PanCam on the ExoMars 2018 Rover: A Stereo, Multispectral and High-Resolution Camera System to Investigate the Surface of Mars. N. Schmitz[1], R. Jaumann[1], A.J. Coates[2,3], A.D. Griffiths[2,3], C.E. Leff[2,3], B.K. Hancock[2], J.-L. Josset[5], D.P. Barnes[4], L. Tyler[4], M. Gunn[4], G. Paar[7], A. Bauer[7], C.R. Cousins[6], F. Trauthan[1], H. Michaelis[1], H. Mosebach[8], S. Gutruf[8], A. Koncz[1], B. Pforte[1], J. Kachlicki[1], R. Terzer[1] & the ExoMars PanCam team. 1 DLR-Institute for Planetary Research, Berlin, Germany; 2 Mullard Space Science Laboratory, University College London, UK; 3 Centre for Planetary Science at UCL/Birkbeck, UK; 4 Computer Science Department, Aberystwyth University, UK; 5 Space Exploration Institute, Neuchatel, Switzerland; 6 School of Physics and Astronomy, University of Edinburgh, UK; 7 Joanneum Research, Austria; 8 Kayser-Threde GmbH, Germany.

Introduction: The ExoMars rover will carry a Panoramic Camera System ("PanCam") being designed to obtain high-resolution colour and wide-angle multi-spectral stereoscopic panoramic images from the rover mast. The PanCam instrument consists of two wide angle cameras (WACs), which will provide multispectral stereo images with 32.28° field of-view (horizontal / vertical) and a High-Resolution Channel (HRC) to provide monoscopic "zoom" images with 4.88° field-of-view (horizontal / vertical). Scientific goals include fulfilling the digital terrain mapping requirements of the mission as well as providing multispectral geological imaging, colour and stereo panoramic imaging, water vapour abundance and dust optical depth measurements. The dedicated high-resolution channel allows for zooming into wide angle panoramas as well as image mosaicking and furthermore enables high-resolution imaging of inaccessible locations on crater walls and in valleys and to observe retrieved subsurface samples before ingestion into the Sample Preparation and Distribution System (SPDS) of the Pasteur payload. Combined with a "Rover Inspection Mirror" (RIM), placed at the front end of the rover body, engineering images of the rover underside as well as views of the rover wheels for soil mechanics science or views of the underside of overhanging rock formations, can be acquired with the HRC.

Figure 1: ExoMars rover, with PanCam on top (as of August 2014*)*

Overview of Scientific Goals: PanCam plays a key role as part of the Pasteur payload: The baseline PanCam uses wide angle stereo imaging and narrow angle monoscopic high resolution imaging to acquire morphological information on its surroundings, while multiple narrow band filters allow the mineral composition of rocks and soils and the concentration of water vapour and the dust optical properties to be measured. Providing these information, PanCam will set the geological and morphological context for the rest of the Pasteur payload. Geological, atmospheric and RGB filters provide a highly powerful camera system for Mars science. Wide angle (WACs) and close up (HRC) capability provide imaging at different scales, from sub-mm resolution (HRC) directly in front of the rover, up to mm-to-m resolution further away. These baseline properties additionally allow acquisition of information to support rover navigation., as PanCam is the only instrument on the rover which can remotely sense the geological context and provide detailed 3D terrain models, slope maps, and further derived products. After a drill site has been selected, based on PanCam's context information, the instrument can also view the drill tailings and thus provide complete geological context for the subsurface samples. PanCam also provides important atmospheric science, e.g. atmosphere water and dust content. Such filters could also be used to detect biological pigments if any have survived, in sufficient abundance, to the present day. In summary, the science objectives of the PanCam system are [1]:

1. Locate the landing site and science sites and the rover position with respect to local references, by comparison and data fusion with data from orbiters.
2. Provide (3D, geological and mineralogical) context information for the rover and its environment, including digital elevation models and their proper visualisation.
3. Support rover track planning with geological context of remote objects
4. Support the selection for rover science and drill sites by providing geological and mineralogical context to select the rover science and drilling sites
5. Geologically investigate and map the rover sites including drilling locations.

