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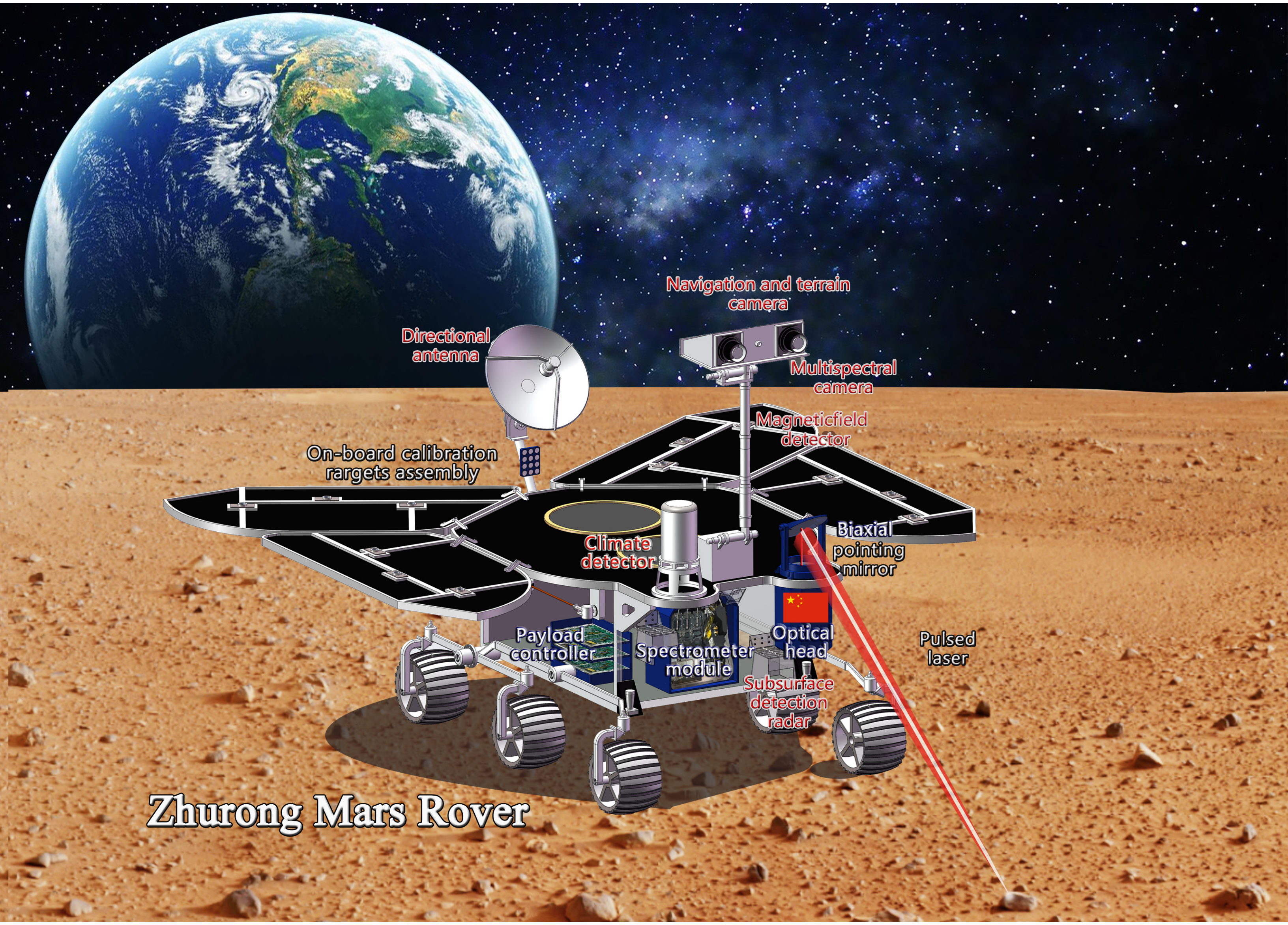

