Science Bulletin 69 (2024) 2183–2186

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

Short Communication

A 76-m per pixel global color image dataset and map of Mars by Tianwen-1

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ARTICLE INFO

Article history:
Received 27 October 2023
Received in revised form 11 April 2024
Accepted 12 April 2024
Available online 23 April 2024

Remote-sensing images of Mars contain rich information about its surface morphology, topography, and geological structure. These data are fundamental for scientific research and exploration. Prior to China's first Mars exploration mission, data from six advanced optical imaging systems of different missions in the Martian orbit had been used to generate Mars global/near-global image datasets with spatial resolutions of better than 1 km: the visual imaging system of Mariner 9, visual imaging subsystem cameras of Viking 1 and 2, Mars Orbiter Camera-Wide Angle (MOC-WA) of the Mars Global Surveyor (MGS), Context Camera (CTX) of the Mars Reconnaissance Orbiter (MRO), High Resolution Stereo Camera (HRSC) of Mars Express (MEX), and Thermal Emission Imaging System (THEMIS) of the Mars Odyssey Orbiter [1,2]. Martian grayscale image mosaics have been created using the datasets acquired by these imaging systems. For example, the "MGS MOC-WA Atlas Mosaic" has a spatial resolution of 256 pixel/degree (approximately 232 m/pixel) in the visible band [3]; the THEMIS infrared band Global Mosaic of the Odyssey offers a spatial resolution of approximately 100 m/pixel [4]; and the MRO Global CTX Mosaic of Mars in the visible band, covering 99.5% of the Martian surface between 88° north and 88° south, has a spatial resolution of approximately 5 m/pixel [5,6]. In terms of global color images, Mars Viking Colorized Global Mosaic 925 m v1 and the optimized version of Mars Viking Colorized Global Mosaic 232-m v2 have spatial resolutions of approximately 925 m/pixel [7] and 232 m/pixel [8], respectively.

The geometric positioning of the aforementioned Mars global image datasets is typically achieved through either uncontrolled positioning using the orbital data at the time of imaging (where positioning accuracy depends on the orbital measurement precision) [9], or controlled positioning using the Mars reference frame established by MGS Mars Orbiter Laser Altimeter (MOLA) topographic data (spatial resolution of approximately 463 m/pixel and horizontal accuracy of approximately 100 m) [10]. The horizontal position accuracy can reach approximately 200 m [2].

Among the available global color-image maps of Mars with spatial resolutions of hundreds of meters, only the Viking Mosaic employs a color composite. However, it utilizes data from three bands at 440, 529, and 591 nm, which are not sufficient to create true-color images. Currently, there is a lack of medium resolution global true-color image datasets and maps of Mars with high positioning accuracy. Compared with grayscale images, true-color images provide a more realistic representation of the Martian landscape, enabling scientists to precisely interpret the geomorphic and geological characteristics, comprehend changes on the Martian surface, and monitor the formation and evolution of dust storms [11,12]. However, improving the spatial resolution and color authenticity of global image maps will be of great significance for advancing Mars science.

Global remote sensing of Mars is one of the primary scientific goals of China's first Mars exploration mission (Tianwen-1). The Moderate Resolution Imaging Camera (MoRIC) [13] onboard the

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https://doi.org/10.1016/j.scib.2024.04.045
2095-9273/

orbiter has obtained 14,757 images, which have allowed for the acquisition of a global stereo image of the entire Martian surface. Additionally, the Mars Mineralogical Spectrometer (MMS) [14] has returned 325 strips of visible and near-infrared spectral measurement data (Figs. S1 and S2, Text S1 online) that have laid the foundation for the development of a high-resolution global color-image map of Mars with high positioning accuracy. In this study, we used these data to develop a new global color-image map of Mars at a scale of tens of meters; this product offers an important new resource for the Mars science community. Data mapping and processing of the Tianwen-1 Mars global mosaic involved three steps: radiometric calibration, geometric calibration, and global image cartography.

