

AUPE: An Emulator for the ExoMars PanCam Instrument

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Abstract

The European Space Agency's ExoMars mission will be the first European-led planetary rover mission and much preparation and rehearsal is required, both for the personnel involved and the data processing pipelines and analysis software. The long instrument development cycle and significant cost associated with flight hardware prohibits their use for extensive field deployment and testing and so emulator systems are required. For this reason an emulator for the PanCam camera system was developed using commercial off-the-shelf components. PanCam's multispectral imaging capabilities will be used to guide the rover to sites of scientific interest, and development of this emulator and the associated data processing techniques are proving invaluable in ensuring the visual-based data products provided to scientists are accurate and that their processing is a transparent and traceable process.

CCS Concepts

• **Applied computing** → Physical sciences and engineering; • **Hardware** → Displays and imagers; • **Computing methodologies** → Camera calibration; Vision for robotics; Image processing;

1. Introduction

The European Space Agency (ESA) ExoMars rover is now expected to launch in 2028 and begin its exploration of the Martian Surface in 2030. The rover, named 'Rosalind Franklin', carries the Pasteur science payload which includes a suite of remote sensing and analytical instruments to enable the mission objective – to search for signs of past or present life. This search will be guided primarily by the mast-mounted panoramic camera system known as 'PanCam' [CJG*17]. Although much can be learned from the numerous successful NASA missions [STB*97; BSH*03; MCE*10; GC16], extensive testing is still required to enable planetary scientists to develop techniques to process and analyse the data. For this reason a PanCam emulator was developed using commercial off-the-shelf components to ensure the system could be easily modified and maintained.

The ExoMars PanCam instrument [CJG*17], shown in Fig. 1, is a mast mounted, panoramic camera system with the ability to capture colour, multispectral and stereo wide angle and high-resolution images. It consists of three individual cameras mounted in an Optical Bench (OB). Two fixed-focus Wide Angle Cameras (WACs) with a Field of View (FoV) of 38° (horizontally and vertically) mounted at either end of the OB with a 500 mm separation to provide stereo image pairs for Digital Terrain Model (DTM) generation. The WACs are fixed-focus monochromatic cameras using 1024 px × 1024 px STAR1000 CMOS image sensors and are fitted with 11 position filter wheels to provide multispectral capabilities tailored to the objectives of the mission [CGC*10; CGP*12].

Mounted between the WACs and offset to the right is a High Resolution Camera (HRC) with a field of view of approximately 5° (horizontally and vertically) to provide more detailed views of objects or regions of interest. HRC uses a Bayer filter array version of the same sensor as the WACs to enable single shot colour images, and additionally has a variable focus lens to provide sharp images at distances ranging from approximately 1m to infinity. PanCam is mounted on a Pan-Tilt Unit (PTU) which allows panning control from -180° to 180° and tilting -90° to 90°, allowing PanCam to view the surrounding area. Rover instruments are tightly integrated to achieve best use of physical space: a pair of navigational cameras (NavCams) also sit on the front of the PanCam OB, and an infrared spectrometer hangs beneath the OB below HRC.

The Aberystwyth University PanCam Emulator (AUPE) system, shown in Fig. 2 and 3, has been designed to provide a field portable emulator to aid the development of the ExoMars PanCam instrument and data processing pipelines, and to provide a training and rehearsal tool for the PanCam team. AUPE has undergone continuous development and refinement since its first incarnation in 2010 [PBT*12] and is now a rugged, reliable field instrument which has been successfully deployed in locations all over the world. The construction, calibration, control software and deployment of the latest iteration of the AUPE system are described in the following sections.

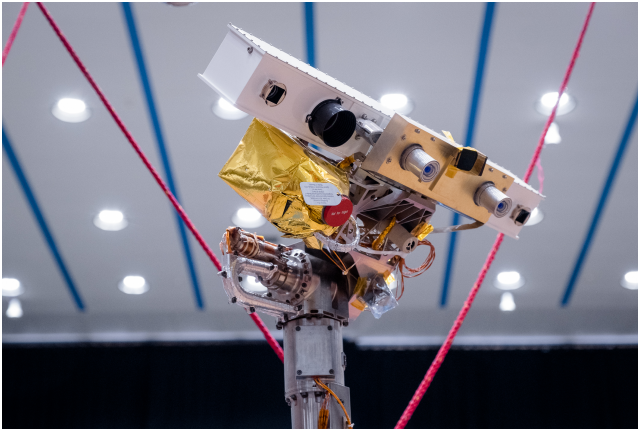


Figure 1: The ExoMars Panoramic Camera PanCam, image credit Thales Alenia Space.



