OPTICAL DESIGN AND BREADBOARD OF THE RAMAN SPECTROMETER FOR MMX – RAX S. Rodd-Routley[1], T. Belenguer[2], U. Böttger[1], M. Buder[1], Y. Cho[3], E. Dietz[1], T. Hagelschuer[1], H.-W. Hübers[1], S. Kameda[4], E. Kopp[1], A. G. Moral Inza[2], S. Mori[3], O. Prieto-Ballesteros[5], S. Rockstein[1], F. Rull[6], C. Ryan[1], T. Säuberlich[1], F. Schrandt[1], S. Schröder[1], T. Usui[7], and K. Yumoto[3]. [1]German Aerospace Center (DLR), Institute of Optical Sensor Systems, Berlin, Germany., [2]Instituto National de Técnica Aerospacial (INTA), Torrejón de Ardoz, Spain, [3]Department of Earth and Planetary Science, The University of Tokyo, Tokyo, Japan, [4]Department of Physics, Rikkyo University, Tokyo, Japan., [5]Centro de Astrobiologia (CAB-INTA-CSIC), Torrejón de Ardoz, Spain., [6]Universidad de Valladolid – Unidad Asociada UVa-CSIC Centrode Astrobiologia, Valladolid, Spain., [7]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (JAXA), Kanagawa, Japan.

Introduction: In planetary exploration, Raman spectroscopy is a very appropriate method to derive the in-situ mineralogical composition of a surface. For this purpose, Raman spectrometers have been developed or are under development: e.g. SuperCam equipped with the stand-off Raman spectrometer for NASA's Perseverance rover [1] and the Raman Laser Spectrometer (RLS) developed for ESA's ExoMars Mission [2]. RAX is a Raman spectrometer onboard the Rover, carried by JAXA on the Martian Moons eXploration mission (MMX) [3,4]. RAX is a very compact and lightweight instrument fitting in the volume of the MMX rover [5].

In this abstract, we present the optical design and breadboard of the RAX instrument and demonstrate its capability of fulfilling the scientific requirements.

RAX optical design: The RAX instrument is a confocal Raman spectrometer. A schematic is presented in Fig. 1. The 532 nm excitation light is transferred to the spectrometer through an optical fiber. The optical fiber bears a 50 µm diameter multimode field with 0.2 NA divergence and the Fiber Collimator (FC) collimates this field into an 11 mm diameter beam. Laser sidelobes are suppressed by the Laser Cleanup Filter. The Dichroic Beamsplitter (DBS) passes the light to the Light Shuttle Objective (LSO), which focusses the light into a 0.2 NA convergence, 50 µm diameter spot on the surface of Phobos, with an 80 mm working distance. Raman scattering in the range of 535–680 nm through the reverse path is gathered from the surface of Phobos and collimated by the LSO, then deflected into the spectrometer path by the DBS and filtered by the Laser Line Quelling Filter to remove Rayleigh scattering. Then, the Slit Input Objective (SIO) focusses it onto the slit to cull outlying rays to achieve 10 cm^{-1} spectral resolution, when the Raman light is re-collimated by the Slit Output Objective (SOO) to be deflected according to wavenumber by the grating, so that the fan of collimated beams with direction set by wavelength can be imaged by the Camera Interface Objective (CIO) onto the CMOS detector, which captures the spectral image.

The most important performance parameters for fulfilling the RAX science requirements are spectral resolution and signal to noise ratio (SNR). The former is set by the slit width and the wavefront aberration performance. The latter is set by the radiometric characteristics, i.e. the numerical aperture of the LSO, losses arising at the slit, losses from scattering and absorption in optical components, grating inefficiency and non-unity detector quantum efficiency. The RAX optics are designed to achieve a spectral resolution of 10 cm^{-1} for a spectral range of up to 4000 cm^{-1}. The SNR must be sufficient to identify several Phobos relevant minerals and is typically on the order of 100.

RAX optical breadboard: To prove the capability of the RAX optical design, a breadboard model (BBM) has been developed (cf. inset of Fig. 1). The BBM design follows the concept of the RAX optics acc. to Fig. 1. However, it is highly simplified since it does not have the same physical limitations, such as small mass and volume. Most of the optical elements have been replaced with commercial components. The off-the-shelf objectives used to simulate the FC, LSO, SIO, SOO and CIO are chosen with numerical apertures to ensure the BBM has similar radiometric properties as the RAX flight model (FM), i.e. a 0.2 NA for the LSO and similar loss performances. The grating efficiency at the BBM is comparable to that of the FM grating. The laser, which is a contribution by INTA, and the detector are performance representative. Therefore, we assume that our setup has similar or slightly worse radiometric performance than the FM. With this approach, the BBM can be used as a baseline reference for the performance, that the RAX optical design should be able to achieve.

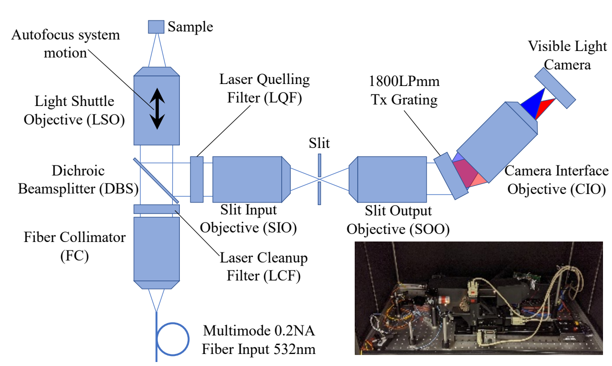

Figure 1: Scheme of the RAX optical system. Inset: Picture of the RAX BBM at DLR-OS.