First, the preprocessed MoRIC image data (Level 2C product) were subjected to radiometric calibration, which included atmospheric, photometric, and color corrections, to obtain individual MoRIC images with accurate radiances (Text S2 online). Atmospheric correction can reduce the influence of Martian atmospheric scattering on image brightness and color by using an analytical atmospheric scattering model. Photometric correction eliminates the influence of varying illumination geometries on image brightness by using the Lommel-Seeliger model, helping to obtain a uniformly bright surface image and correcting the hotspot effect at small phase angles. In terms of color correction, the color-matching function of the CIE 1931 standard observer and color-matching additive method were used to convert MMS multispectral data into RGB images, which were used as reference color values, and the MoRIC image color correction matrix was established according to the MMS RGB images. Furthermore, the image data of the Korolev crater covered by snow/ice was used as a standard for white balance correction to calibrate the relative relationship between the *R, G*, and *B* components in individual images. The color deviation in the input image was significantly improved after color correction, and a true-color image dataset was obtained (Fig. S3 online).

Thereafter, geometric calibrations involving global adjustment and orthorectification were applied to align the image data with the correct geographic positions (Text S3 online). The 14,757 MoRIC images were matched by a coarse-to-fine, hierarchical matching strategy; that is, the matching results were progressively refined layer by layer through the image pyramid. A total of 16,926,721 image tie points across all images were extracted, corresponding to 42,141,227 homologous points; the matching accuracy was better than 0.3 pixels. The photogrammetric bundle adjustment method was employed to correct camera attitude and position and to calculate the Martian surface coordinates of the tie points. After the global bundle adjustments, the average deviation between the image plane coordinates of the calculated tie points derived from the adjustments and the actual image plane coordinates of their corresponding homologous points was 0.5 pixels and the standard deviation (SD) was 0.9 pixels. This indicates that the MoRIC achieved a seamless pixel-level registration on a planetographic coordinate system [15]. A point-cloud data with approximately 1.6 billion data points were used to create a global polygon mesh model of Mars for image orthorectification, which helped eliminate image distortion caused by terrain variations and generate individual orthorectified images.

Finally, the quantifiable criteria were used to eliminate the following four types of images: (a) low spatial resolution (<120 m), (b) low solar elevation angle (<5°), (c) largely veiled by dust storm and cloud (>50%), and (d) failed in the auto-matching because of weak texture. We selected 10,572 good-quality images from 14,757 total images. These images covered 100% of the Martian surface, with resolutions ranging from 57 to 120 m/pixel (average of 76 m/pixel). We established a global color uniformity method, which adjusted the brightness and contrast of each image. The adjustment parameters of each image were calculated by least squares according to the difference of the RGB color component value between the overlapping areas of adjacent images in the global region. After ensuring color uniformity, the calibrated MoRIC images were mosaicked into a global Mars color orthomosaic product in a planetographic coordinate system; the image color of the global map achieved visual consistency. For convenience of use and in line with other Mars global mapping products, the orthomosaic

