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The Close-Up Imager (CLUPI) on board the ESA ExoMars Rover: Objectives, description, operations, and science validation activities

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Running title: CLUPI instrument onboard ESA ExoMars Rover

Abstract

The Close-UP Imager CLUPI on board the ESA ExoMars Rover is a powerful high-resolution colour camera specifically designed for close-up observations. Its accommodation on the movable drill allows multiple positioning. The main science objectives are the geological characterization of rocks in terms of texture and colour and the search for potential morphological biosignatures. We present the CLUPI science objectives, performance, and technical description, followed by a description of the instrument's planned operations strategy during the mission on Mars. CLUPI will contribute to the rover mission by surveying the geological environment, acquiring close-up images of outcrops, observing the drilling area, inspecting the top portion of the drill borehole (and deposited fines), monitoring drilling operations, and imaging samples collected by the drill. A status of the current development and planned science validation activities is also given.

1. Introduction

Following on the exploration successes of NASA's 2003 Mars Exploration Rovers (Spirit and Opportunity) and 2011 Mars Science Laboratory (Curiosity), ESA will contribute to advance our further understanding of Mars with the launch of the 2020 ExoMars Rover.

ExoMars (e.g. Vago et al., 2013) is a collaboration programme between ESA and Roscosmos consisting of two missions, ExoMars 2016 and ExoMars 2020.

ExoMars 2016, was launched on Mars 14th 2016 (e.g. Witasse et al., 2014), consists of a Trace Gas Orbiter (TGO) plus an Entry, Descent and Landing Demonstrator Module (EDM, or Schiaparelli lander) that will land in Meridiani Planum. ExoMars 2020 will land a rover and an instrumented surface platform on Mars.

The ExoMars objectives are two-fold: (i) a technology demonstration, with entry, descent, and landing of a payload on the surface of Mars, surface mobility with a rover, access to the subsurface to acquire samples, sample acquisition, preparation, distribution and analysis, and (ii) scientific investigations aimed at the search for signs of past and present life on Mars, the study of how the water and geochemical environments vary with subsurface depth (up to a few meters), and the analysis of Martian atmospheric trace gases and the identification of their sources.

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6 The ExoMars Rover has a nominal mission duration of 218 sols (approximately
7 seven months). The rover is equipped with a drill for subsurface sample
8 collection. It also includes a complete suite of instruments named Pasteur (after
9 the microbiologist Louis Pasteur): PanCam (Panoramic Camera, two Wide Angle
10 Cameras WACs and a High Resolution Camera HRC), CLUPI (Close-UP
11 Imager), ISEM (Infrared Spectrometer for ExoMars), WISDOM (a ground-
12 penetrating radar), Adron (a neutron detector for determining subsurface
13 hydration), Ma_MISS (Mars Multispectral Imager for Subsurface Studies),
14 MicrOmega (Vis-IR imaging spectrometer for mineralogy studies), RLS (Raman
15 Spectrometer), and MOMA (Mars Organic Molecule Analyser).
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30 In this paper, we focus on the CLUPI instrument, which is being developed
31 through international and multi-disciplinary science and technical teams, as
32 illustrated in Fig. 1. The CLUPI instrument is being developed by a Swiss-French
33 consortium supported by the Swiss Space Office and the French Space Agency
34 CNES under the PI (Principal Investigator) leadership of Jean-Luc Josset with
35 Frances Westall and Beda Hofmann as Co-PIs. The Science Team consists of
36 scientists from Europe, Canada, and New Zealand having a broad range of
37 expertise, including biosignature recognition, geology, microbiology and
38 geomorphology, as well as technical aspects related to CLUPI operations.
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<Figure 1 here >

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9 The following sections describe CLUPI's science objectives and performances,
10 design, operations, as well as its development status and planned science
11 validation activities.
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15 16 17 18 2. CLUPI science objectives and performances 19

20 21 2.1. Science objectives 22

23 CLUPI is a camera system designed to acquire high-resolution, colour, close-up
24 images of outcrops, rocks, soils, drill fines, and drill core samples. The visual
25 information obtained by CLUPI will be similar to what geologists would obtain
26 using a hand lens.
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32 CLUPI will acquire images of rock and unconsolidated materials including dust,
33 regolith, and float rocks (i.e. unattached rocks) with field of views (FOV) ranging
34 from 1.9 cm x 1.3 cm at 10 cm distance from the target (7 $\mu\text{m}/\text{pixel}$ resolution) to,
35 for instance, 104.4 cm x 44.4 cm at 500 cm distance (resolution 394 $\mu\text{m}/\text{pixel}$).
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42 These images will provide visual information of structure and texture of the
43 above-mentioned materials and, specifically, of *in situ* rocks in order to establish
44 rock type, facies, and context stratigraphy in the area of study with the primary
45 aim of interpreting the environment of formation/deposition of the rocks and,
46 thus, the potential habitable paleo-environment. The CLUPI images will
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60 complement those provided by PanCam, thus giving the all-important, detailed

