CLUPI FM
Geometric Calibration
ESTEC
29th-30th June 2019
Version 0.1

Written by	***Responsibility*** + handwritten signature if no electronic workflow tool
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CHANGE RECORDS

ISSUE	DATE	§ CHANGE RECORDS	AUTHOR
D0	2019-07-25	Initial version	Caballo-Perucha
D1	2019-08-05	Results of Martian meteorite data added	Caballo-Perucha

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1 OVERVIEW

1.1 SCOPE

This document describes the geometric calibration of the CLUPI sensor, held at ESTEC (Noordwijk, Holland) on 29th-30th June 2019. The first part of this document is focussed on the acquisition of images in order to calculate CLUPI intrinsic parameters (distortion coefficients, coordinates of the principal point and focal length) and affine transformations between several focus distances (FDs). The second part of this document is dedicated to the calibration results. For calibration, a target had been designed and generated by JR. The whole calibration campaign took place in a clean room at ESTEC in June 2019, to fulfil planetary protection requirements. The last chapter describes the methodology used for a real Martian meteorite data set.

1.2 BACKGROUND

In order to calibrate CLUPI, a triple-scale calibration target was designed by JR. The dimension of the target (420x297 mm) and the different sizes of its dots were calculated considering the sensor FOV and the different spatial resolutions at its working distances on Mars. A total number of 1270 black dots were arranged in three different points´ sizes, as displayed in Figure 1. The calibration target was printed on A3 paper and glued to a rigid plate to avoid deformations.

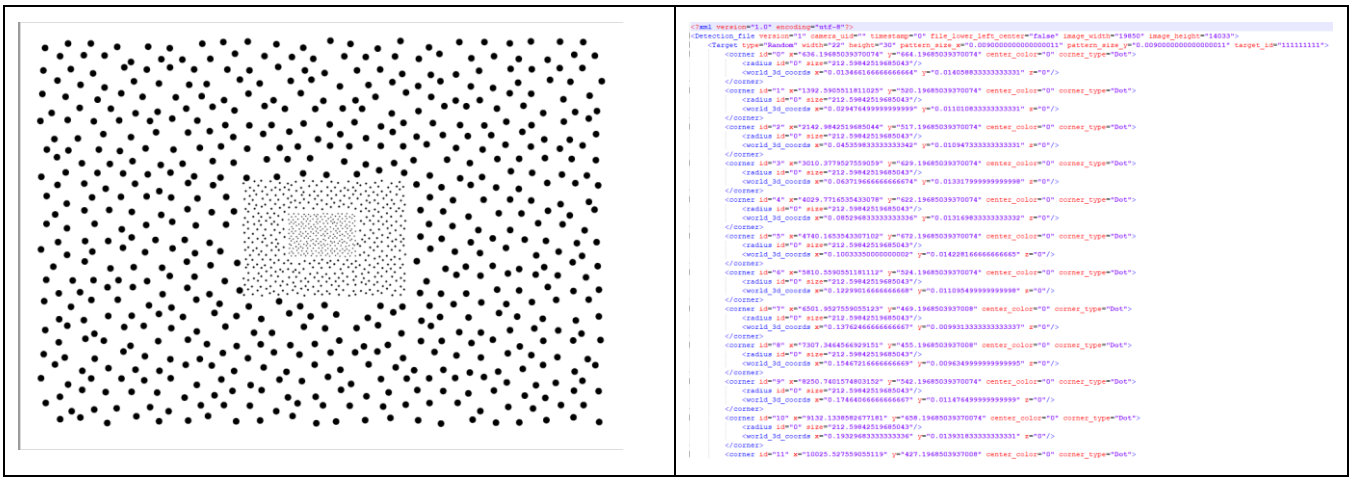


Figure 1.- Left: CLUPI_A3_20190305.pdf file. Right: CLUPI_A3_20190305.xml file containing the 2d and 3d coordinates of the dots.