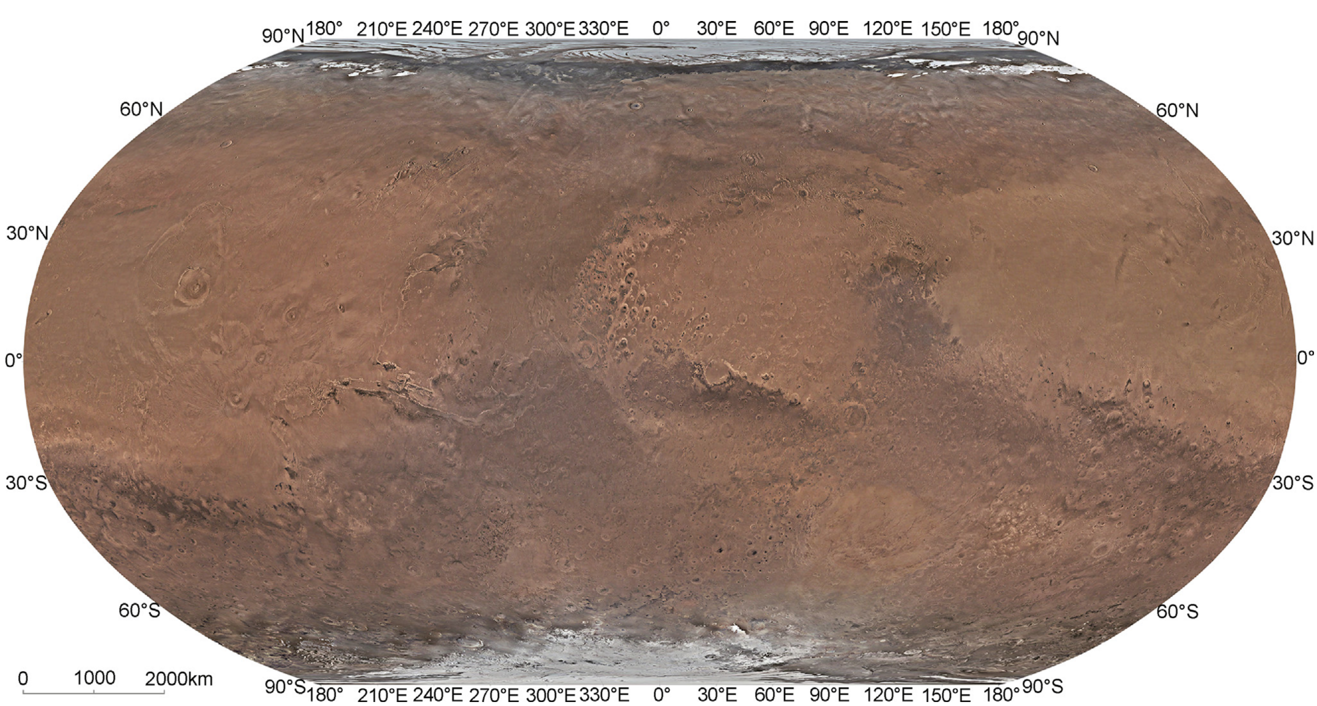

Fig. 1. China's first Mars global color image map in the Robinson projection.

Table 1
Characteristics of Mars globe/near-globe image maps.

Data product	Create time	Data source	Data acquisition time range	Image resolution (m)	Product resolution (m)	Martian surface coverage (%)	Color characteristic
Mars Viking Colorized Global Mosaic 925 m v1	2001	Viking1/2	1976–1982	7–1400	925	100	Pseudo color
The MGS MOC Wide Angle Map of Mars	2003	MGS MOC	1997–1999	230–7500	232	100	Grayscale
Viking MDIM2.1 Grayscale Global Mosaic 232 m	2003	Viking1/2 MGS MOLA	1976–1982 1999–2001	7–1400	232	100	Grayscale
Mars Viking Colorized Global Mosaic 232 m v2	2009	Viking1/2 MGS MOLA	1976–1982 1999–2001	7–1400	232	100	Pseudo color
The Global CTX Mosaic of Mars	2023	MRO CTX	2006–2022	4.93–6	5	99.5	Grayscale
Tianwen-1 Mars Global Color Orthomosaic 76 m v1	2023	Tianwen-1 MoRIC	2021–2022	57–197	76	100	True color

product was converted from the planetographic coordinate system to a planetocentric coordinate system [15], generating "*Tianwen-1 Mars Global Color Orthomosaic 76 m v1*" (Text S4 online).

For the purpose of cartographic visual representation, the Robinson projection was used to project the product to make an image map. To improve visibility of the surface morphological features, a sharpen filter was applied to sharpen and clarify the output image map. The result was China's first Mars global color-image map in the Robinson projection (Fig. 1). Subdivided image map products were designed to facilitate the management, release, and application of the global image map mosaic. Approximately 110 GB of global data were divided into three regions, resulting in a total of 36 map charts, each of approximately 2–4 GB. The subdivided image map product is called "*Tianwen-1 Mars Global Color Orthomosaic Chart 76 m v1*".

