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THE MICROSCOPE FOR THE BEAGLE 2 LANDER ON ESA'S MARS EXPRESS. N. Thomas^{1,2}, S.F. Hviid¹, H.U. Keller¹, W.J. Markiewicz¹, T. Blümchen¹, A.T. Basilevsky^{1,3}, P.H. Smith⁴, R. Tanner⁴, C. Oquest⁴, R. Reynolds⁴, J.-L. Josset⁵, S. Beauvivre⁵, B. Hofmann⁶, P. Rüffer⁷, C.T. Pillinger⁸, M.R. Sims⁹, D. Pullan⁹, and S. Whitehead⁹

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Introduction: The European Space Agency (ESA) will launch the Mars Express spacecraft in June 2003. The mission is intended to provide a flight opportunity for re-builds of experiments lost as a result of the Russian Mars '96 launch failure and will reach Mars around Christmas 2003. The re-build has allowed several instruments to be improved and upgraded. However, a completely novel element of the Mars Express payload is the Beagle 2 lander.

Beagle 2 is designed to descend through the atmosphere of Mars to the surface using a combination of aerobraking, parachutes, and airbags. After coming to rest in the Isidis Planitia region of Mars, (260-270°W, 5-10°N), the lander will deploy solar panels and begin scientific operations. The scientific payload comprises an X-ray fluorescence spectrometer, a Mössbauer spectrometer, a stereo camera system, a stepped combustion mass spectrometer (GAP), a sampling device ("PLUTO"), a set of environmental sensors, and a microscope.

Most of the experiments (the exceptions being the GAP and the environmental sensors) are mounted on a robotic arm referred to here as the ARM. The end of the ARM has a flat experiment "platform", referred to as the PAW (position adjustable workbench), on which the experiments are mounted.

In addition to the experiments, a grinding and coring tool is also available on the PAW to scratch and flatten the surfaces of rocks within reach of the ARM.

This paper describes the aims and performance of the microscope on the Beagle 2 PAW.

Scientific Objectives: A microscope has four distinctly different tasks in a lander package. Firstly, the instrument can be used to study the physical and structural properties of a surface and hence make a geophysical analysis and contribute to the overall geological and mineralogical interpretation of the landing site.

Secondly, a microscope can contribute to studies of the atmosphere of Mars. Specifically, dust particles are

continuously precipitating out of the dusty atmosphere and hence a microscope can be used to constrain the sizes and shapes of particles for input into atmospheric scattering and radiative transfer models of the Martian atmosphere.

Thirdly, the instrument can be used to characterize and/or select a sample before it is passed to another analytical instrument. It is used therefore to assist the chemical analysis.

Finally, the instrument can be used to study the morphology of a potentially biological sample and hence identify structures which are characteristic of past or present biological activity.

Instrument Concept: The concept of the optics for the microscope was based on a system originally designed for the Mars Environmental Compatibility Assessment (MECA) experiment package which was slated for launch on the cancelled Mars '01 mission.

The detailed design of the microscope for Beagle 2 was constrained by even more stringent mass and volume limits. This suggested that we try to keep the focal length of the experiment as short as possible. This, in turn, implied that we should select a relative short working distance (the distance between the object position and the first optical element) of the order of 12 mm. This was considered a reasonable solution given that the ARM would be able to bring the microscope to the sample. The optically active elements comprise a Cook triplet. The optics provides a magnification of 3.5:1.

The sample is unlikely to be well illuminated by sunlight because the microscope itself shadows the sample. This implied that an illumination system would be required. Microscopes in the laboratory use either transmissive illumination or confocal illumination. While a confocal system is desirable, at present the development of such a method of illumination for spaceflight is only at a preliminary stage. For Beagle 2,

we have chosen to use light-emitting diodes (LEDs) mounted around the entrance aperture of the microscope. The system comprises 12 LEDs, 3 red, 3 green, 3 blue and 3 UV. The UV LEDs are designed to induce fluorescence in rocks (or a biological sample). A filter has been introduced into the optics to eliminate reflected UV from the incoming beam.

For mass reasons, it was decided to use a micro-camera head including a CCD detector and its associated electronics (detector control electronics, analogue to digital converter, noise reduction filters, clock, memory buffer, serial digital interface drivers, and 10 Mbit s⁻¹ communication protocol) in a lightweight (ca. 80 g) highly integrated 3D module. This micro-camera has benefited from developments by SPACE-X within a contract from the ESA Technical Research Programme (TRP). The 14 micron pixel pitch leads to a pixel scale of 4 micron px⁻¹. The CCD is a 1k

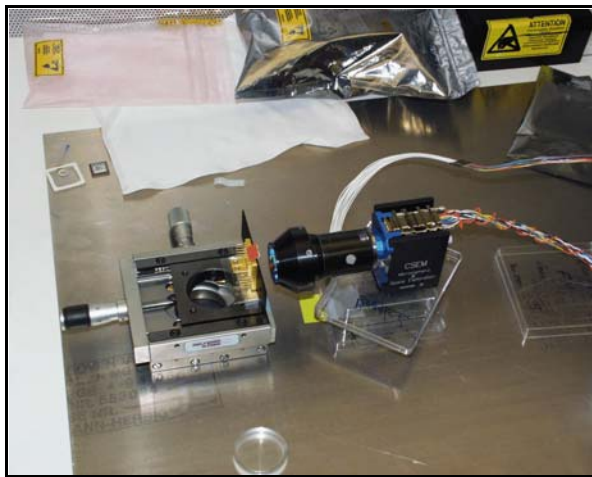


Figure 1 The FM microscope views a target mounted on a translation stage during bench testing.

x 1k device giving a field of view of just over 4 x 4 mm².