6. Image the acquired drill sample(s).
7. Study the properties of the atmosphere and variable phenomena, including water and dust content of the atmosphere.

The PanCam science team has developed a detailed science traceability matrix which links the high level goals to instrument performance [2].

PanCam Instrument Design: The ExoMars Panoramic Camera System is an imaging suite of three camera heads to be mounted on the ExoMars rover's mast, with the boresight 1.8m above the bottom of the wheels when the rover is on a flat surface. The PanCam design for Mars (total mass 1.75 kg) includes the following major items:

a) Wide Angle Camera (WAC) pair, for multispectral stereoscopic panoramic imaging, using a miniaturised filter wheel. The WAC camera units themselves including optics are provided by the Space Exploration Institute, Neuchatel, Switzerland, and the filter wheels and drives are produced by Mullard Space Science Laboratory, University College London (MSSL-UCL).
b) High Resolution Camera (HRC) for high resolution colour images. The HRC hardware is produced by the DLR Institute for Planetary Research, Berlin, Germany, together with Kayser-Threde, Munich.
c) Pancam Interface Unit (PIU) to provide a single electronic interface. The PIU is provided by MSSL-UCL.
d) PanCam Optical Bench (OB) to house PanCam and provide planetary and dust protection. The OB is provided by MSSL-UCL. The optical bench is located on a rover-supplied pan-tilt mechanism at the top of the rover mast, at a height of 1.8 m above the surface.

Further essential PanCam items are:

e) A rover deck mounted Color Calibration Target, and Fiducial Markers (for confirming the geometric calibration on Mars). The PanCam Calibration Target and Fiducial Markers are provided by Aberystwyth University.
f) A wide angle Rover Inspection Mirror (RIM), provided by Aberystwyth University.

The PanCam mechanical design is illustrated in **Figure 3**. As late as the ExoMars Pasteur Payload Design Review (PDR) in 2014, the PanCam consists of two identical wide angle cameras with fixed focal length lenses, and a high resolution camera with an automatic focus mechanism, placed adjacent to the right WAC. The wide angle stereo pair provides same focal length binocular vision for stereoscopic studies as well as 11 filter positions (per camera) for stereoscopic color imaging and scientific multispectral studies. The stereo baseline of the pair is 500mm. A summary of the main characteristics of the WACs and HRC is shown in Figure 2.

	WACs (x2)	**HRC**
FoV (°)	32.28	4.88
Pixels	1024 x 1024	1024 x 1024
Filter type	Multispectral	RGB
Filter type	Filter wheel	On-chip
Filter number	11 per „eye"	3
iFoV (μrad/px)	652	83
Pixel scale (2m)	1.3 mm	0.17 mm
Focus	Fixed: 0.85m-∞	Mechanical Auto - focus: 0.98m-∞

Figure 2: Key parameters of the WAC and HRC cameras

The two wide angle cameras (WACs) have a 22mm focal length, f/10 lens that illuminates a 32.28° square field-of-view (FOV), 1024x1024 pixels. The high resolution camera (HRC) has a ~180mm focal length, f/16 lens that illuminates a 5° square FOV, 1024x1024 pixels. The WAC cameras have fixed focus lenses with an optimal focus set to 1.9m and a focus range between 0.85 m (nearest view to the calibration target on the rover deck, tbc) and infinity. A strict definition of "in focus" is used for the cameras wherein the optical blur circle is equal to or less than 2 pixels across. The high resolution camera is required to be able to focus between ~0.98m (nearest view to a drill core on the rover's sample tray) and infinity. Due to the wide distance range over which sharp images of the surface shall be taken with this high resolution, narrow angle camera, refocusing of the HRC optics with an autofocus mechanism is required in order to achieve optimum pixel resolution (see Figure 6). Bonded over the HRC detector is an RGB (red, green, blue) stripe interference filter to provide colour information.

