Research Assessment Exercise 2020
<u>Impact Case Study</u>

University: Hong Kong Polytechnic University (PolyU)
Unit of Assessment (UoA): 18 – Planning and Surveying (land and other)

Title of case study: Planetary Remote Sensing Contributing to Space Exploration Missions

(1) Summary of the impact

PolyU's research on planetary remote sensing has been adopted by China's space exploration missions for landing site characterization and selection. A new integrated 3D mapping model has been developed for high-precision and high-resolution topographic mapping of the Moon and Mars, surpassing all existing technology such as photogrammetry or laser altimetry. Novel deep learning approaches have also been developed for more automated and robust analysis of planetary remote sensing data. These developments and the results of their application have been used [redacted] o optimize landing site evaluation, change descent orbit design, and improve surface operation of the Chang'E-3 and Chang'E-4 missions. The developments have also been used for landing site characterization and selection in [redacted] mission [redacted].

(2) Underpinning research

High-precision and high-resolution topographic information for surface hazard analysis and landing site evaluation are vital for the success of any landing mission to planetary bodies, such as missions to the Moon or Mars. They are also essential for planetary scientific research, for example, for studying surface geomorphology and geology. Remote sensing to obtain high-precision and high-resolution topographic information on planetary bodies is extremely difficult, unlike that on Earth, due to the lack of control information. Further, weak textures, shadow casts, and specular reflections on a planetary surface could render existing remote sensing techniques unusable. A PolyU research group, comprising Dr. Bo Wu, Prof. Huseyin Baki Iz, Prof. Zhilin Li, Prof. Yongqi Chen, Dr. Bruce King, Prof. Xiaoli Ding, Prof. Wu Chen and Dr. Robert Tenzer, has systematically researched planetary remote sensing over the past decade. They have advanced research and development in planetary mapping [**R1**, **R3-R5**], planetary reference systems [**R2**], and planetary remote sensing data analysis [**R6**].

For high-precision and high-resolution topographic mapping of the Moon and Mars, a new 3D mapping model that integrates several types of planetary remote sensing data [**R1, R2, R3, R4**] and multiple complementary methods [**R5**] was developed by our team. This model enables the combined adjustment of multiple-platform multiple-sensor remote sensing imagery and laser altimeter data [**R1, R3, R4**] to generate high-precision and consistent digital topographic models (DTMs). Nowadays large amounts of planetary remote sensing data have become available. The data sets have different characteristics such as sensor configuration, spatial-temporal attributes, and uncertainty. There are usually different levels of inconsistencies or even contradictions among each other. The integrated 3D mapping model is essential for the proper calibration, registration, and analysis of multiple-source planetary remote sensing datasets. In turn, it facilitates the full comparative and synergistic use of them. These developments led to a "*Gold Medal*" and a "*R. Alekseev Award*" for the PolyU team at the *44th International Exhibition of Inventions* in Geneva in April 2016. The research article [**R3**] about multiple-source data integration for precision lunar topographic mapping was cited by *Nature Index* as "*a landmark paper on lunar topographic models*" in an analysis of the research produced by universities in Hong Kong in 2014 (https://www.nature.com/articles/516S64a).

The current technique of photogrammetry requires stereoscopic images for 3D mapping; however, high-resolution stereoscopic images of planetary surfaces are rare. Moreover, photogrammetry may fail to produce dense mapping results for planetary surfaces due to a lack of image texture. Shape-from-shading (SfS) is a complementary approach to photogrammetry that produces more accurate mapping results for untextured input images. SfS can generate topographic information with pixel-level resolution and can be used for a single image or multiple images. However, SfS alone has never been practically used in planetary mapping due to problems such as uncertainties in the reflectance model and surface albedo. Therefore, a new shape-and-albedo-from-shading (SAfS) approach [**R5**] was developed by our team for generating high-resolution DTMs from a single image with the constraint of a low-resolution DTM generated from photogrammetry or laser altimetry. Further, an SfS-assisted image matching method was developed for the illumination-invariant matching of lunar surface images; with this method, reliable and dense matching results could be generated from images with illumination differences as large as 90°. This pioneering work extends the scope of applying photogrammetry to planetary mapping. The integrated 3D mapping model enables the synergistic integration of complementary datasets and methods to generate higher-quality DTMs of the lunar and Martian surfaces with improved spatial resolution and precision than are attainable using individual datasets or methods.