Figure 2: AUPE, the Aberystwyth University PanCam Emulator, during a field trial at Brimham Rocks, Yorkshire.

2. Hardware

The AUPE system was constructed predominantly from commercial off-the-shelf components, with bespoke parts where required. AUPE is comprised of three Allied Vision Technologies (AVT) Gigabit Ethernet cameras, filter wheels, an embedded control computer, power conditioning circuitry and a PTU, all connected to an OB; see Fig. 3. For some studies, AUPE has been equipped with emulators for the NavCams and infrared spectrometer, however in this paper we focus on the components relevant to PanCam emulation. These are described in more detail below and technical details are summarised in Table 1 for direct comparison with PanCam. Further information on AUPE hardware can be found online at [MG].

2.1. WACs

The WACs are emulated by two AVT Manta G504, monochrome $2/3''$ CCD cameras with a resolution of $2452\text{ px} \times 2056\text{ px}$. These

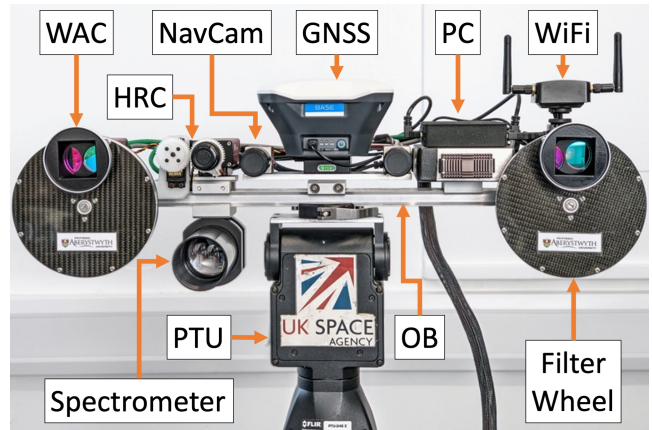


Figure 3: A close up image of the AUPE OB, with the key components labelled. In this image, AUPE is also equipped with a spectrometer, NavCams, GNSS, and WiFi, while Fig. 2 shows AUPE deployed without these components.

are operated with 2×2 binning and windowing to provide $1024\text{ px} \times 1024\text{ px}$ images. The cameras are fitted with Schneider Kreuznach KMP-IR Cinegon 12 mm $f/1.4$ lenses which are corrected for chromatic aberration from 400–1000 nm. The 12 mm lenses give a $33^\circ \times 33^\circ$ FoV over the $1024\text{ px} \times 1024\text{ px}$ effective image. Although a little narrower than the $38^\circ \times 38^\circ$ FoV of the final PanCam design, this was close to the $34^\circ \times 34^\circ$ FoV of PanCam at the time of AUPE's construction [CGL*12]. Cameras with greater native resolution than required were selected for the WACs to enable future investigations with higher resolution imagery. The lenses are stopped down to $f/11$ and set at a hyperfocal distance of 2 m, giving a depth of field of 1 m to infinity.

2.2. HRC

HRC is emulated by an AVT Manta G146 $1/2''$ CCD camera with a resolution of $1388\text{ px} \times 1038\text{ px}$, windowed to give a $1024\text{ px} \times 1024\text{ px}$ image. It is fitted with a 50 mm $f/2$ manual focus lens, stopped down to $f/16$ to give a $4.8^\circ \times 4.8^\circ$ FoV. The PanCam HRC was originally intended to have a novel RGB strip colour filter [CJG*17] and so a monochrome HRC emulator was originally employed. Following the design change of the flight instrument a G146C Bayer filter variant of the Manta 146 camera was substituted. Auto focus was implemented on the HRC emulator in 2018 by adding a 3D printed gear to the lens focus ring driven by a Hitec HS-422 metal gear servo - see Fig. 3.

2.3. Filter Wheels

Bespoke filter wheels and housings were manufactured for the WAC emulators, shown in Fig. 4. Filter wheels were machined from aluminium and are each able to accommodate up to 11 filters, 6 with a diameter of 1" and 5 with a diameter of 1.25". The filter wheels are mounted in aluminium and carbon fibre filter wheel housings which are sealed against the ingress of dust. The filter housing window is a 4 mm thick $1/4$ wave BK7 glass flat with

	PanCam WAC	AUPE WAC	PanCam HRC	AUPE HRC
FOV (°)	38.3 × 38.3	33 × 33	4.88 × 4.88	
Pixels	1024 × 1024	1024 × 1024 (binned & windowed from 2452 × 2056)	1024 × 1024	1024 × 1024 (windowed from 1388 × 1038)
Filter type	Multispectral Filter Wheel		Bayer colour filter array	
Filter number	22 (11 × 2 eyes)		3 (RGB)	
IFOV ($\mu\text{rad px}^{-1}$)	653	575	83	93
Pixel scale (2 m)	1.31 mm	1.15 mm	0.17 mm	0.19 mm
Focus	Fixed (1.0 m to ∞)		Mechanical autofocus (0.98 m to ∞)	Mechanical autofocus (1.0 m to ∞)

Table 1: Technical specification PanCam and AUPE, comparing the WACs and HRC.



