysis, reflectance normalization, thermal modeling, rover landing site planning, and outreach activities
- **Laser Altimetry and Stereophotogrammetry:** accurate absolute heights but digital elevation model (DEM) resolution below image resolution due to artefacts
- **Shape and Albedo from Shading (SAfS)** refines stereo DEM → 3D models at image resolution [1,2,3,4]
- SAfS is well-validated for scientifically calibrated instruments that observe the planetary body under favorable conditions
- **Goal:** SAfS algorithm is applied to planetary flyby images acquired with uncalibrated off-the-shelf cameras to explore the limits of the algorithm

BepiColombo Image

Figure 2:

- Successful surface reconstruction in the center of the image. Algorithm struggles with more extremely illuminated sections at the image's edges.
- Details that are not visible in the input DEM were reconstructed → improved resolution

Figure 3 (row 1-4):

- Comparison of a hillshaded SAfS DEM with MDIS WAC image EW0251718878F
- Small craters, a few kilometers in diameter, not visible in the initial DEM were successfully reconstructed

Figure 3 (row 5):

- Elevation profile of the marked red line
- Small crater on the far right is clearly visible in the SAfS profile

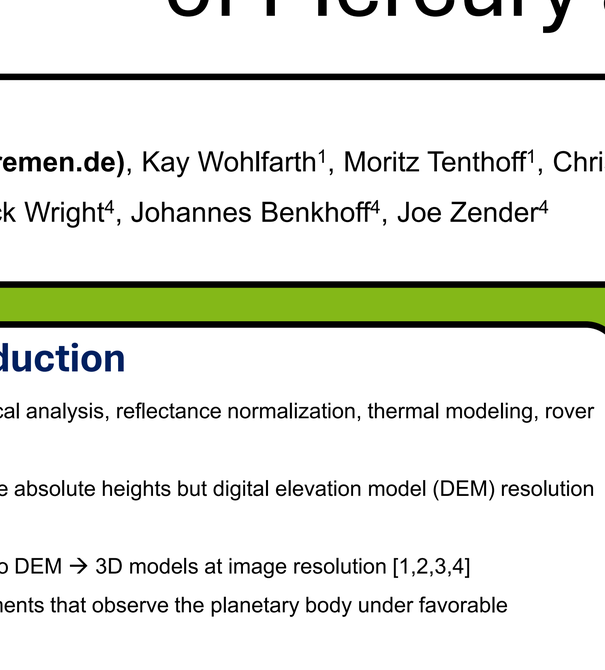

Figure 2. *Color-coded presentation of the reconstructed SAfS DEM from the BepiColombo image. Yellow dashed rectangle was analyzed in more detail.*