Cover Feature:

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Letter

Design, Function, and Implementation of China's First LIBS Instrument (MarSCoDe) on the Zhurong Mars Rover

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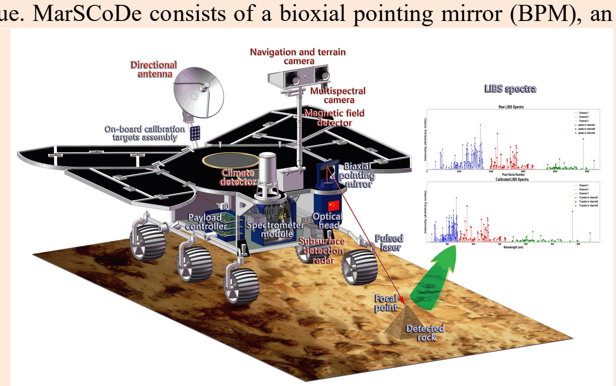
ABSTRACT: MarSCoDe (Mars Surface Composition Detector) is China's first instrument for Mars material analysis, which accompanies the Zhurong Mars rover landing on Utopia Planitia and will detect interested Martian rock and soil targets based on laser-induced breakdown spectroscopy (LIBS) technique. MarSCoDe consists of a bioxial pointing mirror (BPM), an optical head, a calibration targets assembly (CTA), a spectrometer module (SM) and a payload controller. The MarSCoDe is scheduled to analyze twelve major elements. To achieve accurate quantitative analysis and classification of Mars targets, a PSO (particle swarm optimization)-based calibration scheme is adopted to correct the spectral shift due to the temperature change on Mars, and then a convolutional neural network (CNN) was proposed to implement the analysis of elements. Finally, the mineral types of Martian objects will be identified according to the alkali silica ratio. The detection results of the MarSCoDe will provide further information about the evolution of Mars.



In planetary exploration, laser-induced breakdown spectroscopy (LIBS) is an appealing element detection technology due to its special capabilities, such as dust removal, in situ analysis, and analysis of light elements (atomic mass <20). With the successful landing in 2021 of NASA's Perseverance rover and CNSA's Zhurong rover, plus NASA's Curiosity rover in 2012, there are now three LIBS payloads working on Mars.[1-3] The Zhurong rover landing on Utopia Planitia on May 15, 2021, contains China's first LIBS instrument, the MarSCoDe (Mars Surface Composition Detector). Its purpose is to detect the atomic spectra of representative rock and soil targets in the Utopia Planitia area and to analyze the material composition of the Martian surface. The detection results of the MarSCoDe will provide further information about the evolution of Mars.

The Zhurong Mars rover consists of a navigation and terrain camera, a multispectral camera, a magnetic field detector, a climate detector, a subsurface detection radar, and the LIBS instrument, MarSCoDe, shown in Fig. 1. The MarSCoDe (marked in blue in Fig. 1) consists of five parts: a bioxial pointing mirror (BPM), an optical head (Fig. S1), and a calibration targets assembly (CTA), which are outside the rover’s cabin, and a spectrometer module (SM) and a payload controller, which are inside the cabin. Pulsed laser is emitted and focused via the optical head, which is reflected onto the BPM to detect rocks. The excited LIBS signals from the rocks are collected through the optical head