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6 context necessary for aiding interpretation of mineralogy and potential organic
7 biosignature identification, as well as determining drill site location.
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10 In detail, the kinds of essential information that CLUPI can provide to interpret
11 rock type and mode of formation include features related to the individual
12 minerals making up the rocks and textural features related to rock formation.
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15 Furthermore, suitable morphological biosignatures could also be imaged.
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17 For environmental interpretation, it is important to distinguish primary features
18 from secondary features. The former relate to the original rock and its
19 environment of formation while the latter are produced by processes acting at a
20 later stage on the rock. The secondary processes may occur relatively quickly
21 after the formation of the rock, for instance diagenetic changes to sediments
22 deposited in water or to volcanic rocks extruded into water, or they may occur
23 millions of years later due to major environmental changes and/or to external
24 events, such as impacts, later volcanic/hydrothermal events, subsurface fluid
25 migration, or mass wasting/erosional phenomena.
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41 CLUPI close-up colour images will be indispensable for identifying visible
42 minerals. While geochemical mineral identification will be made on powdered
43 core samples, thus losing context and original grain shape and size, CLUPI will
44 provide images of the minerals within their original context, enabling the grains to
45 be observed within their matrix as well as other features of importance for
46 interpreting the nature of a rock and its mode of formation, such as textural
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6 relationship of specific grain types to other types, frequency of occurrence of
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8 certain grain types, variability in grain sizes, specific patterns to grain size
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10 variability and roundness. Individual grains may be identified also on physical
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12 properties such as colour, shape, size, sorting, orientation, twinning, cleavage, and
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14 lustre.
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18 All this information will enable the geologists to distinguish for example a
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20 volcanic rock, such as a basalt, from a sedimentary rock, such as a conglomerate
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22 formed of basaltic fragments, or a sand or siltstone also formed of lithic volcanic
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24 fragments. With respect to sediments, the composition of the individual clasts and
25
26 their textural features are essential for interpreting the mode of formation, such as
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28 *in situ* brecciation, transport by physical mass wasting processes or by water
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30 (rivers, streams, current flow in larger bodies of water). Here, especially grain
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32 size, shape, and size distribution allow interpretation of transport mechanisms and
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34 their duration. Well-rounded clasts would indicate long transport or deposition in
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36 an agitated environment with much grain-to-grain contact and erosion. Angular
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38 clasts would indicate deposition close to the source of the clasts. Finer-grained
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40 sediments may indicate distal deposition, i.e. longer transport, or erosion of
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42 originally fine-grained, friable material. A good example of this kind of textural
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44 analysis is the sedimentological study of the conglomerates at Bradbury Rise in
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46 Gale Crater on Mars that showed fluvial transport at the time of deposition (~3.6
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48 Ga) (Williams et al., 2013).
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7 A particularly important objective of CLUPI is the search for morphological
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9 features that might potentially indicate the presence of biosignatures on outcrops
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11 and drill cores. Westall et al. (2015a) concluded that the lack of long-term
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13 habitability on Mars most likely precluded much evolution of life, with the result
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15 that Martian life probably remained in a very primitive state of evolution, having
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17 evolved no further than the chemotrophic stage. Chemotrophs are microorganisms
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19 that do not obtain their energy from sunlight – they can use redox couples
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21 including organic and/or inorganic species – their source of carbon comes either
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23 from organic carbon molecules or inorganic carbon, e.g. CO₂ dissolved in water
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25 (e.g. Westall et al., 2015a,b). Traces of such organisms may be preserved as
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27 mineralised replacements (microfossils) or as organic signatures in fine-grained,
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29 anaerobic sediments or cements (Westall and Cavalazzi, 2011). Comparison can
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31 be made with fossilised remains of these kinds of microorganisms in Mars-
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33 analogue, volcanic sediments dating back almost to Noachian (> 3.8 Ga) and
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35 certainly Hesperian (> 3.0 Ga) times, when life could have emerged and
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37 flourished at the surface of the planet. Fossilised anaerobic chemotrophs are very
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39 small, < 1µm, occur in colonies up to hundreds of µm in size and, where close to
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41 a significant source of nutrients, i.e. close to hydrothermal sources, can develop
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43 visible, carbon-rich (black) biofilms (Westall et al., 2011, 2015a,b). Although
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45 CLUPI may not be able to observe individual cells, it may be able to distinguish
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47 colonies of cells as dark carbonaceous clots and layers of colonies as biofilms. If
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6 morphological remains are not visible but a suggestive organic signature is
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8 present, the fine-scale context information provided by CLUPI will be absolutely
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10 essential to interpreting the putative signature. Typically, significant sample
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12 preparation, such as thin section preparation or etching of the rocks, is necessary
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14 to be able to image individual cells or their colonies with an optical microscope or
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16 scanning electron microscope. While stromatolites, resulting from the activity of
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18 photosynthetic organisms, may not be likely to be found on Mars, the mineralized
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20 remains of filamentous microbial colonies, typically resulting from the former
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22 activity of chemoautotrophs in both surface and subsurface environments, are
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24 additional biosignatures to look out for using CLUPI. Biofabrics of this type are
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26 observed in various palaeoenvironments on Earth (e.g., see Fig. 2), both in
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28 sedimentary and volcanic settings (Hofmann and Farmer, 2000; Hofmann et al.,
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30 2008; Hofmann 2011).