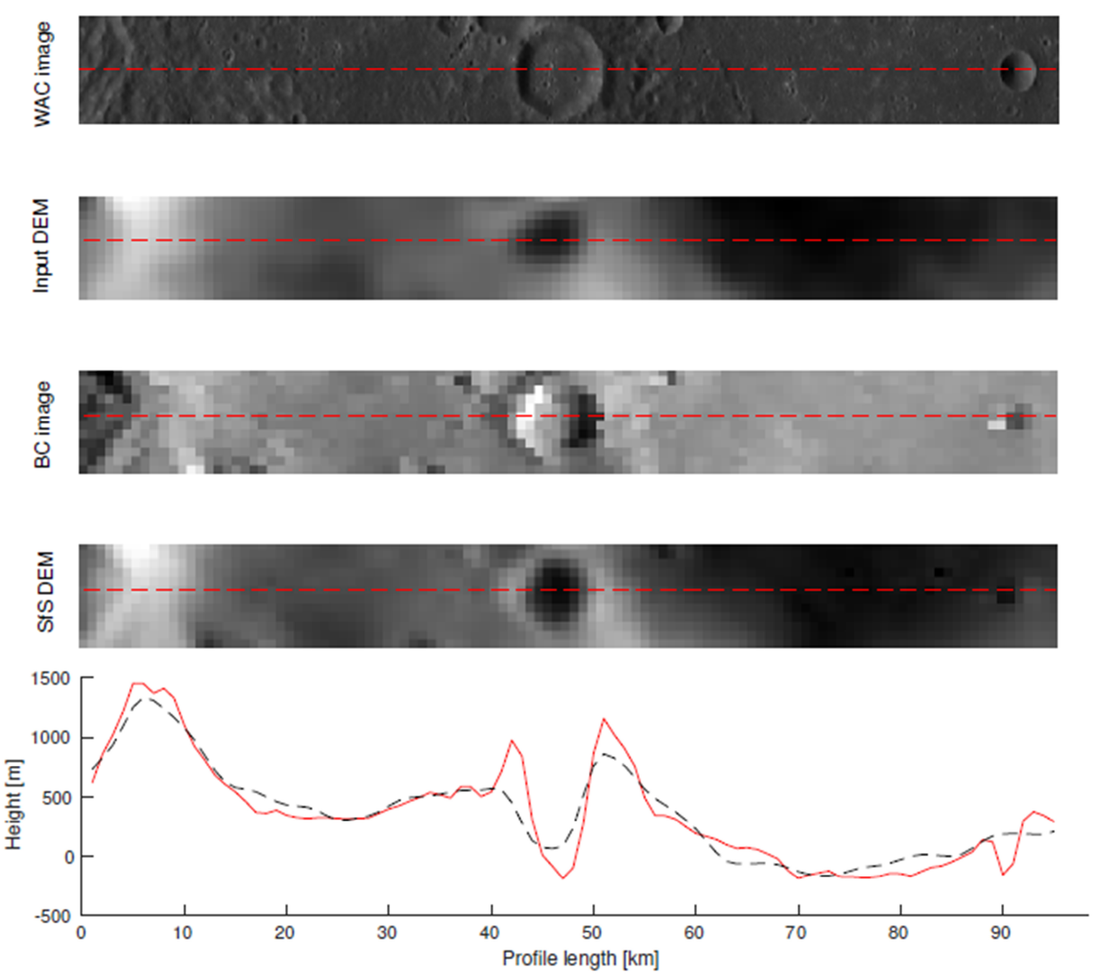

Figure 3. *WAC image (row 1), initial DEM (row 2), BepiColombo (BC) image (row 3), and SAfS DEM (row 4). Row 5: Height profiles of the initial DEM (dashed) and SAfS DEM (red).*

Methods

- **Two images**
  - Flyby image of Mercury obtained with a monitoring camera during BepiColombo's third flyby (Figure 1, left)
  - Flyby image of the Moon captured by a GoPro during the Artemis I mission (Figure 1, right)
- **Image calibration:** We estimate the relationship between the digital number output of the camera and the physical radiances with Hapke parameters from [5]
- **Initial DEMs:** LOLA DEM for the Moon [6], MDIS WAC DEM for Mercury [7]
- We apply our **SAfS** algorithm to the flyby images to refine the initial DEMs
- **Evaluation:**
  - We compare the resulting Mercury flyby DEM to MDIS WAC images [8].
  - We compare the lunar flyby DEM to the SLDEM2015 (60-100 m/pixel) [6]

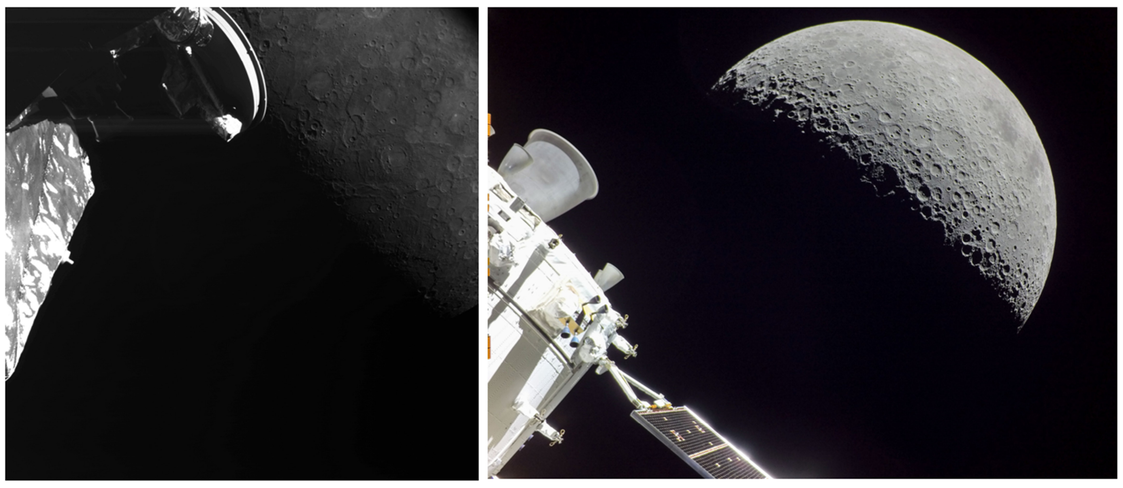

Figure 1. *Left: Flyby image from the BepiColombo mission [9]. Right: Flyby image from the Artemis I mission [10].*

Artemis I Flyby Image

- **Figure 4:** color-coded initial DEM compared to SAfS DEM of a region of interest (ROI)
- **Figure 5:** elevation profile indicated by the dashed line in Figure 4: SAfS DEM (red line) closely resembles the ground truth (GT) DEM (black line)
- **Vertical RMSE** between SAfS DEM and GT: 523 m → lower than pixel size of approximately 1500 m
- **Problems:** inaccuracies near ROIs' edges, and a preferred direction aligned with the illumination direction