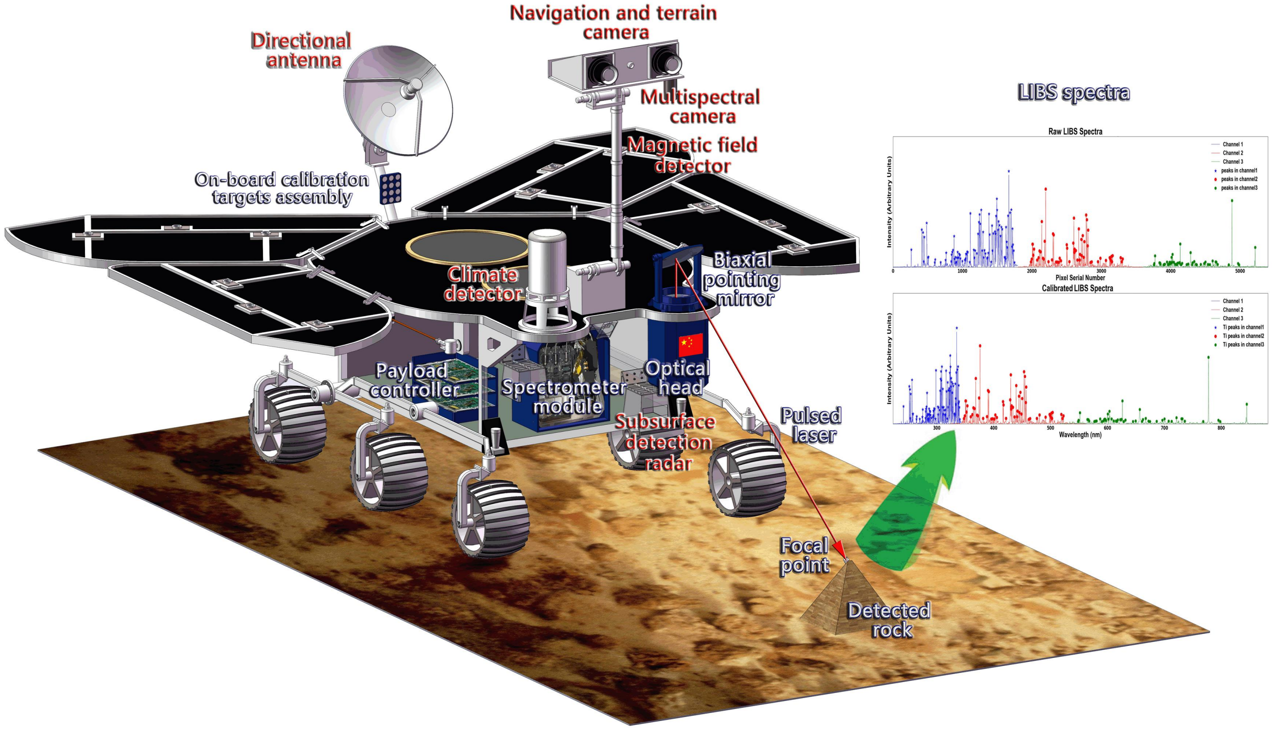


Fig. 1 The Zhurong rover and its payload MarSCoDe.