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32 In addition to these objectives, CLUPI will provide imagery that will aid the
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34 experiments of other instruments, for example, characterisation of present-day
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36 dust and fines, and support for sample extraction and initial handling.
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2.2 Performances

The camera's requirements (summarized in Table 1) have been selected to maximize the instrument's scientific output. CLUPI is an imager with the ability to focus from 10 cm to infinity. At a distance of 10 cm from the target object, the resolution of the images will be high – about 7 $\mu\text{m}/\text{pixel}$. Colour imaging is achieved using a detector with three layers of pixels (red, green, and blue). CLUPI will also have the possibility to perform z-stacking (or focus stacking) of images, when necessary, to increase the scientific return. Z-stacking is a processing technique that combines multiple images taken at different focus distances. The portions that are in focus are extracted to create a new, composite image that has a greater focal depth than any of the original individual images (illustrated in Fig. 3).

The instrument can also perform auto-exposure and auto-focus. Furthermore, binning (2 x 2 and 4 x 4) and windowing functionalities allow adapting the data volume to the available communications budget, i.e. sending a flexible amount of data.

< Figure 3 here >

< Table 1 here >

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6 In the following section we describe the technical aspects of the instrument in
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8 more detail.
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10 11 12 13 3. CLUPI instrument description

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15 The CLUPI camera is a miniaturized, low-power, efficient and highly adaptive
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17 imaging system having a mass of 932 g, with specific micro-technical innovations
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19 regarding its sensor and focus mechanism.
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23 The CLUPI imaging unit (Fig. 4) is the main element of the instrument. It handles
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25 image acquisition and processing. It comprises the optics plus focus mechanism,
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27 the instrument electronics, and the mechanical parts that include the mechanic
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29 interface, bracket, and housing. Contrary to detectors that use a Bayer filter for
30
31 colour acquisition, the CLUPI sensor is made of three layers of pixels (red, green,
32
33 and blue) that preserve spatial resolution better. The focus mechanism is based on
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35 flexible structures, so it does not need a stepper motor, lubrication or gears, and
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37 works without friction.
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41 CLUPI will be accommodated on the drill box of the rover. By using the degrees
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43 of freedom provided by both the rover and the drill box, CLUPI will be angled
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45 and raised so it can observe in a variety of viewing modes. The use of two fixed
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47 mirrors – one flat and one concave (Fig. 5) – will provide three FOV.
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51 The first mirror (or bracket mirror), fixed on the rover bracket that holds the drill
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53 when in stowed position, gives an image of 2652 x 1768 pixels (FOV 1). The
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7 second mirror (or drill mirror), fixed on the drill box near the front end of the box,
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9 splits the FOV into two parts: (i) the main part, 2652 x 1128 pixels (FOV 2), is
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11 not deflected and looks in the direction of the optical axis of CLUPI; (ii) the
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13 smaller part of the sensor, 2652 x 640 pixels (FOV 3), looks towards the drill tip.
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16 Fig. 6 and Fig. 7 illustrate the three FOV and accommodation of CLUPI.
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39 A calibration target (Fig. 5), developed and provided by Aberystwyth University
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41 in the frame of science collaboration agreement with the Space Exploration
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43 Institute, is used to colour calibrate images during science operations. It is
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45 mounted on the right rover bogie bracket, below the drill box, in a position that
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47 can be observed by CLUPI (see section 4.7).
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4. CLUPI scientific operations during the ExoMars mission