1.3 DOCUMENTS

The following documents are referenced for supporting information and are referred to as [RD xx] in the text:

	DESCRIPTION
RD-1	Open CV Distortion Coefficients
RD-2	
RD-3	
RD-4	
RD-5	

RD-6	
RD-7	

1.4 ACRONYMS AND ABBREVIATIONS

CLUPI CLose-UP Imager
FD Focus Distance
JR Joanneum Research
…..

2 GEOMETRIC CALIBRATION: IMAGES ACQUISITION

The acquisition of the images required to calculate the intrinsic parameters of CLUPI (distortion coefficients, coordinates of the principal point and focal length) was done taking into account the different focus distances to be used on Mars, namely: close range for near objects (28 cm), middle range (100 cm) and infinity (250 cm). For each one of these 3 focus distances approximately 80 images of the calibration target in different positions were taken. Figure 2 shows the sensor-target configuration at 28 cm in the clean room at ESTEC.

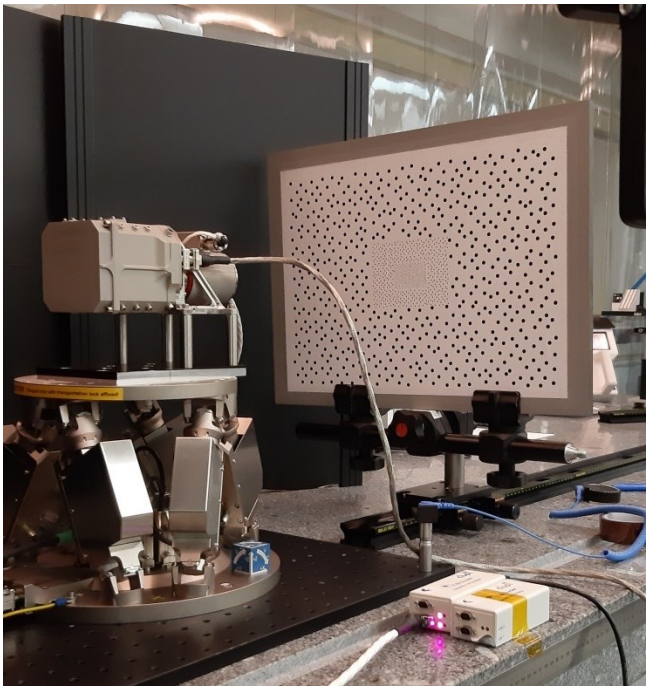


Figure 2.- Acquisition of the JR calibration target with CLUPI FD = 28 cm.

The original images were 16 bit RGB with an image size of 2652x1768 pixels. Just the images in the red channel were used for calibration and later reduced to 8 bit[1].

Following figures (Figure 3-Figure 5) display the thumbnails of the images taken at FD= 28 cm (152 microns focus motor setting), FD= 100 cm (2126 microns) and FD = 250 cm (2656 microns):

