In-Situ Science on Phobos with the Raman spectrometer for MMX (RAX): Preliminary Design and Feasibility of Raman Measurements

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Abstract

Mineralogy is a key to understanding the origin of Phobos and its place in the context of the Solar System evolution. In-situ Raman spectroscopy on Phobos would be an important tool to achieve the science objectives of the Martian Moons eXploration (MMX) mission and maximize the science merit of sample return by characterizing the mineral composition and heterogeneity of the surface of Phobos. Conducting in-situ Raman spectroscopy under the harsh environment of Phobos requires a very sensitive, compact, lightweight, and robust Raman instrument that can be carried by the very compact MMX rover. In this context, a Raman spectrometer for MMX (RAX) is currently under development by an international collaboration between teams from Japan, Germany, and Spain. To demonstrate the capability of a compact Raman system like RAX, we built an instrument that reproduces most of the optical performance of the flight model using commercial off-the-shelf parts. Using this performance model, we measured mineral samples relevant to Phobos and Mars, such as anhydrous silicates, carbonates, and hydrous minerals. Our measurements of these samples indicate that such minerals can be measured and identified with a RAX-like Raman spectrometer with sufficiently high accuracy. We demonstrated a spectral resolution of approximately 10 cm^{-1} and high sensitivity of the Raman peak measurements (e.g. signal-to-noise ratios up to several 100). These results strongly suggest that the RAX instrument will be capable of determining the minerals expected on the surface of Phobos, adding valuable information to address the question on the moon's origin, heterogeneity, and circum-Mars material transport.

1. Introduction

The evolution of the Solar System is a fundamental research topic. One essential approach is the determination of the composition of the Solar System bodies. Their composition provides insights into the possible origin and helps to understand the geochemical and thermal processes to which the body has been exposed during its existence.

Several approaches exist to derive the composition with different kinds of spectroscopic techniques. Earth-based observations were the only one available for observations before space flight was realized. With space missions then coming, satellites with spectrometers and cameras orbited and are orbiting the bodies taking images and spectra in the ultraviolet (UV), visible, infrared, and the spectral range beyond. By comparing these spectra with data obtained on Earth it was possible to derive the surface composition on a macroscale. In-situ exploration and sample return from these bodies back to Earth provide even more information, particularly on a microscale. In-situ measurements give an initial overview of the general composition of the investigated target at single surface points. Detailed measurements of returned samples in the geologic context provide a deeper understanding of the processes on the surface of the investigated body. The combination of this information allows a complete picture about the processes the body may have experienced through its lifetime, as well as verifying existing hypotheses or establishing alternative ones for the evolution of the body and thus that of the Solar System. Numerous examples exist for all the approaches – here is one for illustration from JAXA's Hayabusa mission. During the Hayabusa mission the asteroid Itokawa was first studied using remote instrumentation from orbit

(Krot et al. 2011). Later during the mission, samples were taken from the surface and brought back to Earth, where the samples were studied in the laboratories with highly sophisticated methods, such as back-scattered electron microscopy (Nakamura et al. 2011), neutron activation (Ebihara et al. 2011), synchrotron radiation X-ray tomographic microscopy (SRXTM) (Meier et al. 2013), isotopic measurements and mass spectroscopy (Yurimoto et al. 2011; Nagao et al. 2011; Busemann et al. 2013), and Raman microscopy (Böttger et al. 2013) (Figure 1).

In this context, mineralogy is a key discipline. Mineralogy helps to correlate the occurrence of different minerals to the geochemical, thermal, or radiation processes that led to the formation of these minerals. Thus, techniques to derive the mineralogical composition in situ are of great interest. Raman spectroscopy is a very appropriate method for this purpose. Raman spectroscopy is a nondestructive fingerprint method that requires no sample preparation. It can be applied in the field as well as in the laboratory. It is suitable to investigate various materials including minerals, organic and biological matter, liquids such as brines, gases, and ices.

Thus, the development of Raman spectrometers for in-situ exploration is receiving increased attention in space research (e.g., Rull et al. 2017; Weber et al. 2017, 2018). With SuperCam on the Mars 2020 rover mission (launched in 2020) (Wiens et al. 2021) and the Raman Laser Spectrometer (RLS) on the ExoMars 2022 mission (Rull et al. 2017) for the first time Raman instruments will be used on the surface of Mars for mineralogical analysis and to search for signatures of past or present life. The rover that is developed for the Martian Moons eXploration (MMX) mission by JAXA (Kawakatsu et al. 2019) will carry the Raman spectrometer for MMX (RAX), a very compact Raman spectrometer, to investigate the surface of Phobos (Ulamec et al. 2019; Michel et al. submitted).