The WAC IFOV is 652 μrad/pixel horizontal, yielding 1.31 mm per pixel 1.9m distance and 6.91 mm per pixel at 10 m distance. The HRC IFOV is 83μrad/pixel horizontal, which yields a pixel scale of 0.17mm/px at 2m distance and 8.3mm at 100m. All three cameras are monochrome imagers. Each WAC camera head also has a 11- position filter wheel in front of its optics, with filters covering different, narrow visible and near-infrared wavelengths and neutral density filters for viewing the sun. The filter wavelengths and passes are as listed in **Figure 4**. Each filter wheel includes filters for nominal RGB (red, green, blue) stereo imaging. The "geological and solar" filters are evenly distributed between the left and wide right angle camera to ensure each camera can address some of the compositional

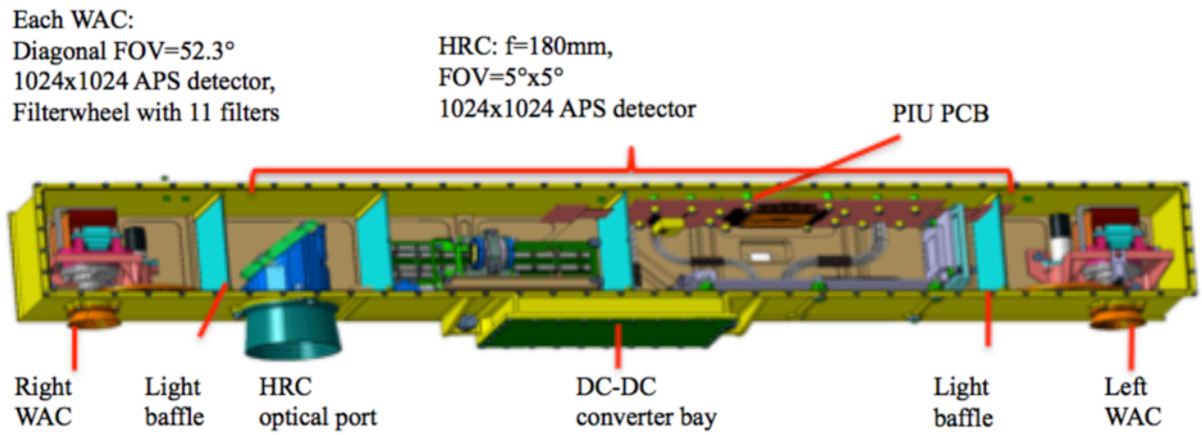

Figure 3: ExoMars PanCam, with left-hand (LH) and right-hand (RH) Wide-Angle Cameras (WAC), High Resolution Camera (HRC), PanCam Interface Unit (PIU), and DC-DC converter

objectives of the investigation should the other camera fail. The filter wavelengths and bandpasses have been optimized especially for the ExoMars investigation [3]. When compared to the filter wavelengths and bandwidths used for the MER and Beagle2 cameras, error scores for mineral identification have been shown to be lowest for the „FERRIC" filter set, which has now been adopted as the baseline for PanCam.

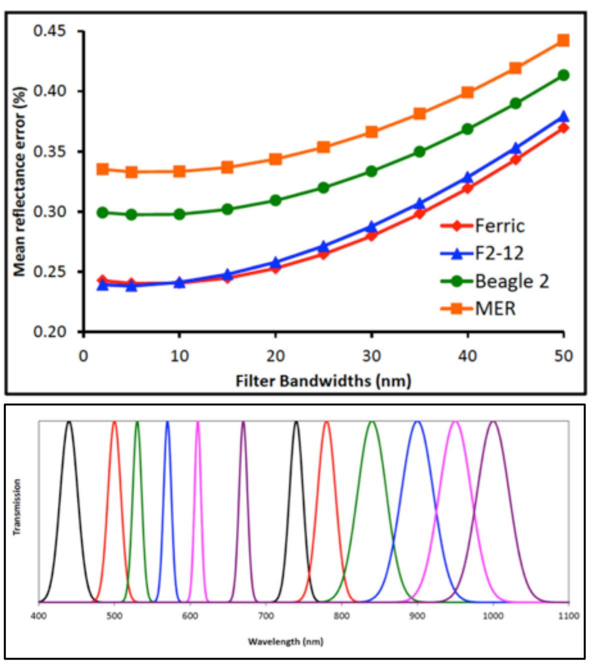

Figure 4: a) Comparison of the mean reflection error of the PanCam „Ferric" filterset with those of Beagle-2, MER, and the originally proposed set (F2-12); b) Modelled filter transmission curves for the PanCam „FERRIC" filter set [3].