Figure 4: Partially-dismantled WACs, showing the filter wheels, front of the wheel housing with protective baffles, and rear of the housing fixed to the cameras.

a Vis-NIR anti-reflection coating. The filter wheels are driven by Hitec HS-422 metal gear 180° servos through a 2:1 gearbox to provide 360° of rotation. The 1" filters cause vignetting of the corners of the image but this size was chosen as obtaining a set of geology filters of the required size would have cost more than the rest of the emulator combined. The AUPE geology filters were selected from the Edmund Optics and Semrock hard coated filter ranges and matched as closely as possible to the PanCam filter wavelengths and bandwidths. The larger filter holes were sized to accommodate Baader astronomical telescope filters which were removed from their 1.25" telescope eyepiece mounts. Baader Luminance (L), Red (R), Green (G) and Blue (B) filters were fitted to each filter wheel, and the remaining position left empty to enable full panchromatic imaging. All filters are retained by nylon tipped set screws and alternative filters can be readily substituted if required.

A comparison of the PanCam and AUPE filters is provided in Table 2, and further details of the PanCam filters may be found in [CGC*10; CJG*17].

2.4. Optical Bench

The AUPE cameras are mounted on a length of Thorlabs XT66 dovetail optical rail. The WACs are mounted with 2.8° of toe-in

to match the 5 m crossover distance of PanCam. HRC is mounted with an offset of 154 mm from the centre line; an exact match to the PanCam instrument was not possible due to the much larger filter wheels on AUPE compared to PanCam. In addition to dovetail clamps, the cameras are secured with bolts to prevent movement and loss of geometric calibration. The dovetail rail allows easy mounting of other components during testing and development such as the collecting optics for a complementary spectrometer.

2.5. Pan-Tilt Unit

The AUPE OB is mounted on and integrated with a FLIR D48E pan-tilt unit to enable automated panoramic image capture. The PTU is usually mounted on a Manfrotto 535 carbon fibre tripod which allows AUPE to be placed at up to 2 m height on any terrain. On occasions the PTU has also been mounted onto the mast of various robotic platforms as part of rover field trials. An earlier iteration of AUPE was mounted on a FLIR D46 PTU but this was not found to be sufficiently rigid to support the instrument in the windy conditions encountered during some field trials, and so was replaced with the heavier duty model. The OB is secured to the PTU with a quick release mount so the instrument can be assembled and disassembled quickly and easily in the field without the need for tools. Two locating pins attached to the underside of the OB ensure a repeatable mating with the quick release mount.

2.6. Control Computer and Electronics

The AUPE system includes an on-board embedded computer configured as a server to handle communication and control of the AUPE Hardware. The computer is a Fitlet fan-less PC fitted with four Gigabit Ethernet ports, three of which are used to drive the PanCam cameras while the fourth allows a client computer to be connected, either via cable or a WiFi router which can be mounted to the OB in situations where wireless control is desirable. An external USB hub with a 10/100 Ethernet adaptor is connected to the the Fitlet's USB2 port; the 10/100 Ethernet is used to control the PTU, and a Pololu servo board for the filter wheels and HRC focus is connected to a USB port.

Filter		PanCam			AUPE		
ID	Description	Wheel Position	Wavelength (nm)	Bandpass (nm)	Wheel Position	Wavelength (nm)	Bandpass (nm)
C01L	Broadband red	L07	640	100	L03	640	100
C02L	Broadband green	L08	540	80	L02	540	80
C03L	Broadband blue	L09	440	120	L01	440	120
C01R	Broadband red	R07	640	100	R03	640	100
C02R	Broadband green	R08	540	80	R02	540	80
C03R	Broadband blue	R09	440	120	R01	440	120
G01	Medium band violet	L06	440	25	L04	438	24
G02	Medium band cyan	L04	500	20	L05	500	24
G03	Medium band green	L02	530	15	L06	532	10
G04	Medium band yellow	L01	570	12	L07	568	10
G05	Medium band orange	L03	610	10	L08	610	10
G06	Medium band red light	L05	670	12	L09	671	10
G07	Medium band red dark	R03	740	15	R04	740	13
G08	Medium band infrared	R02	780	20	R05	775	25
G09	Medium band infrared	R01	840	25	R06	850	25
G10	Medium band infrared	R04	900	30	R07	900	25
G11	Medium band infrared	R05	950	50	R08	950	50
G12	Medium band ultraviolet	R06	1000	50	R09	1000	50
S01	Solar - continuum	L10	925	5	L10	545	290
S02	Solar - water absorption	L11	935	5	L11	Empty	-
S03	Solar blue	R10	450	5	R10	545	290
S04	Solar red	R11	670	5	R11	Empty	-

Table 2: Comparison of the filter specifications for PanCam and AUPE.