The global color orthomosaic maps and datasets of Mars obtained by Tianwen-1 were mosaicked using 10,572 MoRIC orthorectified images processed with radiometric, geometric, and color correction, resulting in a spatial resolution of 76 m and horizontal precision of approximately 68 m (0.9 pixels). This study used bundle adjustment technology to optimize the original orbit measurement data by treating Mars as a unified adjustment network, reducing the position deviation between individual MoRIC images to < 1 pixel, and achieving pixel-level "seamless" global image mosaicking. Brightness and color consistency of the global images was ensured through color correction and global color uniformity. The true colors of the Martian surface were measured using the MMS onboard the Tianwen-1 orbiter, and a true-color reference for the Martian surface was established for true color restoration.

To evaluate the horizontal deviation between *Tianwen-1 Mars Global Color Orthomosaic 76 m v1* and other Mars global maps, we conducted a comparison with Mars Viking Colorized Global Mosaic 232 m v2, which is currently the most widely used map (spatial resolution of 232 m) and is controlled by a Mars reference frame with a horizontal accuracy of approximately 200 m. The comparison results of 1,791 corresponding feature points showed that the average horizontal deviation between the two maps was 280 m, and the root mean square was 309 m, which is equivalent to 1–2 pixels in Mars Viking Colorized Global Mosaic 232 m v2 and approximately 4 pixels in *Tianwen-1 Mars Global Color Orthomosaic 76 m v1*.

Among the five available Mars global/near-global image maps with spatial resolutions better than 1 km/pixel (Viking, MGS MOC, MGS MOLA, and MRO CTX data; Table 1), the two versions of the Viking global map (resolutions of 925 and 232 m) are pseudo-color images, and the others are grayscale images. Thus, the global color-image dataset and map product obtained from Tianwen-1 are the only true-color global maps of Mars.

The Tianwen-1 Mars global color orthomosaic data products developed in this study fill the gap in the high-precision positioning of Mars global color-image data products at a scale of tens of meters. As such, this product is currently the highest resolution global true-color image map of Mars, and significantly improves the resolution and color authenticity of commonly used global Mars images. This mapping product can serve as a new Mars global base map, providing a higher-quality geographic reference for international peers to conduct Mars image mapping at scales of tens of meters, meters, and submeters, as well as supporting subsequent Mars exploration missions and scientific research.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work was supported by the China National Space Administration (CNSA), the National Key R&D Program of China (2022YFF0503204), the Key Research Program of the Chinese Academy of Sciences (ZDBS-SSW-TLC001), and the National Natural Science Foundation of China (12203073, 42371384). We acknowledge the Tianwen-1 project's management, engineering and scientific teams for their diligent efforts in making this mission as effective as possible. We are grateful to team members of the five systems: the probe system, the launch vehicle system, the launch site system, the telemetry track and command system, and the ground research and application system (GRAS). The Tianwen-1 data used in this work is processed and produced by GRAS.

Author contributions

Chunlai Li, Rongqiao Zhang, Jianjun Liu, and Yan Geng designed the research, and helped with spacecraft and instrument operations. Jianjun Liu, Xin Ren, Wei Yan, Wangli Chen, Xingguo Zeng wrote the manuscript. Chunlai Li reviewed and finalized the manuscript. Jianjun Liu, Xin Ren, Wei Yan, Wangli Chen, Chunlai Li, Xiaoxia Zhang, Xu Tan, Xingye Gao, Qiang Fu, Dingxin Liu, Lin Guo, Qing Zhang, Jingjing Zhang, and Guobin Yu conducted Tianwen-1 MoRIC data processing, calibration and validation. Jianjun Liu, Xin Ren, Wei Yan, Wangli Chen, Xiaoxia Zhang, Xu Tan, Lin Guo, Qing Zhang, and Zhiping He performed Tianwen-1 MMS data processing, calibration and validation. Xin Ren, Wei Yan, Wangli Chen, Xingguo Zeng, and Xingye Gao conducted the Tianwen-1 MoRIC image cartography and dataset production.

Appendix A. Supplementary materials

Supplementary materials to this short communication can be found online at https://doi.org/10.1016/j.scib.2024.04.045.

Data availability

The global color image dataset and map of Mars, *Tianwen-1 Mars Global Color Orthomosaic 76m v1*, and *Tianwen-1 Mars Global Color Orthomosaic Chart 76m v1* are available at https://clpds.bao.ac.cn/web/enmanager/mars1.

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