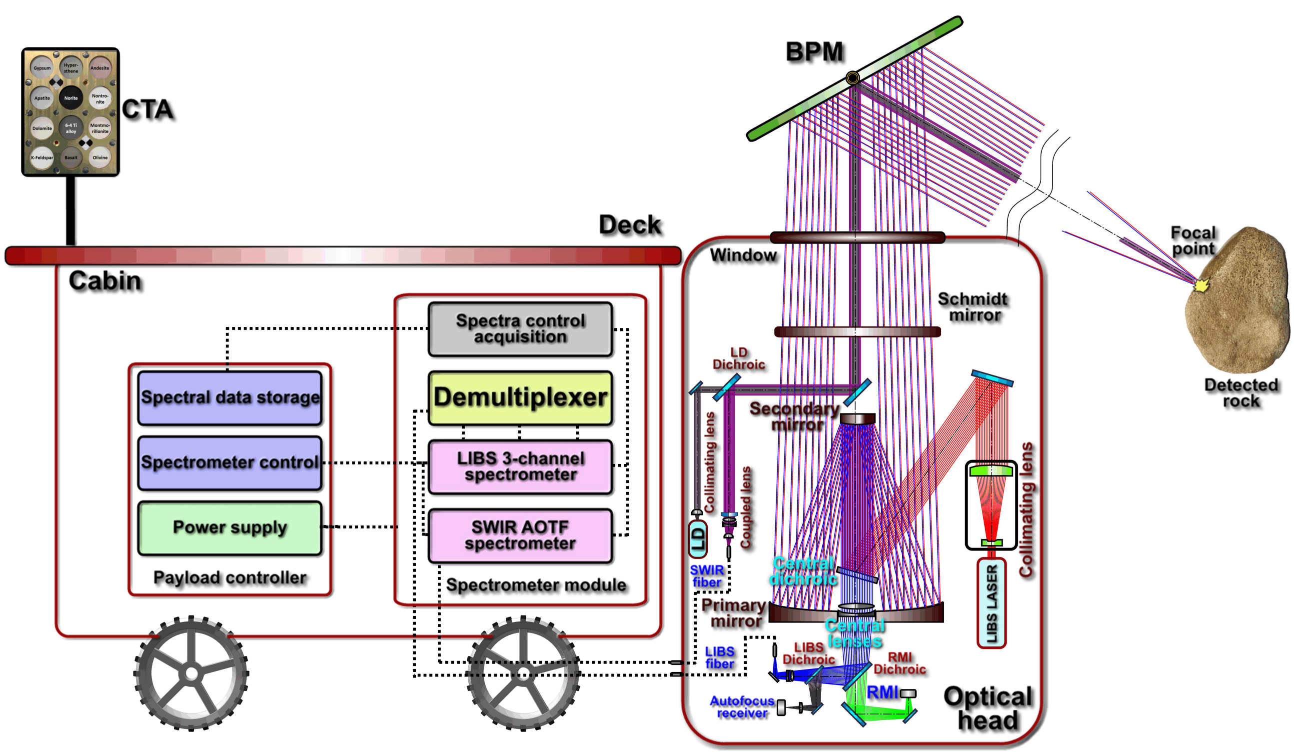


Fig. 2 Structural design of MarSCoDe.

and enter the spectrometer module via a LIBS fiber. The operating parameters of the MarSCoDe are generated by the payload controller which is also used to store the raw LIBS spectral data. The typical operating parameters of the LIBS laser are listed in Table S1.

The optical head, shown in Fig. 2 and Fig. S2, is a key component of the MarSCoDe. It mainly includes a LIBS laser-emitting module (LEM), an autofocus mechanism (AM), a remote micro imager (RMI), and a telescope. The telescope has a Ritchey-Chretien structure, including a primary mirror, a secondary mirror, and a Schmidt mirror. This structure can eliminate typical optical aberrations, such as chromatic, spherical, and coma aberrations. The telescope is mainly used to focus the LIBS laser beam onto the target and to collect the LIBS signal light, whose 106 mm aperture can ensure the acquisition of relatively strong spectral signals at the distance of several meters. The supporting structure of the optical head is its main framework, which determines the global stiffness of the optical system and guarantees the relative position precision of optical components in a harsh temperature and a vibration environment. Based on the above considerations, the main framework is made of carbon fiber and the telescope is of silicon carbide. These two materials have the advantage of high rigidity and low weight and are suitable for the structural support of aerospace instruments.

The LIBS LEM consists of a compact passively Q-switched laser, a collimating lens, and a reflector. The laser has the following parameters: wavelength 1064 nm, pulse width 4.5 ns, pulse energy 23 mJ, and repetition rate 1 to 3 Hz. Under the condition that the energy exceeds the LIBS threshold, considering the simplicity of the laser system, the laser energy of the MarSCoDe is fixed and, therefore, no mechanism for adjustments is needed.