In this paper, we focus on the presentation of Raman spectroscopy on Phobos, the Martian moon. It is shown how Raman spectroscopy can support science to address the question of the origin of Phobos and thus add valuable input for the discussion on the evolution of the Solar System. First, the main scientific questions related to Phobos are briefly described. Second, the current instrument design to achieve the science goals is illustrated. Then, our measurements on several mineral samples relevant to Phobos and Mars are reported to demonstrate the capability of RAX.

2. Exploration Of Phobos And The Rax Instrument

2.1 Science on Phobos

Phobos is one of the Martian moons orbiting Mars at less than 6000 km in 7.65 hours. One Phobos-day is the same as the orbital period because of a tidal lock. The second moon Deimos is more than 23460 km above Mars' surface and needs 1.2624 days for one orbit. Both moons show similarities in their albedo and spectral behavior, but their origin is still unknown. Several models for their origin have already been discussed in detail (e.g., Pieters et al. 2014; Usui et al. 2020; Michel et al. submitted). Here we focus on how Raman spectroscopy can contribute to address the question of Phobos origin.

To address the issue, we need to briefly review the five most-relevant ideas about the origin of Phobos. Behind each hypothesis stands a selection of minerals that are expected to be present on Phobos. The expected mineralogy and geochemistry on Phobos with respect to the origin hypothesis was described by Murchie et al. (2014) and Usui et al. (2020).

These theories formulate the origin of the moons based on capture or by in-situ formation. The “capture” hypothesis includes (1) the capture of an organic- and water-rich outer Solar System body; (2) an organic- and water-poor outer Solar System body or (3) an inner Solar System body. The “in-situ formation” hypothesis either propose (4) the co-formation with Mars or (5) the formation from the ejecta after an impact of a large body onto Mars. Each of these hypotheses predicts a specific composition as well as elemental and mineral abundances (Table 1). The currently available reflectance spectra measured remotely from orbit are not conclusive because of the lack of features attributable to specific minerals. The low albedo of Phobos can be explained by either a carbonaceous origin or by darkening through strong space weathering (e.g. Shirley and Glotch, 2018 and references therein), with the corresponding mineralogy supporting the different processes. The spectra of the ‘red’ and ‘blue’ areas on Phobos best match those of D-type and T-type asteroids, respectively (Rosenblatt 2011). The striking blue/red contrast could be caused by compositional variations on Phobos or spatial variations of its physical surface properties (Rosenblatt 2011; Ballouz et al. 2019). Understanding the nature of color difference and its relationship to mineralogy is important to resolve this. Endogenous materials, such as fragments of Mars ejecta (Ramsley and Head 2013; Hyodo et al. 2019) and projectiles that hit Phobos are also expected and should be distinguished from the original Phobos material as anomalous minerals deviated from the majority of materials found on Phobos. A measurement technique that is capable of identifying the different minerals, like Raman spectroscopy, would therefore be of great benefit.

2.2. Science with RAX

In Figure 2, Raman spectra of some representative minerals predicted by the origin theories of Phobos are shown. The spectra are well distinguishable and the fingerprint characters are obvious. So, spatially distributed Raman measurements on Phobos would provide initial in-situ information on its mineralogical composition and distribution, which would help narrow down the origin hypotheses.

In addition to the capability of mineral identification, the need of only optical access to the sample and the fact that no sample preparation is necessary make Raman spectroscopy a very suitable technique for space exploration. Regardless certain technique limitations such as spectrally superimposing fluorescence or the relatively low Raman scattering efficiency of certain materials, it is an appropriate method for the initial examination of an unknown surface.

To accomplish the in-situ mineralogy on Phobos, RAX is developed in Japanese-Spanish-German cooperation to participate in the Japanese MMX Mission as part of the payload on the DLR-CNES Rover that will be brought to Phobos’ surface during this mission (Hagelschuer et al. 2019). The MMX mission (Kawakatsu et al. 2019) and the rover are described in more detail elsewhere in this issue (Michel et al. submitted; Kuramoto et al. submitted).