In order to allow AUPE to be used in the field it was designed to run from a variety of power sources. The input power is supplied to a 60 W DC-DC converter which will run from 9–30 V and provide an output of 12 V. This is fed directly to the cameras, PTU and on-board computer. The filter wheel servos require 5 V which is provided by a switching regulator. For most field deployment AUPE is run from Tracer lithium-ion polymer battery packs. 12 V 8 Ah packs typically give 2–4 h operating time depending on the amount of PTU use, and most airlines will allow these packs to be carried in hand luggage when transporting the system abroad for fieldwork.

2.7. Geolocation

A quick release mount at the centre of the AUPE OB allows an Emlid Reach RS+ GNSS receiver to be fitted. When used in combination with a second receiver acting as base station, highly accurate and precise location data can be recorded for each instrument position during fieldwork. GNSS integration was added in 2021 to support activities such as DTM fusion, where location data can be used to co-register 3D products captured at different positions (by AUPE or e.g. a terrestrial laser scanner) or used as ground-truth for validating e.g. visual co-registration techniques.

2.8. Transport

The AUPE system is designed to be deployed in remote field locations, so has been built with portability in mind. The instrument can be dismantled into three sections without tools (less to lose when out in the field) to enable it to be packed into a single PELI iM2950 case. The OB separates from the PTU by releasing an Arca Swiss quick release and the PTU separates from the tripod by unscrewing a single threaded handle. The AUPE instrument, along with a laptop for control and batteries for remote operation can be packed into the Peli case in a few minutes for shipping, or transport in the field, as shown in Fig. 5.

3. Calibration

Radiometric and geometric calibration has been carried out on the AUPE system, both as part of the development of the calibration processes for the PanCam instrument and to enable scientific interpretation of its results. These calibration processes are described in the following sections.

3.1. Radiometric Calibration

Each of the AUPE cameras have undergone radiometric calibration to allow camera artefacts to be corrected and to allow pixel val-

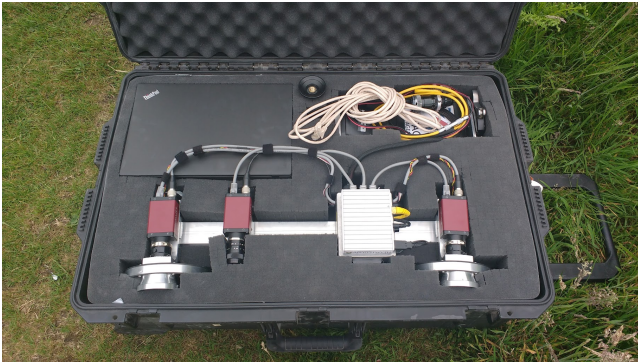


Figure 5: AUPE packed into its transport container. The tripod is stored below the Optical Bench and the batteries are stored below the laptop.

ues to be converted from raw Digital Numbers (DN) into physical units of spectral radiance - $\text{W sr}^{-1} \text{m}^{-2} \text{nm}^{-1}$. Radiometric calibration measurements were carried out using a Labsphere 12" uniform light source integrating sphere fitted with an external 100 W Labsphere tungsten lamp and variable aperture to allow adjustment of the illumination level. The sphere illumination level was monitored with a (calibrated) silicon photodiode connected to a Thorlabs photodiode amplifier. The sphere spectral radiance was measured using a calibrated Spectral Evolution RS-3500 spectrometer. For each camera, the following image types were captured:

- zero-exposure bias (40)
- dark current (300; 5 each for 60 exposure times from 41 μs to 2 s)
- flat field (440; 40 each for all 11 filters)
- linearity (600; 10 each for 60 exposure times from fully under-saturated to fully saturated)

For all the setups the instrument was left powered on in an indoor environment for a period of time to let it reach normal operating temperature. For the bias and dark current images the instrument was placed in a dark room and additionally covered in a light proof fabric to ensure that the induced signal would be due to thermal currents alone. For the flat field images the exposure was set such that the bulk of the pixels would be exposed to within 60–80 % full well.