In order to achieve CLUPI's objectives and optimise the instrument's science return, science operations and specific related configurations have been designed by the scientific and technical team at the Space Exploration Institute (see CAD illustrations in Fig.6 to Fig.14). Both the rover's mobility and the drill's degrees of freedom are taken into account.

4.1. Geological environment survey

For the geological survey, CLUPI will observe the area immediately in front of the rover, using one of the fields of view – FOV 1.

This will allow for the characterisation of the physical properties (including hardness, induration, friability) and morphological features of rocks, such as outcrop structure, and fine-scaled features such as laminae, bedding, fractures, veins and voids, as well as textures of rocks and regolith and the morphology of surfaces. Texture categories include: grain and crystal sizes and their size distribution, grain forms, grain distribution within a matrix, crystal forms and their size distribution and interrelation; porosity and vesicularity and their sizes, morphology and distribution or infilling by secondary minerals; layering and lamination and texture of layers such as gradation, ripples, or cracks; internal texture of grains, such as occurring in ooids etc. These observations then allow to determine if the rock in question is of volcanic (such as lava, tephra or ash),

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7 aeolian (dune sediments, loess), fluvial (gravel, sands) or lacustrine/marine (such
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9 as fine-grained and/or laminated chemical deposits), subterranean (such as crack
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11 fillings) in origin or has been deposited as an impact breccia. Only then can critic
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13 questions, such as habitability and the possible presence of biosignatures (e.g.
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15 biologically induced deposit or a permineralised (fossilised) microbial mat, be
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17 discussed.
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21 In this mode the soil, and in particular the rover's track marks, can also be
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23 examined in great detail, thus allowing observation of grain size, soil consistency,
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25 and depth of the superficial oxidised layer. This close-up characterization of the
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27 surface is complementary to the PanCam WACs, whose resolution is lower and
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29 has a wider FOV. An excellent synergy exists between the images that can be
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31 captured by PanCam and CLUPI. The PanCam WACs provide observations at
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33 panoramic (tens of metres to sub-m) scale. The PanCam HRC can acquire images
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35 of relatively large areas. CLUPI allows zooming in and focusing on the critical
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37 cm to sub-mm range of observations. By carefully planning and nesting
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39 observations between these two instruments, it is possible to perform a very
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41 exhaustive visual examination of interesting targets.
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47 The Geological Environment Survey is performed while the drill is in stowed
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49 position, with CLUPI using the FOV 1 to look in front of the rover, as illustrated
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51 by Fig. 8.
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11 The characteristics of CLUPI images at various working distances for geological
12 environment survey are presented in Table 2.
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15 16 17 18 4.2. Close-up observation of outcrops 19

20 For close-up outcrop observation, CLUPI will look to the side, using another field
21 of view – FOV 2. In this mode, and by using the rover’s motion, CLUPI can be
22 panned across a rock surface to image its structure in 2D and 3D (the latter by
23 making use of highly overlapping images and structure-from-motion processing
24 techniques). With this observation mode, basic geological information on
25 outcrops is obtained, including rock texture and structure, possible secondary
26 alterations related to water and the effects of erosion. This will allow establishing
27 the geological history of targets as well appraising the potential preservation of
28 biosignatures.
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41 Moreover, imaging of the same target from different working distances (in
42 collaboration with PanCam), and thus at various resolutions, gives access to a
43 multiscale analysis, which can provide information about the target’s overall
44 morphology, structure, and texture down to its individual components.
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49 Complementary to PanCam WACs and HRC, CLUPI offers high resolution at
50 close distances and a specific capacity to observe outcrops. The various
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7 movements of the rover (forward, backward, turn left and right, sideway or
8 “crabbing”) and the two degrees of freedom of the drill when in a non-stowed
9 position (380 mm vertical movement and 360° rotation), along with the wide
10 range of working distances of CLUPI, allow imaging a large variety of outcrop
11 configurations with CLUPI FOV 2 at distances from ~65 cm to infinity (for
12 instance, the working distance in Fig. 9 is ~110 cm).
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28 The characteristics of CLUPI images for outcrop observation from various
29 distances are presented in Table 2.
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33 34 35 4.3. Drilling area observation