Even before detailed design commenced it was clear that the depth of focus of the microscope would be under 100 microns. It was also apparent that the accuracy with which the PAW could bring the microscope to the sample would be at least a factor of 20 larger than this. Thus, a focussing mechanism was necessary. Translation of the entire microscope at the interface to the PAW was implemented. The PAW provides a means of bringing the microscope to within ± 3 mm of its target. A "thumb" on the PAW prevents the microscope from impacting

rocks unless their surface roughness is greater than ± 12 mm (the working distance). The full range of the stepper motor is ± 3 mm, matching the accuracy of the PAW motion. The instrument is shown in Fig. 1.

Test Results: An image scale of 4.075 micron px⁻¹ at the best focus position was derived in bench tests. The variation in the image scale across the field of view of the microscope corresponds to a 0.2% distortion. The FWHM of a point source at the nominal focus position is 4.50 microns (1.10 px) and is less than 6 microns (1.5 px) within 50 microns of the nominal focus position. This result indicates that the accuracy of the stepper motor motion (20 microns) should be more than sufficient.

The flat-field shows some slight evidence of vignetting at the corners of the FOV. This is partly due to a slight misalignment of the detector in its housing and partly due to the baffling system.

The red LEDs are slightly susceptible to temperature and their central wavelength decreases from nominal (642 nm) at room temperature to 625 nm at 183 K. The wavelengths of the other LEDs vary by less than 2 nm over this temperature range. The output of the UV LEDs is strongly temperature dependent below 220 K and they become very faint below 200 K.

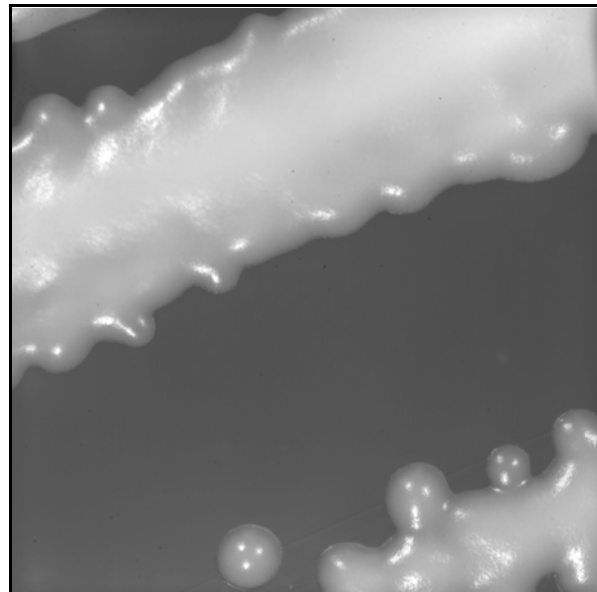


Figure 2 Microscope image of yeast on agar. The field of view is 4 x 4 mm². The bright dots on the surface of the yeast come from specular reflections from the LEDs. Individual organisms are below the resolution limit.

The illumination field has been calibrated for all LED combinations and the system absolute response computed. (Care needs to be taken here because, unlike most imagers, the microscope also provides the irradiance of the target.)

For amusement we show in Figure 2 an image of some yeast grown on agar. This shows that the microscope still does not have high enough resolution to resolve individual organisms.

Flight Software: The microscope can generate a huge volume of data. In particular, because we have no a priori knowledge of the focus position and because different parts of the field will have different focus positions as a result of surface roughness, many images at different positions need to be acquired to ensure that all parts of the field are in focus at some point. Potentially, 60 or more images may be required to guarantee that we obtain all parts of the field in focus at some stage.

Two approaches to solving the problem of data volume have been implemented on Beagle 2. Firstly, a wavelet compression algorithm has been incorporated into the lander software to reduce the total data volume from the experiment. The algorithm will also be used to support the other imaging experiment (the stereo panoramic camera) onboard Beagle 2. Wavelet compressors resolve the image into a series of coefficients which are related to spatial frequencies. The more detail one wishes to see in an image, the more coefficients one has to return. For the microscope this scheme is extremely effective. The reason is because an out of focus image does not require many coefficients. It is smooth. Therefore, unfocussed frames compress extremely well with ratios in excess of 40:1 often achievable with almost no loss. Hence, one possibility is to transmit all 60 frames compressed according to a quality criterion.

The second approach is to analyse the data onboard. Here we acquire all 60 frames but investigate the entropy at each position in each image to determine which image has the best focus for that position. We then downlink a completely focussed composite image.

In both cases, an important result from the analysis is that the image in which focus has been achieved for a position allows us to define unambiguously its depth. Hence, not merely does the microscope give us a 2-D picture of the surface, it also gives us a depth map allowing complete 3-D reconstruction of the surface.

Summary: The microscope for Beagle 2 is a highly compacted (160 g) device which will provide 6 micron resolution images of surface material in Isidis Planitia. The elegant design of the system makes it ideal for future landed missions where microscopic imaging might be required. Adaptation of the system to support other experiments (e.g. Raman spectrometer or laser mass spectrometer) should be relatively straightforward.

This abstract is a summary of a more detailed instrument paper submitted to Planetary and Space Science.

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