The calibration measurements were subsequently analysed using the methods outlined by [Jan07] to create Calibration Data Products (CDPs) which can be used as corrective inputs by the radiometric calibration processor during image pre-processing (see Section 4.3.2).

The AVT cameras were found to exhibit a low zero-exposure bias level at around 0.1 % full range mean ($\sigma = 0.1\%$). While largely negligible on their own, bias CDPs were nevertheless created due to their ease of application and role in the creation of other calibration products. Thermal noise (dark current) was similarly found to be minuscule: an approximate mean contribution of only $0.013\% \text{ s}^{-1}$ was observed over the 41 μs to 2 s exposure time range, with an apparent negligible dependence on ambient

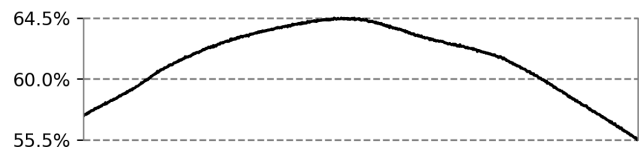


Figure 6: (top) An AUPE L02 flat field image and (bottom) its averaged column-wise brightness profile. A "cosine fourth" falloff can be seen towards the periphery, along with several localised nonuniform structures. This lens and filter combination exhibits an asymmetric falloff, with global brightness variations between pixels on the order of 20 %.

temperature variations. With a limited number of observed outlier pixels (e.g., "hot" pixels) it was therefore decided to not pursue the creation of a dark current model and associated CDP. Linearity measurements revealed only minor deviations as expected for CCD sensors, in the worst case approaching 0.3 % towards full well. As the effect on image calibration was found to be insignificant, no nonlinearity CDP was created. Optical nonuniformities were observed in the flat field images, including light falloff as shown in Fig. 6. The calibration measurements were stacked and normalised for each camera and filter combination to create flat field CDPs. The flat field stacks were additionally used together with spectral radiance measurements of the sphere measured with the RS-3500, to create spectral responsivity CDPs.

3.2. Geometric Calibration

To use the two WACs and HRC in tandem, the cameras must be geometrically characterised once in position on the OB in order to determine their principal point, focal length, and lens and filter distortion effects. In brief, this entails individual calibration of each camera, the cross-calibration between the cameras and with the PTU and mast/tripod to determine the relational geometry. The process of geometric calibration for PanCam is outlined in more detail in [CJG*17], and the same process is used for AUPE. Once

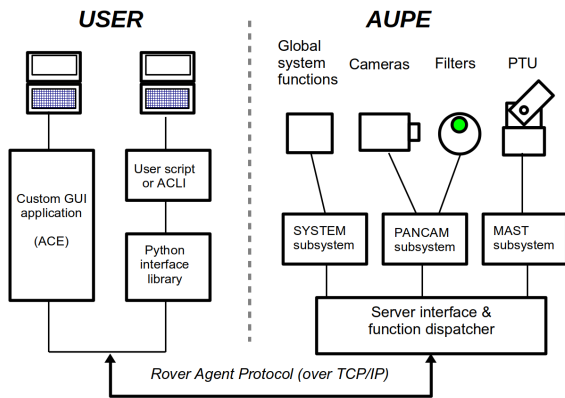


Figure 7: AUPE control and capture system overview. The server provides unified access to the various hardware subsystems and allows multiple client applications to connect in parallel.

the calibration data has been collected it can be used in the Planetary Robotics Vision Processing (PRoViP) framework to produce geometrically-corrected images, stereo panoramas, and 3D vision products (DTMs), as outlined in [POT*23].

4. Software

A diverse suite of software components cover the various aspects of PanCam emulation that AUPE enables, from hardware drivers and abstraction layers that run on the embedded computer, through client programs that manage image capture in the field, to data processors which perform instrument calibration and analysis tools used to generate science products. The following sections describe these component categories and how they fit together within the broader AUPE ecosystem.

4.1. Hardware Interface

The software system which drives AUPE has been designed to allow easy and efficient access to the PanCam emulator primitives while hiding the low-level details of the camera hardware drivers (see Fig. 7). The system is based on a client-server architecture using a custom binary protocol (Rover Agent Protocol) running over TCP/IP.

The server runs under a version of Linux on the embedded AUPE control computer, and directly controls all relevant aspects of the various hardware subsystems, including cameras, filter wheels and pan-tilt unit. A TCP socket interface is exposed via a Gigabit Ethernet port for client connections. The AUPE server is capable of controlling nearly all of the hardware parameters of the cameras, operating the pan-tilt unit, focus and filter wheels, and capturing image data in a wide variety of resolutions and formats (including HRC raw Bayer data). The server also provides extra capabilities such as a fully configurable implementation of auto-exposure and synchronisation of image capture for use in stereo visual odometry.