The filter wheel and WAC camera system is illustrated in Figure 5. Figure 6 shows the HRC subsystems: the HRC optical path with its 180 mm efective focal length is housed within the optical bench structure, and folded with the help of a 45° mirror arrangement.

The PanCam Interface Unit (PIU) is the main interface between the ExoMars rover and the PanCam subsystems, and uses an FPGA implementation. The final system component is the Optical Bench, which provides a planetary protection barrier to the external environment (including a HEPA filter), as well as mechanical positioning of the PanCam components. A view of the prototype is shown in Figure 6.

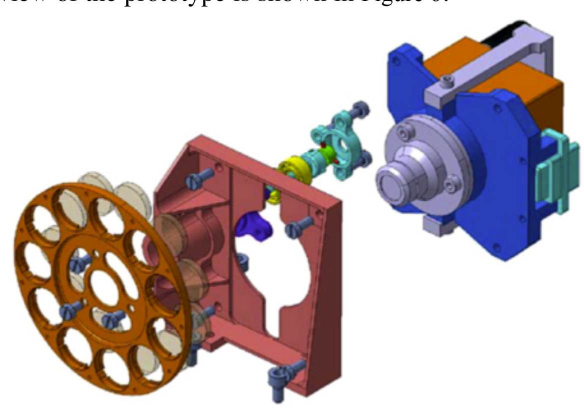

Figure 5: Mechanical configuration of WAC filter wheel (C. Theobald/MDO, MSSL-UCL) and cameras (Space Exploration Institute)

On-surface calibration uses a rover deck-mounted color calibration target (provided by Aberystwyth University). The PanCam calibration target (PCT) is implemented using coloured glass elements similar to „stained glass" (see prototype in Figure 7).

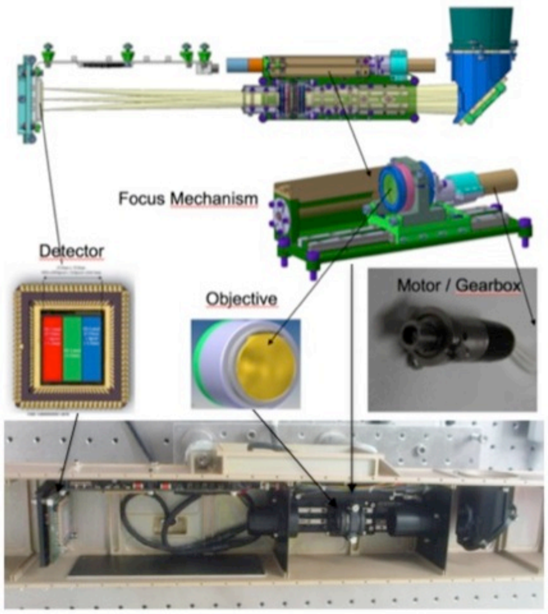

Figure 6: HRC subsystems: (a) exploded view and (b) accommodated into an Optical Bench prototype

Part of PanCam is also a wide angle Rover Inspection Mirror (RIM), mounted near the front of the left hand drill stowage bracket, enabling engineering images of the rover (front, sides, and underside) as well as views of the rover wheels for soil mechanics science or views of the underside of overhanging rock formations.

Figure 7: Prototype of the PanCam Calibration Target, current design.

In addition to the PanCam hardware components mentioned above, the ExoMars PanCam team includes a 3D vision team which provides key software and calibration support for the PanCam team. Some of the procedures for radiometric, colourimetric and geometric data flow, visualization and operations as envisaged by the 3D vision team, for 3D vision [4] and for colour image processing [5] have been tested in the field particularly during the Arctic Mars Analogue Svalbard Expeditions (AMASE) and SAFER expeditions, as discussed in the next section.