The science objectives are derived for RAX according to the scientific goals formulated for the MMX mission (Kuramoto et al. submitted). First of all, RAX shall investigate the surface mineralogy on Phobos by measuring Raman spectra of the surface and identifying mineral composition by comparing the spectra with those available in databases. The rover's ability to move over the surface opens the possibility to measure Raman spectra at different locations on Phobos and to study the surface heterogeneity. This might be used to support the characterization of a landing site under consideration and potentially to support the selection of samples for return to Earth. The obtained data can also be compared to those of Raman spectrometers on the surface of Mars to check the origin hypothesis of co-formation with Mars or accretion from ejecta after a giant impact on Mars. The measurements of returned samples would give a firm confirmation on the results of RAX. Comparing relative abundances of minerals on the surface of Phobos with those found in the returned samples will help ensure the representativeness of returned samples, and thus maximize the scientific value of this sample return mission.

The RAX measurements will be performed during Phobos nights or in the shadow of the rover to avoid ambient light, which could be stronger than the Raman signals by orders of magnitude. Coarse laser focusing will be achieved with raising/lowering the main body of the rover which contains the RAX instrument. Images of the RAX footprint will be taken by the WheelCam (Michel et al. submitted). This function provides the geologic context of measured samples, including their albedo, texture, and grain size. Measuring in the tracks of the Rover wheels and therefore sampling freshly exposed materials might provide information on space weathering. RAX can also be used without the laser, obtaining reflectance spectra in a wavelength range of approximately 532-680 nm, which could be used for evaluating the albedo and color of surface material.

2.3. Design of RAX

Albeit the high scientific values, conducting Raman spectroscopy on Phobos and fulfilling its science objectives are a technical challenge. The instrument must endure the harsh environment on Phobos, such as a large temperature range and fast diurnal cycles during one Phobos day (requiring RAX to withstand $-55\sim+70^{\circ}\text{C}$ for storage and $-40\sim+50^{\circ}\text{C}$ for operation), low surface gravity (making rover operation less straightforward), dust (potentially contaminating optics and actuator mechanism), vacuum (complicating the heat distribution within the instrument), and radiation (potentially deteriorating the transmission of optics and electronics). Furthermore, the RAX instrument must be particularly small and lightweight to fit in the low-mass rover. To illustrate the design to overcome these constraints, the overview of the RAX instrument, its general specification, and current status of its development are described in this section.

The RAX instrument consists of two physically separated units: the RAX Laser Assembly (RLA) and RAX Spectrometer Module (RSM) (Figure 3). The Autofocusing Subsystem (AFS), dedicated to focusing the laser on the surface of Phobos, is accommodated within the RSM. The entire RAX instrument has a volume of approximately $81 \times 125 \times 98 \text{ mm}^3$ and a mass of approximately 1.4 kg. RAX is jointly developed by an international collaboration among Germany, Spain, and Japan (Figure 3). The Institute

of Optical Sensor Systems at Deutsches Zentrum für Luft- und Raumfahrt (DLR) develops the RSM. The University of Tokyo, JAXA, and Rikkyo University are in charge of AFS development. Instituto Nacional de Técnica Aeroespacial (INTA) and University of Valladolid, who built the RLS laser unit for the ExoMars 2022 mission, provide the RLA (Figure 3).

The RLA is a compact laser module that emits a 532 nm continuous wave (CW) laser beam at a variable power of up to 35 mW (Figure 4). This is essentially a flight spare of the laser unit developed for the ExoMars2022 mission (Rull et al. 2017). The RLA (Ribes-Pleguezuelo et al. 2019) provides laser light to the RSM (Figure 5) through an optical fiber. The collimated laser beam is focused onto the surface of Phobos through the Autofocusing Subsystem (AFS). The scattered light is collected and collimated by an entrance objective and sent back to the spectrometer module. A series of optics, such as a dichroic mirror, collimator lenses, slit, transmission grating, Raman edge filter, and camera objective lenses, are mounted inside the RSM. The image of the slit is acquired by the 3D-plus CMOS sensor. The 2-dimensional image is integrated to form a 1-D line spectrum. The electronics for controlling the laser and focus actuator are accommodated in the RSM. Focusing the laser beam is required to maximize the intensity of Raman signals emerging from the target surface below the rover. The AFS comprises of light-shuttle objective lens (LSO) and actuator mechanism (Figure 6). The laser spot diameter on the sample is designed to be 50 μm . The distance between the lowest tip of LSO and laser focus is 78 mm. The stroke of LSO and its resolution are better than 13 mm and <50 μm by design. The autonomous focusing will involve a two-step procedure. In the first step, the reflectance spectra of surface materials, which are illuminated by the LED placed near the entrance aperture, are used for focusing on the sample surface using the rover legs and AFS actuator. The second step is the fine focusing using the laser and only the AFS actuator in order to maximize the signal-to-noise-ratio (SNR) of potential Raman signals. Furthermore, the backscattered laser light will be measured in the RLA autofocus photodiode as well, for accurate focus distance determination.