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37 While the study of outcrops is an important task for CLUPI, the subsurface
38 deposits are also of primary interest from a scientific point of view, specifically
39 for the analytical instruments. Although CLUPI could possibly observe and
40 identify morphological biosignatures on the scale of tens of microns, as noted
41 above, the kinds of organisms expected on Mars, if they existed at all (Westall et
42 al., 2015a) may not leave signatures that are morphologically visible. For this
43 reason, the emphasis for biosignature detection in the ExoMars mission is the
44 analysis of organics of potential biological origin. Such molecules are likely to be
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6 preserved only in the subsurface, below 1.5 m in depth, away from oxidants,
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8 ultraviolet light, and cosmic radiation damage. Thus, subsurface samples are the
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10 best with which to test the hypothesis of the existence of life on early Mars.
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13 Once the drilling area has been chosen, using its capacity for high-resolution
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15 survey of the geological environment, CLUPI can carry out its characterization
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17 prior to drilling under two configurations using the FOV 2.
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20 As the drill box is rotated, CLUPI can either be in a high position (incidence angle
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22 of $\sim 11^\circ$, Fig. 10) or in a low position (incidence angle of $\sim 18^\circ$, Fig. 11). In the
23
24 low position, it is able to help the characterisation of rocks and structures, such as
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26 crystals in igneous rocks, grain size and shape distribution and sorting, fine scale
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28 structure, fracture mineralization, secondary minerals, and soil particles. In the
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30 higher position, CLUPI can achieve a wider coverage, albeit with a somewhat
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32 lower resolution.
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49 The characteristics of CLUPI images for the drilling areas from both high and
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51 close-up distances are presented in Table 2.
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4.4. Drilling operation observation

Mars missions up to now have penetrated the subsurface to depths on the order of 10 cm. The extraction and analysis of subsurface samples whether from 0.5 m, 1 m, or 2 m depth has not been attempted so far. These kinds of subsurface samples can provide invaluable information about the subsurface geological composition, especially regarding traces of past life.

While the drilling operation is being performed, CLUPI's third field of view (FOV 3) can be used to monitor the process and observe the mound of fines that is generated. Colour and textural variations can be used to infer whether the drill has encountered a different type of material or deposit. FOV 3 can also be used to obtain information on the mechanical properties of the soil, such as grain size, shape, and cohesion.

This ability is complementary to that of the Ma_Miss instrument (borehole-side-facing IR spectrometer integrated in the drill rig). It can also be of use in case a problem arises during drilling (the MAHLI microscope on the Curiosity Rover detected wear on the metal wheels of the rover, thus critically aiding mission operations).

Fig. 12 describes the position of the drill for the drilling operation, and the CLUPI FOV in such a configuration.

< Figure 12 here >

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9 The characteristics of CLUPI images for the drilling operation are presented in
10 Table 2.
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16 4.5. Observation of the drilled core sample

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18 For the first time in Martian exploration, fresh samples from depths in the 0–2-m
19 range will be collected and analysed by several instruments after being delivered
20 to the Core Sample Transportation Mechanism (CSTM) —the small open box that
21 extends to receive a sample from the drill. CLUPI’s FOV 3 will be used to image
22 the collected core material prior to delivery to the rover’s analytical laboratory for
23 further processing and studies. Whereas the PanCam high-resolution camera can
24 obtain a total-view image of the core sample, only CLUPI can image the sample
25 at very high resolution. This will be important for recording sample shape, colour,
26 homogeneity, texture, vespicularity, and mineral grain size. This information can
27 then be used to compare the core sample with the general environment in the
28 rover sampling area, providing a valuable link between surface and subsurface
29 analyses. Once inside the rover’s laboratory, the sample is crushed, and only
30 crushed mineral grain assemblages can be observed and analysed.
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49 The visual examination of the sample (with CLUPI and PanCam) prior to
50 ingestion and crushing is possible because of the position of the drill after the
51 delivery of the drilled core sample to the CSTM, which allows the observation of
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6 the drawer's content from above (incidence 7.5°) at a distance of about 28.5 cm
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8 using the FOV 3 (see Fig. 13).
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13 < Figure 13 here >
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18 The characteristics of imaged drilled samples in the CSTM with CLUPI are
19 presented in Table 2.
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24 4.6. Observation of the drill hole (and deposited fines)