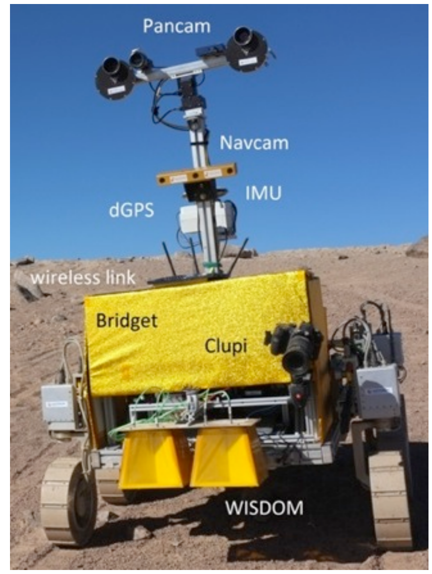

Figure 8: AUPE-2 PanCam Emulator on top of the ExoMars prototype in Chile (at SAFER campaign)

Aberystwyth University PanCam Emulator (AUPE) and field trials: A number of ExoMars-related fieldtrials and tests have been performed in the last few years, including participation in recent Arctic Mars Analogue Svalbard Expeditions (AMASE) 2008–13, (see e.g. [6], [7]). For these tests, a representative PanCam simulator (AUPE, [8]) was used, provided by Aberystwyth University. This simulator includes representative (though not the final) filter wavelengths from which spectral information may be used to study mineralogy [e.g. 8].

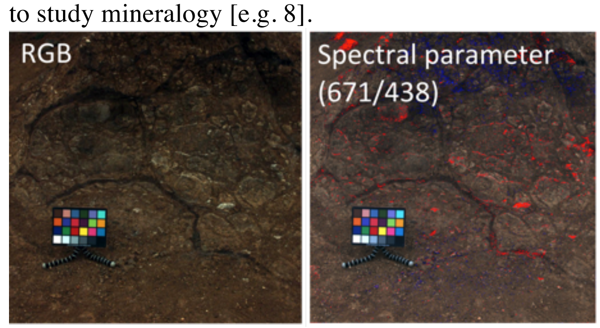

Figure 9: Representative colour (RGB) and falsecolour spectral parameter (671/438 nm) WAC data from an AUPE field test in Iceland 2013. Falsecolour image shows distribution of zeolite mineral veins (red). Credit: Jennifer Harris

These campaigns have been used, in combination with teams from other ExoMars instruments, to develop working procedures representative of a mission to Mars, as well as to test instrument performance, develop calibration techniques and pursue scientific investigations of particular Mars-analogue areas.

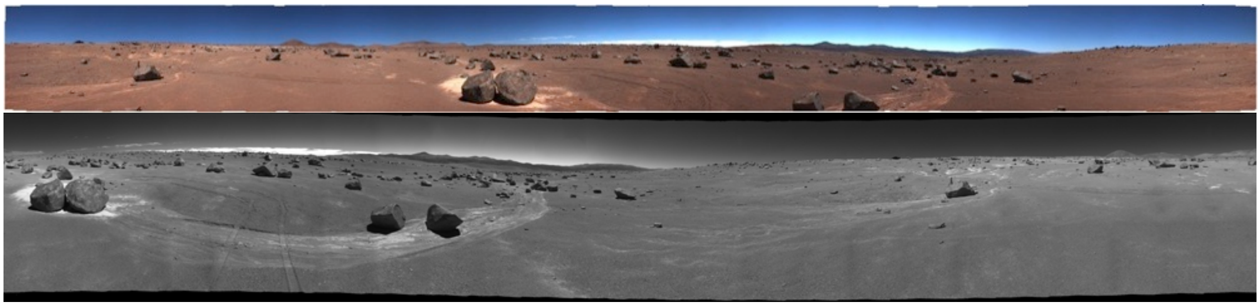

Figure 10: PanCam panoramas acquired with the Aberystwyth University PanCam Emulator (AUPE-2) and processed by the PanCam 3D Vision Team in mission emulation real-time during the SAFER campaign

Other PanCam ground tests have included „blind“ geological identifications performed in the AU Mars analogue facility, and tests in a quarry in Hertfordshire with the Astrium UK „Bridget“ prototype rover.