The emitted laser beam is first expanded and collimated by the collimating lens, then is reflected in the telescope by the reflector. After the laser beam enters the telescope, it is reflected by a central dichroic mirror and then is reflected and expanded by the secondary mirror to the primary mirror. Afterwards, the primary mirror focuses and the BPM directs the beam to the detected rocks. The BPM is driven by a worm gear and two stepping motors to make a rotation of up to 210 and 45 degrees, respectively, in the azimuth and pitch direction. The pointing accuracy of the azimuth and pitch shafting is 0.0225° and 0.036°, respectively. The LIBS signal light passes through the telescope along the reverse light path and is focused into a LIBS fiber by central lenses via an RMI dichroic mirror and a LIBS dichroic mirror successively.

The AM consists of a laser diode (LD) and an autofocus receiver. The laser beam emitted from the LD, which has a wavelength of 1550 nm, is expanded and collimated, then transmits through an LD dichroic, and is pointed by the BPM towards the detected rock.

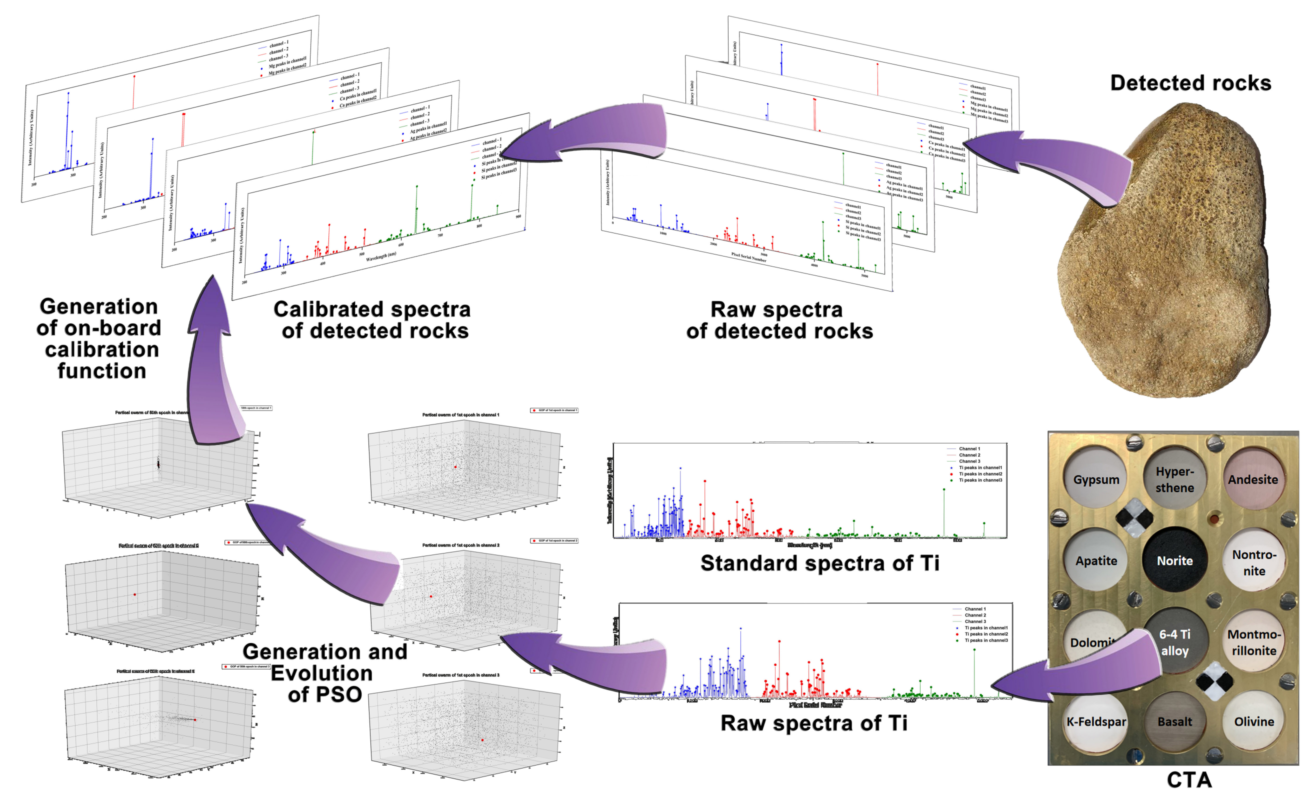


Fig. 3 On-board spectral calibration with MarSCoDe.