[1] Later analysis may reveal chromatic aberration effects from this data set

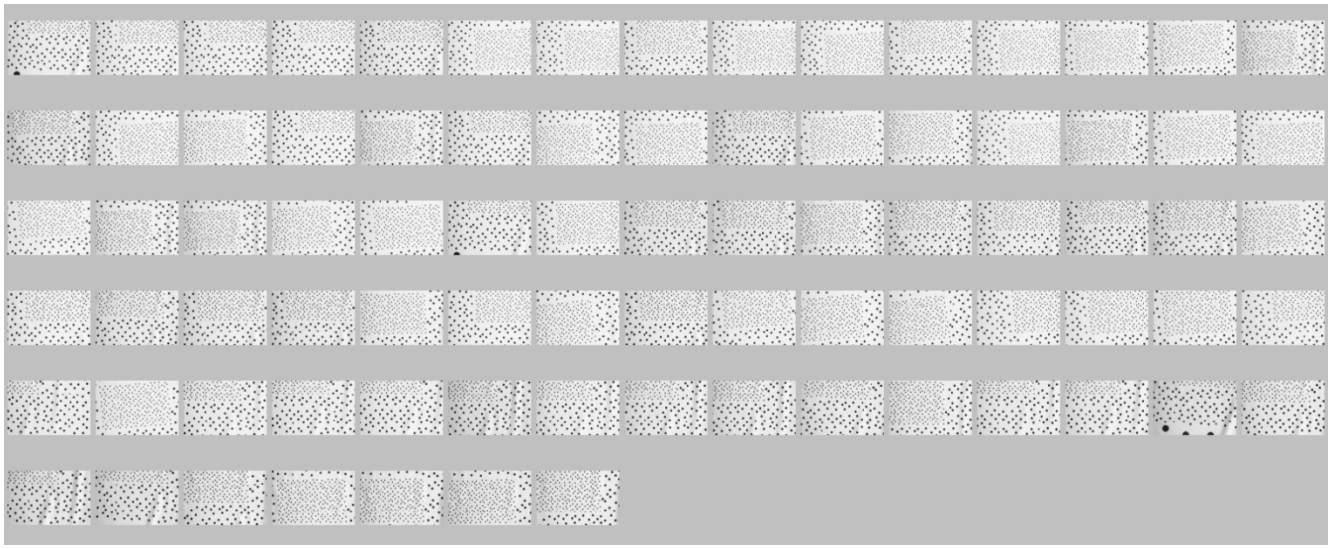


Figure 3.- 82 images of the JR calibration target taken at FD= 28 cm. The smallest and medium sized dots were kept mainly within CLUPI FOV.

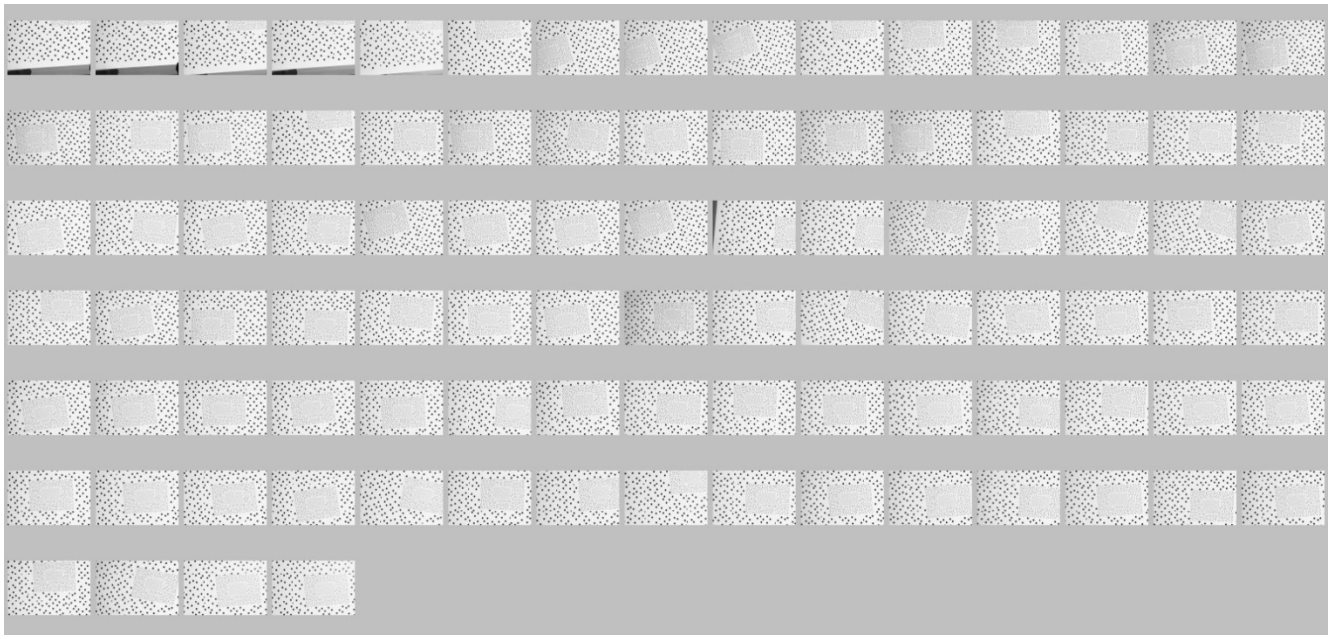


Figure 4.- 94 images of the JR calibration target taken at FD= 100 cm. The biggest and medium sized dots were kept mainly within CLUPI FOV.