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26 Once the drilling operations have been completed and the sample has been
27 delivered, CLUPI's FOV 2 can be used to image the state of the surface after
28 drilling, the amount of dislodged fines, their colour and physical properties.
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30 Drill hole observations can be performed with the drill resuming the same tilted
31 position for imaging the sampling area prior to drilling (see section 4.3), from
32 both high and low positions (Fig. 10 and Fig. 11). With an optimal solar
33 illumination angle (ideally with light shining vertically into the hole, although the
34 drill itself may cause some shadowing), and depending on the mound of fines, it
35 may be possible to observe the walls to some depth within the hole (up to 10 cm
36 deep from the high position, and up to 6 cm deep from the low position), which
37 would add significant information on the first centimetres of subsurface layering,
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6 given that the drilled core sample will come from a greater depth than what can be
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8 observed with CLUPI.
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11 The characteristics of CLUPI images for the drill hole from both high and close-
12
13 up distances are presented in Table 2.
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16 17 18 4.7. In-situ calibration 19

20 In-situ calibration is performed by acquiring an image of the calibration target,
21
22 ideally at least once per operational sequence. The calibration target consists of
23
24 nine 6.5 mm diameter glass colour patches with their surfaces processed to obtain
25
26 a uniform diffuse reflectance. The absolute spectral reflectance and Bidirectional
27
28 Reflectance Distribution Function (BRDF) of each colour patch will be accurately
29
30 determined as part of the pre-launch calibration. The colours observed by CLUPI
31
32 on Mars, in combination with a knowledge of the relative illumination angle,
33
34 which can be determined from the shadow post, will allow CLUPI data to be
35
36 calibrated to provide true colour images and accurate reflectance measurements.
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38 During the mission the CLUPI calibration target will be protected from the worst
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40 of the Martian aeolian dust by the drill box and so is not expected to become
41
42 contaminated to the same extent as other calibration targets. Low levels of dust
43
44 contamination can be compensated for with numerical models.
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50 The calibration target will be located and observed as described in Fig. 14. Its
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52 surface is 25 mm x 25 mm, the height of the shadow post is 4.1 mm, and it has a
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6 mass of 4.5 g. CLUPI imaging of the calibration target will take place at an
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8 incidence angle of 19.5°.
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18 The characteristics of CLUPI images for the calibration operation are presented in
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20 Table 2.
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30 5. Development status and planned science validation activities

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32 An important part of an instrument development is its calibration, as well as the
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34 science validation activities. During phase B of CLUPI development, a CLUPI
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36 analogue instrument (same detector as the flight model) was used on several Mars
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38 analogue field campaigns, including AMASE (Arctic Mars Analogue Svalbard
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40 Expedition) in 2009, 2010 (e.g. Steele et al., 2011), 2011, 2013, and 2014 (the
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42 latest expedition having been in the Faroe Islands, e.g. Amundsen et al., 2016),
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44 SAFER (Sample Acquisition Field Experiment with a Rover) in 2013, and
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46 MINAR II and III in 2014 (Josset et al., 2014; Payler et al., in press). The CLUPI
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48 calibration target prototype (manufactured by Aberystwyth University) has been
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6 used during several field test campaigns (Fig. 15). Lab science validation
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8 activities have also been performed (Bost et al., 2015).
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18 The phase C/D of the CLUPI development started in July 2015. A control loop
19 through simulation for the focus mechanism is currently being developed and a
20 focal plane assembly is being tested at the Space Exploration Institutes premises
21 (Fig. 16).
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35 Planned activities with the next models include calibration (dark current, light
36 transfer/linearity, flat fielding, cosmetic defects, distortion, detector colour
37 calibration) and characterization (field of view, spatial resolution, depth of field),
38 as well as testing of the implemented functionalities (auto-exposure, autofocus,
39 binning, windowing, z-stacking).
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46 Training and rehearsal of CLUPI operations (see section 4) will also be performed
47 under controlled lighting conditions and using a geometric drill simulator (scale
48 1:1 to the ExoMars 2020 Rover, Fig. 17) for realistic geometrical configurations.
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11 A specific project aiming for using CLUPI images for the identification of rocks
12 by using the powder generated by the drill is also under discussion in
13 collaboration with the French Centre de Biophysique Moléculaire (Co-PI and Co-
14 investigator partnership).
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17 The CLUPI team is also working with the Rover Operation Control Centre
18 (ROCC), and future training and rehearsals of the camera's operations are
19 planned.
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30 6. Conclusion