Results: The spectral range of 535–680 nm is well covered by the emission spectrum of a Ne glow lamp, so we used it for spectral calibration and verification of the resolution. The black inset in Fig. 2 presents the image of the Ne calibration spectrum on the CMOS detector. Each spectral line forms an individual slit image and can be assigned to its known wavelength from literature. The outermost lines are marked in the inset with their wavelength, indicating that the detector perfectly covers the targeted spectral range. The calibration is done on the wavenumber scale relative to the 532 nm laser emission line, which forms its slit image near camera pixel position 2000. The calibration curve can be approximated by a third-order polynomial function and shows that the dispersion varies between 2.8 cm^{-1}/pixel at low and 1.4 cm^{-1}/pixel at high wavenumbers.

The spectral resolution of the BBM was determined by the FWHM of each spectral slit image acquired with the neon spectrum and is presented in Fig. 3. Due to the replacement of the CIO by a commercial objective, which suffers some longitudinal chromatic aberration and field curvature, the widths of the individual slit images vary from 3 pixels near the detector center to about 6 pixels towards the detector edges. This leads to a spectral resolution with a peak value of nearly 6 cm^{-1} around the sweet spot, which was set to the 1500 cm^{-1} position. Towards the upper spectral edge at 4000 cm^{-1} the resolution drops to 10 cm^{-1} due to the aberrations of the camera interface lens used at the BBM. The steeper decrease of resolution towards the lower spectral edge is additionally driven by the lower dispersion at this end. However, the real RAX FM of the CIO is expected to outperform the breadboard substitute and should show a more uniform resolution over the spectral range. Nevertheless, our results at BBM level already demonstrate the required spectral resolution of 10 cm^{-1}.

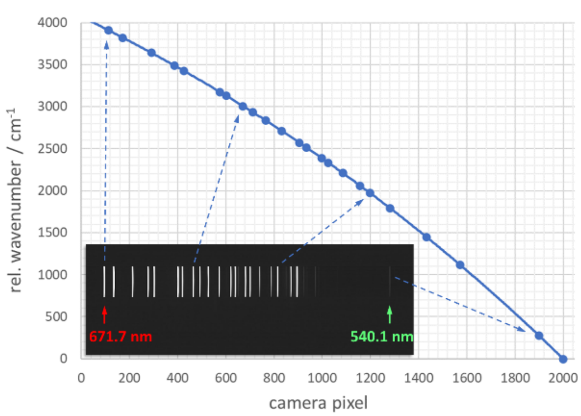

Figure 2: Spectral calibration of the BBM with a Ne lamp in the range of 0 to 4000 cm^{-1}. Inset: Raw detector image with the individual slit images.

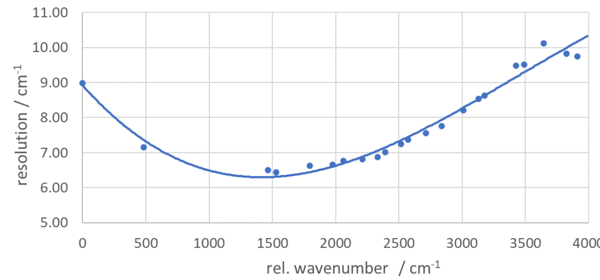

Figure 3: Spectral resolution across the spectral range.

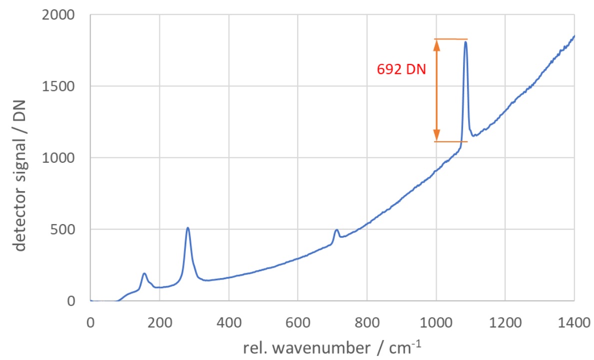

Figure 4: Raman spectrum of calcite. The 1086 cm^{-1} line achieves an SNR of > 800 (exposure time: 60s).

The SNR is often used to compare different spectrometers. Here, we define the SNR of a Raman line as the height of the Raman signal on top of the fluorescence divided by the temporal standard deviation of all signal contributions at this spectral position. As shown in Fig. 4, we observed a signal height of 692 DN with a standard deviation of 8.6 DN for the 1086 cm^{-1} Raman line of calcite for a laser optical output power of approximately 31 mW. The signal height unit DN refers to the raw pixel data value of the AD-Converter of the detector and is proportional to the detected number of photons. For 100 successive measurements with an accumulated exposure time of 60s, this yields a SNR of 805 for this specific Raman line.

Summary: We have developed a breadboard model that confirms that the proposed RAX optical design fulfills the performance goals. The Raman spectra recorded by the RAX-FM during the MMX mission will allow for the determination of the surface mineralogy on Phobos.

References: [1] Wiens R. C. et al. (2020) SSR*, 217, 4.* [2] Rull F. et al. (2017) *Astrobiology 17, 627*. [3] Kawakatsu Y., Mission Definition of Martian Moon Exploration (MMX), 70th Int. Astronautical Congress, 2019. [4] Ulamec S. et al. "A rover for the JAXA MMX Mission to Phobos". In: *IAC 2019*. Oct. 2019, IAC–19. [5] Hagelschuer T. et al. "The Raman spectrometer onboard the MMX rover for Phobos". In *IAC 2019*. Oct. 2019, IAC–19.