3. Experimental Setup

To assess the capability of Raman spectroscopy using RAX, we built a breadboard model (BBM) from commercial components that simulates the performance of the actual RAX instrument aboard the Rover on Phobos. In this section, we describe the experimental setup of our BBM in comparison with the RAX instrument.

3.1 Breadboard model

We used a fiber-fed Nd:YAG laser that emits CW radiation at 532.2 nm (JUN0532FC, SOC, Japan). The laser power was set at 32 mW, which results in a laser irradiance of 1.6 kW/cm^2 at the target surface to simulate the output of RLA. The laser beam was delivered to the inlet of our BBM through a multimode optical fiber. This fiber was used for simulating the non-Gaussian beam pattern of the flight laser. The spot size at the sample was designed to be 50 μm .

To simulate the performance of the LSO in terms of light collection capability, the numerical aperture (NA) of the lens in our BBM was set at 0.20, which is comparable to 0.22 of the actual LSO. The lens moves vertically as the stepping motor rotates via the combination of a linear guide and lead screw (Figure 7). The stepping motor and attached gear box was identical to the one we plan to use for RAX. The objective lens has a mass of 143 g, comparable to that of LSO (129 g). Dedicated printed circuit boards (PCBs) simulating that used for flight model were used to verify the electrical behavior of the motor. The resolution of vertical motion, which can be activated by one motor pulse, was measured to be $< 25 \mu\text{m}$.

A CMOS camera (MAKO G419, Allied Vision) was used as detector to simulate the actual flight CMOS sensor. The width of a slit placed between a couple of collimator lenses was $50 \mu\text{m}$. Because of the magnification of the optical system in our BBM, the slit width was imaged at $25 \mu\text{m}$ on the sensor, the same image size as that of the RAX design. A transmission grating (1200 grooves/mm) was used. A camera lens was connected to the commercial-off-the-shelf (COTS) CMOS camera with a custom-made flange.

3.2 Measurement protocol

Using this BBM, bulk natural mineral samples relevant to the science objectives were selected and measured: anhydrous rock-forming minerals (olivine, quartz), carbonates (calcite, magnesite), sulfate (gypsum), and magnesium hydroxide (brucite). Once a sample is placed in the sample holder, the objective lens was brought to the focus position by the actuator motion. In this study, the focus was adjusted manually using a motor control software to maximize the intensity of the Raman signals. The measurements were conducted under air and at a room temperature.

The entire BBM was placed in an optical enclosure to avoid the ambient light coming into the system through the objective lens. Furthermore, the optical path was covered by black plastic or anodized aluminum to prevent strong Rayleigh light entering the optical path. The relation between CMOS sensor pixel numbers and Raman shift (cm^{-1}) was calibrated with a Ne lamp. One pixel corresponded to 3.2 cm^{-1} in $0\text{--}4000 \text{ cm}^{-1}$ range. Out of 2048 vertical pixels of the CMOS sensor, 500 lines containing the spectral images were integrated in our BBM. The exposure time of the Raman measurements was set to 1 or 3 s for each specimen. Either 100 or 50 spectra were averaged to enhance the signal-to-noise ratios of the spectra. Background (dark) spectra were measured with the same exposure time and number of averaging when the laser was turned off. The dark spectra were subtracted from the signal spectra to remove thermal noise. The relative spectral response of the system was corrected with a standard halogen lamp. Nevertheless, because of a peak in the sensitivity of BBM's CMOS sensor, a false dip/peak sometimes appeared at approximately 2500 cm^{-1} . This wavenumber range was therefore not used for the peak identification in this study. This artifact is expected to be removed for the actual RAX instrument by further characterizing the spectral response function.