Moreover, novel deep learning approaches were developed for the analysis of planetary remote sensing data; these approaches improved surface hazard (e.g., rocks, craters) evaluation and landing site characterization. An automatic rock detection method was developed to extract rocks from high-resolution lunar images. Based on that, we developed a new rock abundance model to study the rock distribution pattern on the lunar surface [**R6**]. A new active learning approach was also developed for more automated and robust crater detection using planetary remote sensing data [**R6**], which solves the cumbersome task of providing training samples of favourable quality and quantity that is required in conventional deep learning approaches. [redacted]

All of this underpinning research was funded by the Research Grants Council of Hong Kong [**G4, G6**] [redacted] [**G1-G3, G5**]. The research has been published in over 50 top journals (in Quartile 1 of the Journal Citation Ranking of the Web of Science). Four postdoctoral researchers and six PhD students have also worked in this area over the past six years using these research grants.

List of Grants:

[G1] [redacted] HK$1,318,440, 03/2017-12/2020.

[G2] [redacted] HK$ 1 million, 03/2015-03/2020

[G3] [redacted] HK$1,318,440, 03/2017-02/2020.

[G4] High-Resolution and High-Precision 3D Modeling of Lunar Topography by Integrating Multi-Image Shape-from-Shading, Image Matching and Range Data, Funded by The Research Grants Council of Hong Kong (GRF), HK$695,788, 01/2016 - 12/2018

[G5] [redacted] HK$ 378,996, 05/2012-12/2013

[G6] Integration of Multi-Source Lunar Orbiter Camera Imagery and Laser Altimeter Data for Precision Lunar Topographic Mapping, Funded by The Research Grants Council of Hong Kong (GRF), HK$ 589,558, 01/2011 - 12/2013

(3) References to the research

[R1] Bo Wu, Jian Guo, Yunsheng Zhang, Bruce King, Zhilin Li, Yongqi Chen, 2011. Integration of Chang'E-1 Imagery and Laser Altimeter Data for Precision Lunar Topographic Modeling, ***IEEE Transactions on Geoscience and Remote Sensing***, vol. 49, no. 12, pp. 4889-4903.

[R2] Huseyin Baki Iz, Yongqi Chen, CK Shum, Xiaoli Ding, Bruce King, Wu Chen, M Berber, 2012. Assessing consistency of Chang'E-1 and SELENE reference frames using nearly-colocated laser altimetry footprint positions. ***Journal of Geodesy***, vol. 86, no. 2, pp. 109-117.

[R3] Bo Wu, Jian Guo, Han Hu, Zhilin Li, Yongqi Chen, 2013. Co-Registration of Lunar Topographic Models Derived from Chang'E-1, SELENE, and LRO Laser Altimeter Data Based on a Novel Surface Matching Method, ***Earth and Planetary Science Letters***, vol. 364, pp. 68-84.

[R4] Bo Wu, Fei Li, Lei Ye, Si Qiao, Jun Huang, Xueying Wu, He Zhang, 2014. Topographic Modeling and Analysis of the Landing Site of Chang'E-3 on the Moon. ***Earth and Planetary Science Letters***, vol. 405, pp. 257-273.

[R5] Bo Wu, Wai Chung Liu, Arne Grumpe, Christian Wöhler, 2017. Construction of Pixel-Level Resolution DEMs from Monocular Images by Shape and Albedo from Shading Constrained with Low-Resolution DEM. ***ISPRS Journal of Photogrammetry and Remote Sensing***, vol., 140, pp. 3–19.

[R6] Bo Wu, Jun Huang, Yuan Li, Yiran Wang, Jing Peng, 2018. Rock Abundance and Crater Density in the Candidate Chang'E- 5 Landing Region on the Moon, ***Journal of Geophysical Research - Planets***, vol. 123, no. 12, pp. 3256-3272.

(4) Details of the impact

<u>1) Chang'E-3 landing site mapping and selection</u>

In recognition of PolyU's research achievements in planetary remote sensing, the research team was invited in 2012 [redacted] to work on the topographic mapping and analysis of the landing site for the Chang'E-3 lunar landing mission [**G5**]. The integrated 3D mapping model and analysis methods were extensively used, contributing to the success of the mission in 2014 [**S1**]. [redacted] "*The research and developments from Dr. Bo Wu and his team are very helpful for us to understand the topographic and geomorphological information of the landing area*" [**S1**].