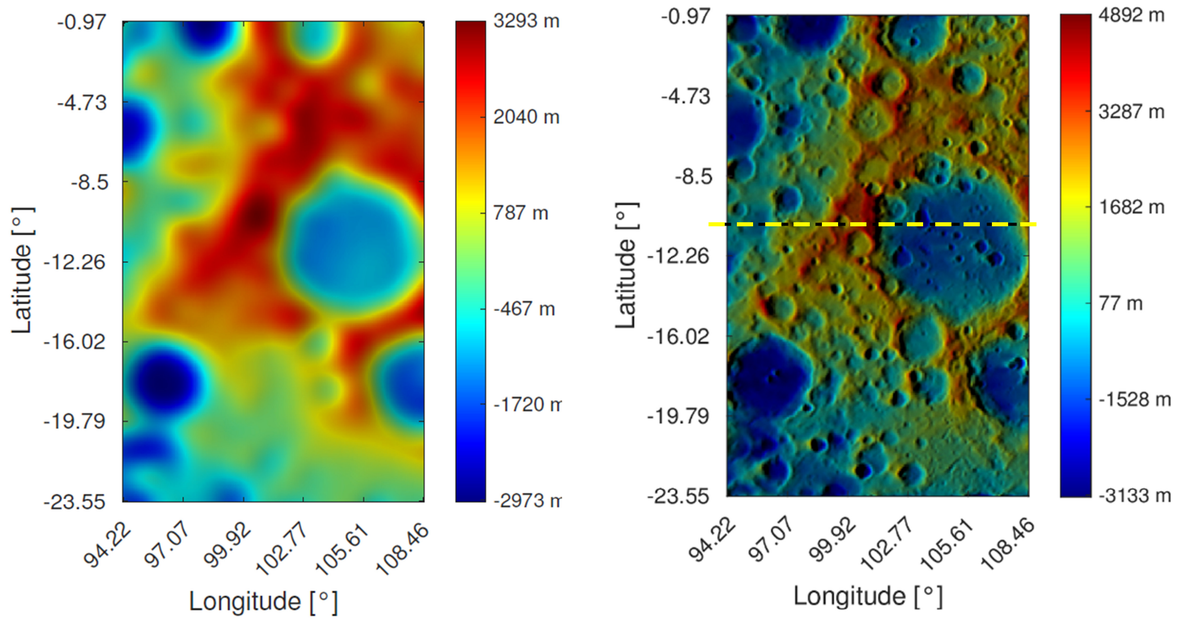

Figure 4. *Left: Color-coded initial DEM. Right: SAfS DEM. Yellow dashed line: profile that was analyzed in detail (see Fig. 5).*

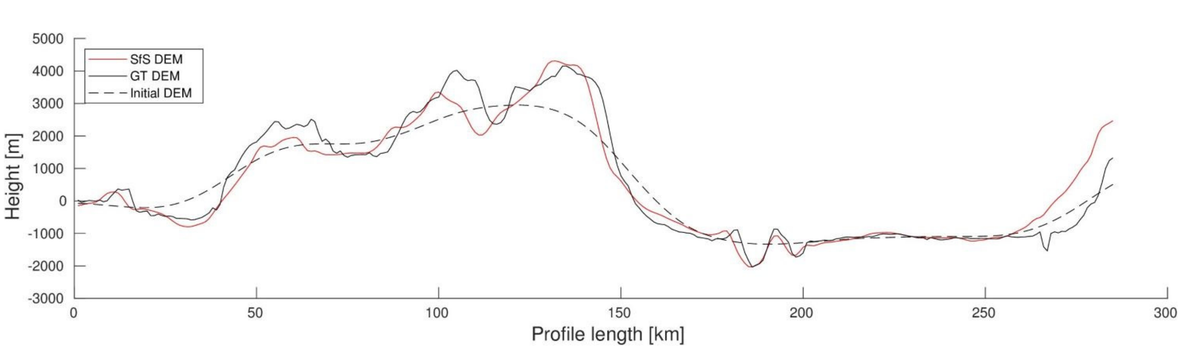

Figure 5. *Height profile of a selected terrain profile (see yellow dashed line in Fig. 4). Red line: DEM generated with the SAfS algorithm. Black line: Ground truth DEM. Dashed line: Initial DEM (input for the SAfS algorithm).*

Conclusion

In conclusion, it is possible to obtain sharp and accurate results by applying our SAfS framework to flyby images. Both results show that, despite the challenging conditions, the SAfS algorithm could reconstruct the surface up to image resolution and increase the level of detail of the input DEM. The quality differences between the two images can mainly be attributed to the (spatial) resolution of the original images and the oblique illumination direction. Usually, the image center is distortion-free, and the illumination geometry is best suited for SAfS. We found that the surface reconstruction at the edge of the image is also possible, but the quality decreases. All in all, our flyby-derived DEMs are accurate. They provide excellent outreach products, as demonstrated by ESA's BepiColombo flyby movie (see QR code on the left).

References

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