Client applications access the command and capture functions by calling high-level routines within a provided client library API.

The client library makes a TCP connection to the AUPE server host, sends the appropriate function request and parameters and returns any reply and data to the calling program. The client application does not need to deal directly with the hardware or the underlying protocol. Basic client libraries have been written in C and Java, while a set of Python modules provide a convenient high-level interface for scripting by using proxy objects. Clients may run on any machine on the external network which can make a TCP/IP connection to the server process, and multiple clients may connect at the same time.

4.2. Capture Software

ACE (Aberystwyth Camera Environment) is a Java GUI application that provides facilities for AUPE camera control and bulk image capture. It allows camera preview, pan-tilt adjustment, selection of filter sequences and exposure settings, and setting up parameters to capture entire panoramic datasets in an automated manner. It has been the primary tool used to capture AUPE image data in field trials prior to 2018.

ACLI (AUPE Command Line Interface) is a Python application originally developed for use in the ExoFit rover-based field trials in 2018 and 2019. As a command line utility, ACLI allows more advanced AUPE image capture sequences to be fully scripted and automatically triggered, for instance by a host rover's on-board computer as part of a field trial activity plan. In addition to supporting panorama and multispectral intents, ACLI provides high-level commands for HRC super resolution imaging and in-situ calibration, and is capable of combining metadata from AUPE and external sources into XML sidecar files tailored to a given campaign. Several supporting tools facilitate the use of ACLI for more traditional fieldwork: ALIVE, a multi-camera live preview and statistics (e.g., false colour and histogram) GUI application; and APTU, a virtual joystick and panorama sequence building utility.

4.3. Data Processing

Images captured with AUPE are stored as PNG files with metadata such as bit depth, PTU angles, image timestamp, active filter, and exposure time, written to the file header. An advantage of using the PNG format for AUPE raw images is that relatively simple or one-off processing tasks, such as assembling an individual 2D panorama or composing a spectral parameter image from a multispectral set, can be performed by virtually any third party application. However, to assist the definition and development of the software processors and analysis applications that will form the PanCam ground processing landscape, pre-processing scripts have been developed which transform AUPE images into the format used for PanCam.

4.3.1. Pre-processing Scripts

The ExoMars mission will utilise the Planetary Data System version 4 (PDS4) standard for its long term data archive. In addition to governing archive design and implementation, PDS4 acts as a file format which specifies the structure of mission "data products" (e.g., images, calibration data, DTMs, etc.) and their metadata. To

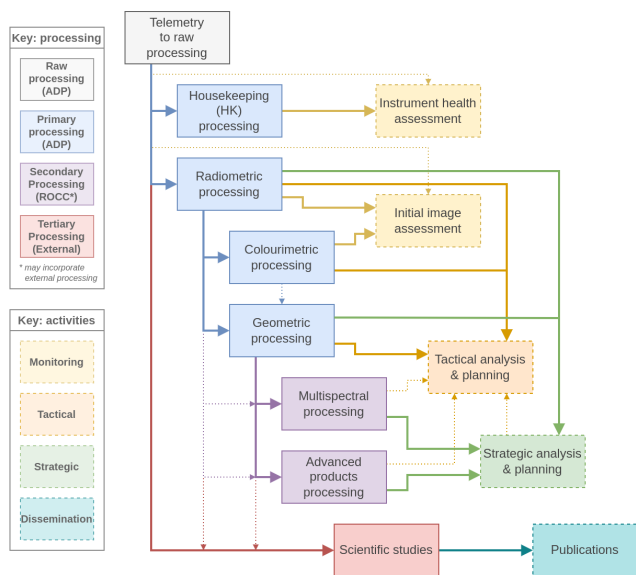


Figure 8: An overview of the PanCam ground processing pipeline components and the rover operations activities they feed into.

streamline the archiving process, PDS4 will also serve as the primary interchange format for ExoMars data processors and operations tools. PDS4 products consist of two conceptual parts: an XML "label" file which contains identifying information and other metadata, and (usually) one or more associated data files.

The AUPE pre-processing scripts fulfil a similar role to the PanCam telemetry-to-raw processor in Fig. 8. In order for AUPE images to masquerade as PanCam raw products, their image data must be transcoded and their metadata remapped to the XML structure used by PDS4. Because PanCam products are created within a rover context which includes metadata entries either unavailable (e.g., sensor temperatures) or not applicable (e.g., rover motion counter values) to AUPE, the process involves a combination of static and user supplied shim values to enable the masquerade. Various helper scripts have been written to handle campaign-specific tasks, such as updating pose or geolocation metadata for groups of products based on offline refinements.