Each Raman feature was fitted with a Gaussian profile. The height S , width W , and position C of each Gaussian fit were derived. The continuum due to fluorescence was fitted simultaneously and subtracted

from the spectrum. The noise level N associated with individual peaks was then defined by the standard deviation of the signals over the 40 pixels in the continuum-subtracted spectra. The signal-to-noise-ratio was calculated by dividing the peak signal S by the rms signal measured across a spectral band of 20 pixels (approximately 60 cm^{-1}) at a distance of $3 \times$ peak width W from the Raman feature peak.

4. Results And Discussion

The Raman spectra obtained with our RAX performance model are shown in this section to verify the detectability of these minerals with the RAX instrument. Figure 8 shows the Raman spectra of the minerals measured with our BBM. The double peaks characteristic to olivine at 823 cm^{-1} and 854 cm^{-1} are clearly detected and resolved with our BBM. The peak positions are consistent with those of forsterite (Kuebler et al. 2006). The Raman spectrum of quartz shows a peak attributable to SiO_4 stretching mode at 467 cm^{-1} (Figure 8). These samples did not exhibit fluorescence. The Rayleigh light from the laser was observed at $< 100\text{ cm}^{-1}$ with this BBM. The measurement capability of such low-wavenumber peaks will be characterized with the engineering model of RAX using the flight-like laser and edge filter.

Figure 8 also shows the Raman spectra of the two carbonates: calcite (CaCO_3) and magnesite (MgCO_3). Both calcite and magnesite yielded unambiguous Raman peaks above the continuum due to fluorescence. For calcite, the peak at 160 cm^{-1} was detected, which shows the smallest Raman shift observed in this study. OH-related bands at wavenumber $> 3000\text{ cm}^{-1}$ were seen for the gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and brucite ($\text{Mg}(\text{OH})_2$). The gypsum showed the Raman peaks characteristic to water at 3383 and 3474 cm^{-1} , while brucite exhibits one at 3633 cm^{-1} (Figure 8). The signal-to-noise ratios of the individual peaks that are currently achieved with our BBM are summarized in Table 2. The grain size, mineral mixtures, and surface roughness can influence the intensity of specific Raman features (Foucher et al. 2013; Böttger et al. 2017). These aspects will be characterized in further investigation with a focus on expected Phobos mineralogy. Nevertheless, our data suggest that a very compact Raman spectrometer like the RAX instrument will be capable of in-situ detection of minerals expected on Phobos.

5. Conclusion

For in-situ analysis of the mineralogy on Phobos, Raman spectroscopy is very suitable to address the question of the origin of Phobos. RAX (Raman spectrometer for MMX) is a very compact and robust instrument that is being developed for the rover in the scope of the MMX mission to Phobos. In this paper, we showed the main design of the instrument, particularly with respect to the challenges connected with a mission to Phobos and the constraint to fit on the small MMX rover. First results of Raman measurements of Phobos-relevant minerals with a breadboard model of similar performance as expected for the flight model show that RAX will fulfill the requirements, such as the capability of resolving the olivine peaks 30 cm^{-1} apart and measuring with high sensitivity as required for the identification of minerals. Our results indicate that RAX will be able to obtain the Raman spectra of key minerals potentially distributed on Phobos.