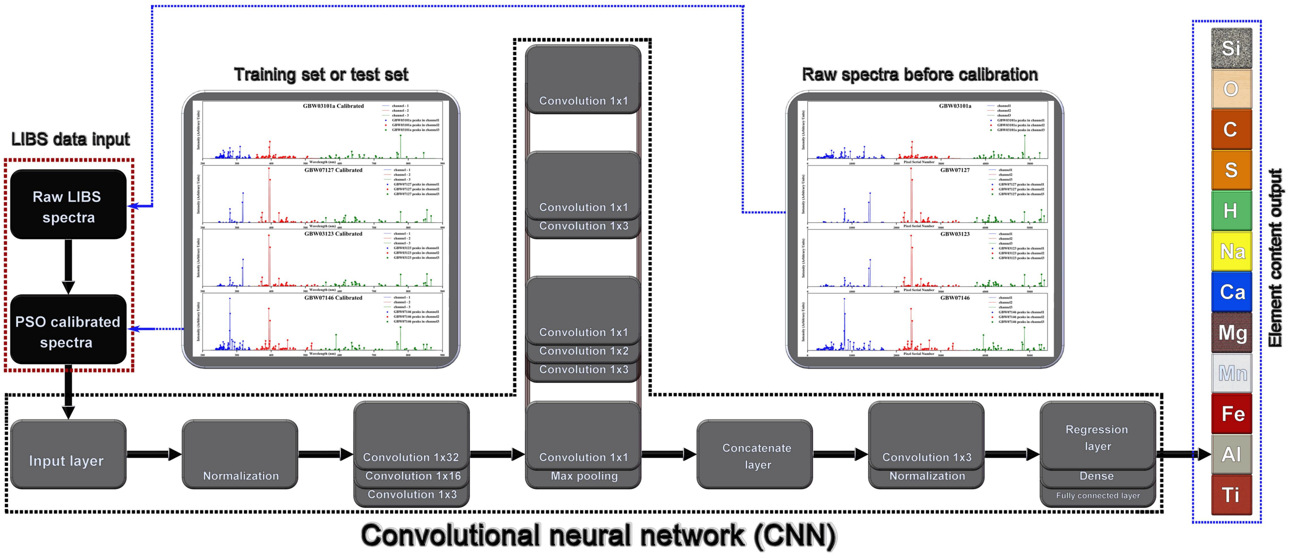


Fig. 4 Elemental analysis approach of MarSCoDe.

The reflected light is collected through the telescope and is then sensed by the autofocus receiver, a PIN photodiode, by focusing of the central lenses and reflecting by the LIBS dichroic mirror. By moving the secondary mirror of the telescope along the central axis, and monitoring the output of the PIN simultaneously, the autofocus can be accomplished when the PIN output reaches a peak. The focusing accuracy of AM is better than 1 cm. The RMI is used to obtain the image of the ablation hole and the surrounding environment on the target's surface before and after LIBS detection. The image resolution and the spectral range of RMI is 2048×2048 pixels and 900-1000 nm, respectively. The light emitted from the focal point transmits through the telescope and is focused to the RMI by the central lenses via an RMI dichroic. The RMI has an angular resolution of ~45 microradians which corresponds to a spatial resolution of ~0.18 mm at 4 m distance.