<u>2) Chang'E-4 landing site characterization, selection, and mission operation</u>

Another invitation from [redacted] led to the PolyU team working on topographic and geomorphological mapping and analysis for the characterization and selection of the Chang'E-4 landing site [**G3**]; this work ultimately contributed to the successful landing of Chang'E-4 on the far side of the Moon [redacted] [**S2**]. Notably, the high-precision and high-resolution topographic mapping results revealed the very rough terrain of the landing surface. This enabled the decision to change the descent orbit design from the Chang'E-3's smooth descent orbit to the Chang'E-4's nearly 90º orbit manoeuvre during the descent phase, which proved critical for the successful landing. Based on the high-precision and high-resolution topographic models, the research team identified the exact location of the lander within an hour after the landing; this was faster than the mission requirement of three hours and added two hours to the time available for the deployment of scientific instruments to begin operations. Also, the research team generated a 1.5 m resolution DTM using the SAfS approach [**R5**] based on a single satellite image, which was the best quality DTM available immediately after landing. Knowledge of the exact lander position and the 1.5 m resolution DTM enabled detailed measurement and analysis of the topographic features (surface hazards, slopes, and occlusions) of the area surrounding the lander, which was critical for subsequently carrying out the surface operations of the mission [**S2**].

3) Landing site characterization and selection for the [redacted] the research team is currently working on landing site characterization and selection for the [redacted] (a lunar soft-landing and sample-return mission to be launched [redacted] [**G2**] [redacted] [**G1**]. The developed topographic and geomorphological mapping methods were used for hazard analysis and evaluation of the [redacted] landing site [**S3**]. Topographic and geomorphological analysis was also conducted to identify a suitable [redacted] landing site [redacted] [**S4**]. In September 2016, Dr. Bo Wu was appointed [redacted] to advise on the mission design and landing site selection [**S4**]. He was further appointed by the [redacted] in February 2019 and has since become a member [redacted] [**S4**]. He has been invited [redacted] to join over 10 meetings and give talks on the developed techniques to the PIs of the main payloads, engineers, and scientists involved in the mission.

4) International collaboration

The PolyU team's achievements in planetary remote sensing and mapping have been recognized by the international community. PolyU organized the International Conference on Planetary Remote Sensing and Mapping in August 2017, which attracted over 100 participants from NASA, the European Space Agency, China, and other countries [**S5**]. Dr. Bo Wu was invited to present at workshops and meetings organized by the European Space Agency (ESA) and German Aerospace Center (DLR) [**S6**]. The Taylor and Francis Group/CRC Press published a book titled *Planetary Remote Sensing and Mapping*, in 2019, which was edited by Dr. Bo Wu and co-editors from the German Aerospace Center, Chinese Academy of Sciences, and Moscow State University of Geodesy and Cartography of Russia, and over 60 contributors from different countries [**S7**].

5) Media coverage and outreach activities

The PolyU team's achievements have received wide coverage by various media outlets, both locally and internationally. There were over 200 related news reports from 2013 to 2019, with an estimated readership number of millions [**S8**]. The achievements have also led to various public outreach activities [**S9**]. For example, the exhibition about our involvement in the Chang'E-3 mission at the Hong Kong Science Museum from 21 July to 24 August 2014 attracted over 300,000 people. Over ten public seminars and talks regarding our involvement in the Chang'E-3 and Chang'E-4 missions have been given to secondary school students and the general public. A video on our "Integrated 3D Mapping Model" is available on the YouTube Channel of the Hong Kong Research Grants Council and it garnered 475 views from April 2017 to September 2019 [**S10**].

(5) Sources to corroborate the impact

- **[S1]** Letter [redacted] stating PolyU's contribution to the Chang'E-3 mission
- **[S2]** Letter [redacted] stating PolyU's contribution to the Chang'E-4 mission
- **[S3]** Evidence of participation [redacted]
- **[S4]** Evidence of participation [redacted]
- **[S5]** PRSM2017 Conference: http://event.lsgi.polyu.edu.hk/prsm2017/index.html
- **[S6]** Invitations for talks at workshops organized by ESA and DLR
- **[S7]** *Planetary Remote Sensing and Mapping*: https://www.crcpress.com/Planetary-Remote-Sensing-and-Mapping/Wu-Di-Oberst-Karachevtseva/p/book/9781138584150
- **[S8]** Examples of media coverage
- **[S9]** Examples of outreach activities
- **[S10]** Online Video "Integrated 3D Mapping Model", YouTube Channel of the Hong Kong Research Grants Council: https://www.youtube.com/watch?v=ilDwPrvbz_Q