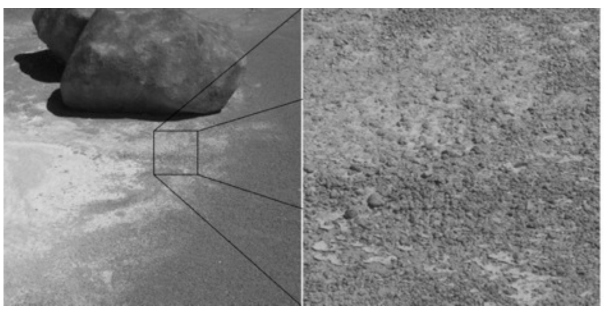

Figure 11: a) Detail of a PanCam panorama taken during the SAFER campaign in Chile, and b) close-up image of a region of interest, taken with PanCam HRC.

The PanCam team has also participated in ESA's first rover operations test in the Atacama desert in Chile in October 2013. For the „SAFER" (Sample Acquisition Field Experiment) campaign, the ASTRIUM UK ExoMars rover prototype has been fitted with prototypes of PanCam, Wisdom (ExoMars GPR), and CLUPI (ExoMars close-up imager). In order to built up experience, rover operations was done remotely from the Satellite Applications Catapult facility in Harwell, UK. Each day of the five-day test was treated as equivalent to two Sols. The three rover instruments worked together to select a sample site with outcrops of bedrock beside looser material. A human-operated hand drill gathered underground samples for later cross checking of the remote operations geologist's conclusions on the best locations to drill. This campaign included the first attempt to integrate data from surface and subsurface instruments to explore how to transition from topsoil to underground operations. Two PanCam panoramas from the test site (RGB and black-and-white) and a part of the panorama, with a HRC image of a region-of-interest, are shown in figures 10 and 11.

References: [1] Coates et al., Lunar PanCam: Adapting ExoMars PanCam for the ESA Lunar Lander. PSS (2012). http://dx.doi.org/10.1016/j.pss.2012.07.017; [2] Jaumann et al., 2010,The PanCam instrument on the 2018 Exomars rover: Scientific objectives, EGU General Assembly 2010; [3] Cousins, C., et al., 2012, Selecting the geology filter wavelengths for the ExoMars Panoramic Camera instrument, PSS 71, 80-100; [4] Paar, G., et al., 2009, 3D Vision Ground Processing Workflow for the Panoramic Camera on ESA's ExoMars Mission 2016. In: Proceedings of the 9th ISPRS Conference on Optical 3-D Measurement Techniques; [5] Barnes, D., et al., 2011. Multi-Spectral Vision Processing for the ExoMars 2018 Mission. In: Proceedings of the 11th Symposium on Advanced Space Technologies in Robotics and Automation. ASTRA.;[6] Steele, A., et al., 2009,Arctic Mars Analogue Svalbard Expedition (AMASE) 2009, 41st Lunar and Planetary Science Conference, held March 1-5, 2010 in The Woodlands, Texas. LPI Contribution No. 1533, p.2398, 2010.[7] Schmitz, N., et al., 2009, Field Test of the ExoMars Panoramic Camera in the High Arctic - First Results and Lessons Learned, EGU General Assembly 2009, p.1062, 2009. [8] Pugh, S., et al., 2012, AUPE – A PanCam emulator for the ExoMars 2018 mission. International Symposium on Artificial Intelligence, Robotics and Automation in Space; [9] Cousins, C.R. et al., 2013, Mars analogue glaciovolcanic hydrothermal environments in Iceland: detection and implications for astrobiology. JVGR, 256, 61 – 77.