A notable caveat to the use of AUPE PDS4 products for development and testing of PanCam software is that the software must be aware of, and be able to handle, any relevant differences between AUPE and PanCam, such as sensor FoV. The PanCam product labels allow the instrument model (e.g., flight model, ground test model, training model, etc.) to be identified, and this feature has been extended to accept "AUPE" as a recognised model variant, enabling processors to distinguish its images and act accordingly.

4.3.2. Radiometric Correction

As the DN values of pixels in a raw image do not directly represent the actual illumination in a scene, to be useful in a radiometric context images must undergo several transformations: first, the salient camera specific noise sources and spatial nonuniformities identified in Section 3.1 must be corrected. Second, the image

must be divided by its exposure time to obtain the independent rate in DN s^{-1} . Finally, the characterised responsivity of the active filter is applied to scale the pixel values into physical units of spectral radiance.

AUPE has been integral to the development of the PanCam Radiometric Calibration Processor (RCP). Early iterations supported ingesting AUPE PNG files directly, but this feature has since been deprecated in favour of PDS4. RCP borrows several core concepts from the James Webb Space Telescope (JWST) Science Calibration Pipeline [BDG15], notably the use of modular correction steps (for instance tailored to a given instrument model variant), Data Quality (DQ) tracking and per-pixel uncertainty propagation.

4.3.3. Analysis Tools

Once images have undergone radiometric correction, they provide a true representation of the illumination in the scene and are ready for further processing and analysis. Due to the multitude of capabilities of PanCam and AUPE, numerous analyses are possible depending on the objective of the study. The two main use cases are based around 3D reconstruction or multi-spectral analysis.

3D vision processing of AUPE image data is carried out using the PRoViP pipeline [POT*23] which transforms radiometrically corrected stereo images to Ordered Point Clouds and panoramic mosaics. This data is then ingested into the PRo3D analysis software [POT*23] which allows the data to be analysed in order to determine information such as structural characteristics of rock outcrops.

Multispectral analysis of AUPE image data has previously been carried out using the IDL/ENVI-based ExoSpec analysis toolkit [ACGC20]. This toolkit allows stacks of radiometrically corrected images to be calibrated into relative reflectance using an in-situ calibration target (such as the PanCam Calibration Target, see [CJG*17]) and then analysed to determine the spectral content and distribution in the scene. An example of multispectral data analysis using ExoSpec is shown in Fig. 9. Due to licensing issues with the ENVI platform, the functionality of ExoSpec has now been ported to the open source Python-based PanCam Operations Toolkit (PCOT) [Fin] which will be used during ExoMars surface operations.

The processing required to convert the radiometrically corrected images into secondary data products requires the application of further transformations, each of which can introduce new errors or artefacts into the images. A common scheme has been developed which specifies how applications should propagate radiometric uncertainty and data quality flags on a per-pixel level, and the scheme additionally leverages PDS4's unique product identifiers and inter-product reference capabilities to ensure the traceability of processing.

5. Deployments and Results

AUPE has been through three major iterations as a result of lessons learned during deployment in the field.

AUPE1 was designed and assembled in approximately 6 weeks in preparation for the AMASE (Arctic Mars Analogue Svalbard