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32 The CLUPI instrument on board the ESA ExoMars Rover is a powerful
33 miniaturized camera capable of providing high-resolution, close-up images in
34 colour of rocks, outcrops, drill fines, and drill core samples in an autonomous and
35 flexible way. CLUPI possesses many in-built functionalities (autofocus, auto-
36 exposure, binning, windowing, z-stacking) that can be used to ensure high-quality
37 images and adapt the data output to the available resources the rover can handle
38 during a particular observation cycle. CLUPI's implementation and operation
39 make the best possible use of the rover and drill motion capabilities. The
40 instrument is able to acquire images in several configurations, achieving a large
41 observational flexibility. CLUPI images will provide essential high-resolution
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7 complementarity to visual information obtained by PanCam and other instruments
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9 in the Pasteur payload.

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11 CLUPI's development entered phase C/D in July 2015 and calibration and science
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13 validation activities are on-going, both in field test campaigns and in the
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15 laboratory.
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23 Acknowledgements

24
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27 PRODEX Office, and the contribution from the French Space Agency CNES.
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35 Author Disclosure Statement

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37 No competing financial interests exist.
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Table 1. Main characteristics of the CLUPI instrument

Specification	Value
Detector type	Full colour APS (Active Pixel Sensor)
Image dimension	2652 x 1768 x 3 pixels in colour
Pixel size	7.8 μm x 7.8 μm
Field of view (FOV)	14° \pm 2° diagonal (11.9° x 8.0°)
Image resolution / Viewed area	7 μm /pixel at 10 cm distance, viewed area 1.9 cm x 1.3 cm 39 μm /pixel at 50 cm distance, viewed area 10 cm x 7 cm 79 μm /pixel at 100 cm distance, viewed area 21 cm x 14 cm
Working distance	10 cm to infinity with variable focus
Focal length	Varying to take sharp images from 10 cm to infinity
Quantization	8 – 14 bits
Dynamic range	62 dB (sensor) quantified on up to 16 384 levels (14 bits)
Electrical interface	SpaceWire on LVDS
Exposure time	Up to 1024 seconds
Spectral range	400–700 nm
Electronic features	Sequencer, Converter, Internal buffer, Internal clock of 40 MHz, SpaceWire Data Coding

Data Processing	Automatic Exposure Time, Autofocusing, Binning 2x2 and 4x4, Z-stacking (between 2 and 16 images), Windowing
Data Storage	4 Gb
Max. mean power consumption	< 15 W incl. 20% margin (25 W when firing the launch lock)
Power lines	+ 28 V
Operating temperatures	-120°C to +30°C
Storage Temperatures	-120°C to +50°C
Environment	Compatible with ExoMars Rover 2020 Environment
Allocated Volume	170 mm× 80 mm ×100 mm
Mass of instrument	932 g

Table 2. Characteristics of CLUPI images under the different operations configurations

Operation	Working distance	Viewed area	Resolution	Depth of Field
Geological environment survey	10 cm	1.9 cm x 1.3 cm (2652 x 1768 pixels)	7 $\mu\text{m}/\text{pixel}$	0.12 cm
	50 cm	10.4 cm x 7.0 cm (2652 x 1768 pixels)	39 $\mu\text{m}/\text{pixel}$	1.6 cm
	100 cm	20.9 cm x 13.9 cm (2652 x 1768 pixels)	79 $\mu\text{m}/\text{pixel}$	5.9 cm
	111 cm	23.2 cm x 15.4 cm (2652 x 1768 pixels)	87 $\mu\text{m}/\text{pixel}$	7.1 cm
Close-up outcrops observation	65 cm	13.6 cm x 5.8 cm (2652 x 1128 pixels)	51 $\mu\text{m}/\text{pixel}$	2.7 cm
	85 cm	17.7 cm x 7.5 cm (2652 x 1128 pixels)	67 $\mu\text{m}/\text{pixel}$	4.4 cm
	110 cm	23.0 cm x 9.8 cm (2652 x 1128 pixels)	87 $\mu\text{m}/\text{pixel}$	7.1 cm
	155 cm	32.4 cm x 13.8 cm (2652 x 1128 pixels)	122 $\mu\text{m}/\text{pixel}$	13.7 cm