Abbreviations

AFS

Autofocusing subsystem

BBM

Breadboard model

CAD

Computer-aided design

CMOS

Complementary metal oxide semiconductor

COTS

Commercial off-the-shelf

CW

Continuous wave

DLR

Deutsches Zentrum für Luft- und Raumfahrt

EM

Engineering model

FM

Flight model

INTA

Instituto Nacional de Técnica Aeroespacial

JAXA

Japan Aerospace Exploration Agency

LED

Light emitting diode

LSO

Light shuttle objective

MMX

Martian Moons Exploration

Nd

YAG:Neodymium-doped yttrium aluminum garnet

RAX

Raman spectrometer for MMX

RLA

RAX laser assembly

RSM

RAX spectrometer module

SEM

Secondary electron microscope

SNR
Signal-to-noise ratio
STM
Structure and thermal model

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

YC wrote the paper, with contributions from UB, FR, HWH, AMI, GLR, JAO, and IW. Conception, design, and revision of the work: YC, HWH, FR, MB, SK, SRR, PS, SU, and TU. Conception of the instrument: UB, HWH, AB, ED, TH, CR, and FS. Data acquisition and analysis: YC, SM, JAO, MP, SR, TS, SS, KY. Interpretation of the data: YC, UB, FR, MP, SR, TS, and IW. TB, AB, ED, TH, MP, GP, CR, FS designed the instrument. YC, ED, SM, GP, and KY built the instrument. YB, SM, KW, KY created the software used in this study. The concept of the autofocus algorithm was developed by TS. EK developed the new electronics used in this study. ML, SR, and CR created the new structure models and analyzed its data. New detector models were developed by CP. AMI, CCP, and PRP contributed to the conception and design of the laser. SS led the discussion on the concept of operation. The discussion on the science of in-situ Raman spectroscopy was led by GLR, OPB, CS, and IW. MB was in charge of project management.

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The authors wish it to be known that, in their opinion, the first 4 authors (YC, UB, FR, and HWH) should be regarded as joint First Authors.

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Tables

Table 1 Origin hypotheses for Phobos and the predicted mineral abundances (Murchie et al. 2014).

Hypotheses for Origin	Mineral abundances
1. Capture of organic- and water-rich outer solar system body	Abundant phyllosilicates; carbonates and organic phases; anhydrous silicate phases rare
2. Capture of organic- and water-poor outer solar system body	Anhydrous, med.Fe (20–40%) pyroxene + olivine; abundant amorphous carbon or graphite?
3. Capture of inner solar system body	Low carbonates, phyllosilicates; pyroxene, olivine probably in range of known meteorites
4. Co-accretion with Mars	Anhydrous silicates with Fe, Mg of bulk Mars; low abundance of C-bearing phases
5. Giant impact on Mars	Evolved, basaltic mineralogy consistent with many datasets for Mars

Table 2 Identified Raman peaks and their signal-to-noise ratios.

Sample	Sample type	Peak position (cm ⁻¹)	Signal-to-noise ratio	Number of spectra used for averaging	Exposure time for a single spectrum (s)
Olivine	Crystalized bulk	823	102	100	1
		854	77		
Quartz	Bulk	467	582	100	1
Calcite	Bulk	160	14	50	1
		284	45		
		711	9		
		1078	72		
Magnesite	Bulk	333	12	100	1
		1088	22		
Gypsum	Bulk	1001	43	100	1
		1124	10		
		3383	4		
		3474	7		
Brucite	Bulk	3633	98	100	3

Figures

Figure 1

(a) Microscopy image of a cut, sputtered and polished Hayabusa Particle RA-QD02-0051 embedded in epoxy. (b) Color composite of mineral composition derived from Raman spectral imaging at DLR Berlin. (c) Raman spectra of typical minerals found on #51. The colors of the spectra correspond to the colors of the Raman spectral image. Plagioclase is a Na, Ca-feldspar (Böttger et al. 2013).

Figure 2

Raman spectra of some representative minerals predicted for the origin hypotheses of Phobos.

Raman Spectrometer for MMX (RAX)

Figure 3

Block diagram of the RAX instrument. RSM, RLA, and AFS are developed respectively by Germany, Spain, and Japan.

Figure 4

Engineering model of the RLA. Its mass is 112 g including the laser module, thermo electrical module (TEM), interface plate, cables, and connectors. A new laser assembly batch, based on RLS (Ribes-Pleguezuelo et al. 2016) design, will be manufactured for the use in RAX. (credit: RLS project).

Figure 5

(a) CAD model of the RAX spectrometer module (RSM). The AFS is seen in the frame. (b) Structural and thermal model (STM) being assembled at DLR.

Figure 6

Autofocusing subsystem (AFS) assembled in Japan. Light-shuttle objective (LSO) is put on the linear translation mechanism. An end-stop sensor is placed between the two green printed circuit boards.

Figure 7

Breadboard model of RAX. (a) Entire breadboard. (b) Focusing unit. Actuator rotations are converted to vertical motion with a lead screw and linear guide. The actuator and linear guide are the COTS component used for the RAX flight model after screening. Mass of the lens is comparable to flight lens barrel.

Figure 8

Raman spectra of minerals obtained with a RAX BBM. Anhydrous minerals (olivine and quartz), carbonates (calcite and magnesite), hydrated sulfate (gypsum) and magnesium hydroxide (brucite). Each spectrum is offset for clarity.

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