The SM consists of a spectra control acquisition circuit, a demultiplexer, a LIBS 3-channel spectrometer, and a SWIR (short wave infrared) AOTF (acousto-optic tunable filter) spectrometer. The demultiplexer is connected to LIBS fiber, and splits the LIBS signal light into three spectral bands using two dichroic mirrors. The three channels have the same Czerny-Turner structure, whose spectral ranges are 240–340, 340–540, and 540–850 nm, respectively, with corresponding spectral resolutions of 0.19, 0.31, and 0.45 nm. Three identical UV-enhanced CCDs (Hamamatsu) are adopted for the channels, which have high sensitivity in the UV band where many nonmetallic elements have abundant LIBS spectral lines. Each CCD has 2048 pixels, among which the middle 1800 pixels are chosen as the effective data. Thus, the 3-channel LIBS spectrometer has raw spectra of 5400 pixels totally. A SWIR fiber directs the infrared light emitted from the detected rocks into the SWIR spectrometer, which uses AOTF to split the infrared light into optional 64 or 330 spectral bands with a range of 850–2400 nm.

The function of the SWIR spectrometer is to identify the mineral types of Mars targets. To guarantee the performance of the spectrometer in a low temperature environment, carbon fiber was chosen as the framework material of the LIBS spectrometer, which can stabilize the size of the spectrometer system and eliminate the influence of thermal stress.

The energy supply of the Zhurong rover is solar power, which does not provide enough heat for the spectrometer to maintain the temperature in the low temperature (usually below -50^{o}C) environment of Mars. Thus, a precise and robust on-board calibration method is required. A PSO (particle swarm optimization)-based calibration scheme was adopted to correct the spectral shift due to the temperature change on Mars.[4]

This scheme uses the LIBS spectra of a Ti alloy calibration target on CTA and includes three interrelated processes, as shown in Fig. 3. First, a standard wavelength set (SWS) of the Ti target was established in a Mars simulation environment before launch. Second, on Mars, the LIBS spectra of the Ti target are obtained. Particle swarms are generated and their corresponding particle wavelength sets (PWS) are calculated based on the Ti on-board spectra. The similarity between SWS and PWS corresponds to the fitness of each particle. Thus, with the evolution of particles, the difference between SWS and PWS is gradually narrowing. After the evolution is finished, an optimal particle is selected, whose position coordinates correspond to the coefficients of the on-board calibration function (OCF). Third, after the LIBS detection for any interested objects is finished, the raw spectra are calibrated by OCF.

The MarSCoDe is scheduled to analyze twelve major elements: Si, O, C, S, H, Na, Ca, Mg, Mn, Fe, Al, and Ti (Fig. S3). To implement the analysis of these elements in Martian targets, an approach based on convolutional neural network (CNN) was proposed, as shown in Fig. 4. The CNN, including Normalization, Convolutional, Pooling, Concatenate, Regression, Dense, Input and Output layers, is used to predict the content of major elements based on their LIBS spectra and to further identify the mineral types of the detected targets.[5-8]

After this CNN was built, the LIBS spectra and the elemental contents of 59 standard samples (including 12 on-board calibration targets) were selected as the training set. Here, the LIBS spectra of the samples were obtained using the MarSCoDe in the Mars simulation environment of our local earth Laboratory. The network parameters of the CNN were optimized during the training process before launch. After launch, the raw spectra, calibrated by OCF, of the Martian objects will be sent to the Input layer. Then their major element content will be predicted by the CNN. Finally, the mineral types of those objects can be identified according to the alkali silica ratio (Fig. S3).

At present, three LIBS payloads, namely ChemCam on Curiosity, SuperCam on Perseverance, and MarSCoDe on Zhurong, are exploring the material composition in different areas of Mars. These LIBS instruments will help to determine the types of rocks and secondary minerals present, as well as investigate the composition of the minerals. Further, because different locations are investigated, the characteristics of different representative minerals in different regions of Mars can be obtained. This collaboration will add to obtaining a better understanding of the geological evolution of Mars.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information (Fig S1-S3, Table S1) is available at www.at-spectrosc.com/as/home

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Notes

The authors declare no competing financial interest.

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