	200 cm	41.7 cm x 17.8 cm (2652 x 1128 pixels)	157 $\mu\text{m}/\text{pixel}$	22.5 cm
	500 cm	104.4 cm x 44.4 cm (2652 x 1128 pixels)	394 $\mu\text{m}/\text{pixel}$	135 cm
Drilling area / drill hole observation	50 cm	10.4 cm x 4.4 cm (2652 x 1128 pixels)	39 $\mu\text{m}/\text{pixel}$	1.6 cm
	16.5 cm	3.4 cm x 1.5 cm (2652 x 1128 pixels)	13 $\mu\text{m}/\text{pixel}$	0.25 cm
Drilling operation observation	24 cm	5.0 cm x 3 cm (2652 x 640 pixels)	19 $\mu\text{m}/\text{pixel}$	0.4 cm
Drilled core sample observation	28.5 cm	5.9 cm x 3.2 cm (2652 x 640 pixels)	22 $\mu\text{m}/\text{pixel}$	0.6 cm
Calibration	26.5 cm	5.5 cm x 2.4 cm (2652 x 1128 pixels)	21 $\mu\text{m}/\text{pixel}$	0.5 cm

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11 FIG.1. CLUPI working team organisation.
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16 FIG.2. Filamentous fabric consisting of microcrystalline quartz formed by
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18 mineralization of filamentous microbes in a cavity of a basalt. Ballina, New South
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20 Wales, Australia. Field of view is 25 mm (image acquired with CLUPI analogue
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22 test model).
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28 FIG.3. Illustration of the z-stacking processing: individual images with different
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30 sharp areas (small pictures on the left), and the resultant overall sharp image after
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32 processing (large picture on the right). The ten original images were acquired with
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34 a CLUPI-analogue camera during the AMASE 2014 campaign in Tindhólmur,
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36 Faroe Islands, at 38 cm working distance, and the processed image (about 10 cm
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38 wide) results from focus stacking experiments by Joanneum Research.
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44 FIG.4. CLUPI imaging unit (CAD © Space Exploration Institute).
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49 FIG.5. CLUPI, bracket mirror (a), drill mirror (b), and calibration target (c).
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7 FIG.6. CLUPI mirrors accommodation (the 1st and 2nd mirrors refer to the bracket
8 mirror and the drill mirror respectively) with the corresponding FOV when the
9 drill is in stowed position (a) and in non-stowed position (b).
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16 FIG.7. Definition of the three fields of view (FOV) of CLUPI.
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21 FIG.8. Drill in stowed position (a) and CLUPI FOV 1 looking at the surface in
22 front of the rover (the tiles are squares of 12.5 mm x 12.5 mm projected on the
23 surface) (b).
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30 FIG.9. Drill high (a) (b) and low (c) positions for close-up observation of
31 outcrops, and CLUPI FOV 2 looking at an outcrop on the side of the rover in the
32 non-stowed position (d).
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40 FIG.10. Drill high position during drilling area observation (a) and corresponding
41 CLUPI FOV 2 (the blue circle, corresponding to the prospective drill hole, is 2 cm
42 in diameter and tiles are squares of 12.5 mm x 12.5 mm projected on the surface).
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49 FIG.11. Drill low position during drilling area observation (a) and corresponding
50 CLUPI FOV 2 (the blue circle, corresponding to the future drill hole, is 2 cm in
51 diameter and tiles are squares of 12.5 mm x 12.5 mm projected on the surface).
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9 FIG.12. Drill position during drilling operation observation (a) and CLUPI FOV 3
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11 looking at the fines during the drilling (b).
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16 FIG.13. Drill position for the drilled core sample observations (a) and CLUPI
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18 FOV 3 looking at the drilled core sample in the CSTM (b).
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23 FIG.14. Drill position during calibration (a), and calibration target for CLUPI in
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25 the FOV 2 with accommodation on the rover (b).
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30 FIG.15. Examples of pictures with the CLUPI calibration target prototype (2.5 cm
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32 x 2.5 cm) during the AMASE 2014 campaign (a) and MINAR III (b).
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37 FIG.16. CLUPI focus mechanism breadboard developed and assembled at the
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39 Space Exploration Institute (a) and focal plane assembly breadboard (b)
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41 developed by Ruag Space.
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46 FIG.17. Geometric drill simulator corresponding to the ExoMars 2020 Rover
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48 mission (scale 1:1) built at the Space Exploration Institute premises.
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