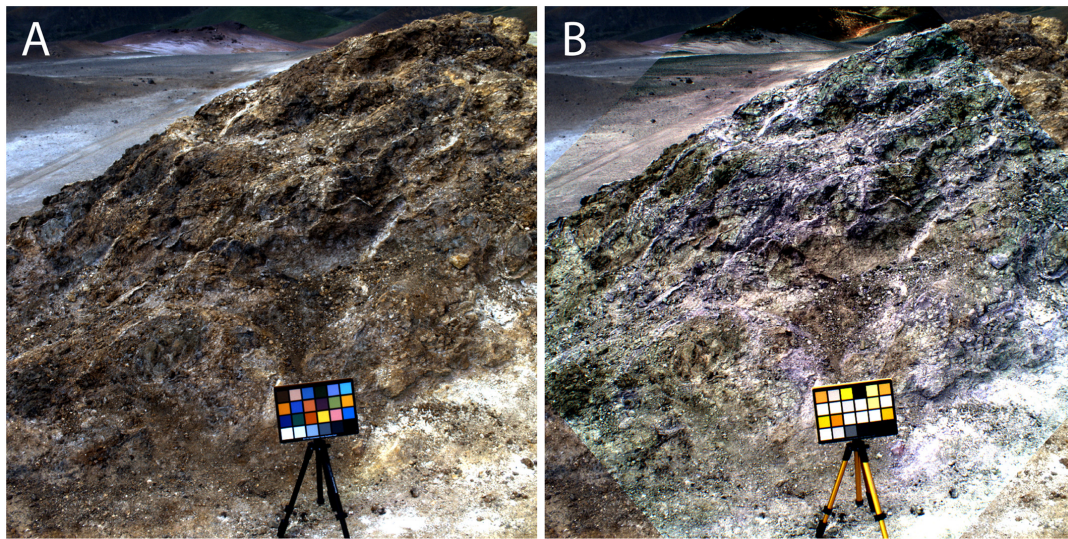


Figure 9: (a) AUPE3 RWAC true color RGB for visual comparison with (b). (b) AUPE3 RWAC composite with geology filters 6, 3, and 1 (1000, 850, and 740 nm) assigned as RGB, respectively. Pixels which appear violet are indicative of Fe³⁺-bearing mineralogy such as hematite, which has an absorption feature at around 900 nm. Scale is given by the Macbeth ColorChecker© which is 21 cm in width. Image reproduced with permission from [ACGC20].

Expedition) campaign in 2009 [CGS*09]. It featured Imaging Source firewire cameras and manually-operated filter wheels. The cameras were interfaced directly to the control laptop and data was collected and saved manually.

Following the 2009 AMASE campaign, AUPE was automated – motorised filter wheels, a motorised Pan-Tilt Unit and a server to interface the the cameras and motors with the control computer. AUPE2 was built with better cameras, lenses and filters to overcome shortcomings with the AUPE1 system in 2011. The new cameras used Gigabit Ethernet connectivity and have a higher dynamic range. The new achromatic lenses were substituted to provide sharply focused images with all filters. The new filter wheels were fitted with hard coated interference filter which provide higher transmission, better out of band blocking and less stray light in the images. The laptop which acted as the server on AUPE1 was replaced with a compact FitPC. The FitPC, PTU control electronics and LiPO battery were contained in a Peli case.

Although the AUPE2 system was a vast improvement on the previous version, the control case was heavy and cumbersome and the PTU was underrated for the mass it was supporting. In preparation for the field trials planned as part of the UK Space Agency funded science investigations, AUPE was rebuilt again in 2015. AUPE3 used the cameras and filter wheels from AUPE2. The PTU was replaced with the much more substantial model which also contained the control electronics in its base. The FitPC in the case and network switch on the OB of AUPE 2 were replaced with a new FitLet PC which has four Gigabit Ethernet ports and all of the electronics were mounted on the OB, making the separate control case unnecessary. Minor additions have been made to the AUPE3 system including the addition of auto-focus to the HRC emulator in 2018 and the fitting of a mounting point for a GNSS receiver in 2021.

The AUPE system has been deployed in numerous field trials and expeditions and the data collected with it has fed into many publications, including trips to Iceland [HCC*13; HCG*15; ASG*18; ACGC20], Tenerife [PWB*12; PTB*13], the USA [ACGB18; BCB*19; ACGC20], Chile [GKvW*14], and across the UK [BWG*11; PBC*17; BGG*18]. It has also been deployed in laboratory-based experiments to measure Martian meteorite samples [MGS*20].

6. Discussion and Conclusion

The AUPE system has evolved over a number of years and has become a robust and reliable tool for collecting PanCam-like data for the development of analysis tools and techniques whilst the PanCam flight instrument was developed. The system has been successfully deployed in Mars analogue field sites all over the world and contributed greatly to the development of image analysis tools and techniques in preparation for the ExoMars surface mission.

The development and manufacture of PanCam has now been completed and there are now multiple flight like models available for many testing applications going forward. However the high value and lower robustness of these models means they are unlikely to be used in remote field deployments and so the AUPE system will continue to be valuable for these applications. AUPE will also be valuable for training of staff who will operate the PanCam instrument during the ExoMars surface mission. To aid this application the ACLI interface will be updated to accept activity plans in the same format used to command image sequences on Mars. In this role it is expected that AUPE will be used at least until the beginning of the surface mission in 2030.

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Glossary

ACE	Aberystwyth Camera Environment
ACLI	AUPE Command Line Interface
AUPE	Aberystwyth University PanCam Emulator
DN	Digital Number
DQ	Data Quality
HRC	High Resolution Camera
OB	Optical Bench
PTU	Pan-Tilt Unit
RCP	Radiometric Calibration Processor
WAC	Wide Angle Camera

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