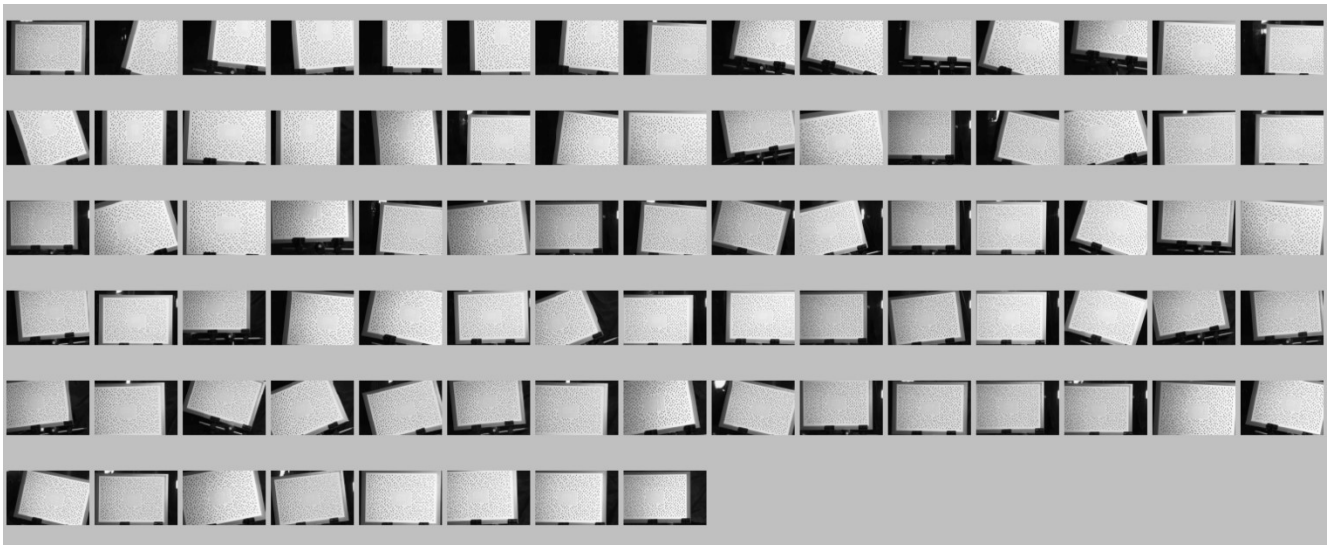


Figure 5.- 83 images of the JR calibration target taken at FD= 250 cm. The biggest sized dots were kept mainly within CLUPI FOV.

3 FOCUS STACKING: IMAGES ACQUISITION

For the computation of the affine transformations between successive FDs, several images of the calibration target at fixed positions were taken. The FDs used (centimetres and microns) are shown in Table 1 (central and right columns). The left column displays the fixed distances set at each FD sequence between CLUPI and the calibration target.

d	WDs	Focus travel
27.0 cm	26.3 cm to 27.3 cm	-24 um to 84 um
28.0 cm	27.3 cm to 28.8 cm	84 um to 230 um
30.0 cm	28.6 cm to 31.5 cm	212 um to 457 um
32.5 cm	31.1 cm to 33.9 cm	426 um to 628 um
59.0 cm	55.5 cm to 62.5 cm	1498 um to 1654 um
68.0 cm	61.0 cm to 75.0 cm	1623 um to 1862 um
80.0 cm	73.0 cm to 87.0 cm	1833 um to 2009 um
100 cm	86.0 cm to 114.0 cm	1998 um to 2232 um
120 cm	106.0 cm to 134.0 cm	2176 um to 2342 um
150 cm	129.0 cm to 171.0 cm	2318 um to 2484 um

Table 1.-Left: fixed distances between CLUPI and the calibration target. Right and centre: Focus distances (cm and microns) used for images acquisition.

The images taken at FDs between -24 and 628 microns are exemplarily displayed in Figure 6. The calibration target was placed at 27, 28, 30 and 32.5 cm from CLUPI.

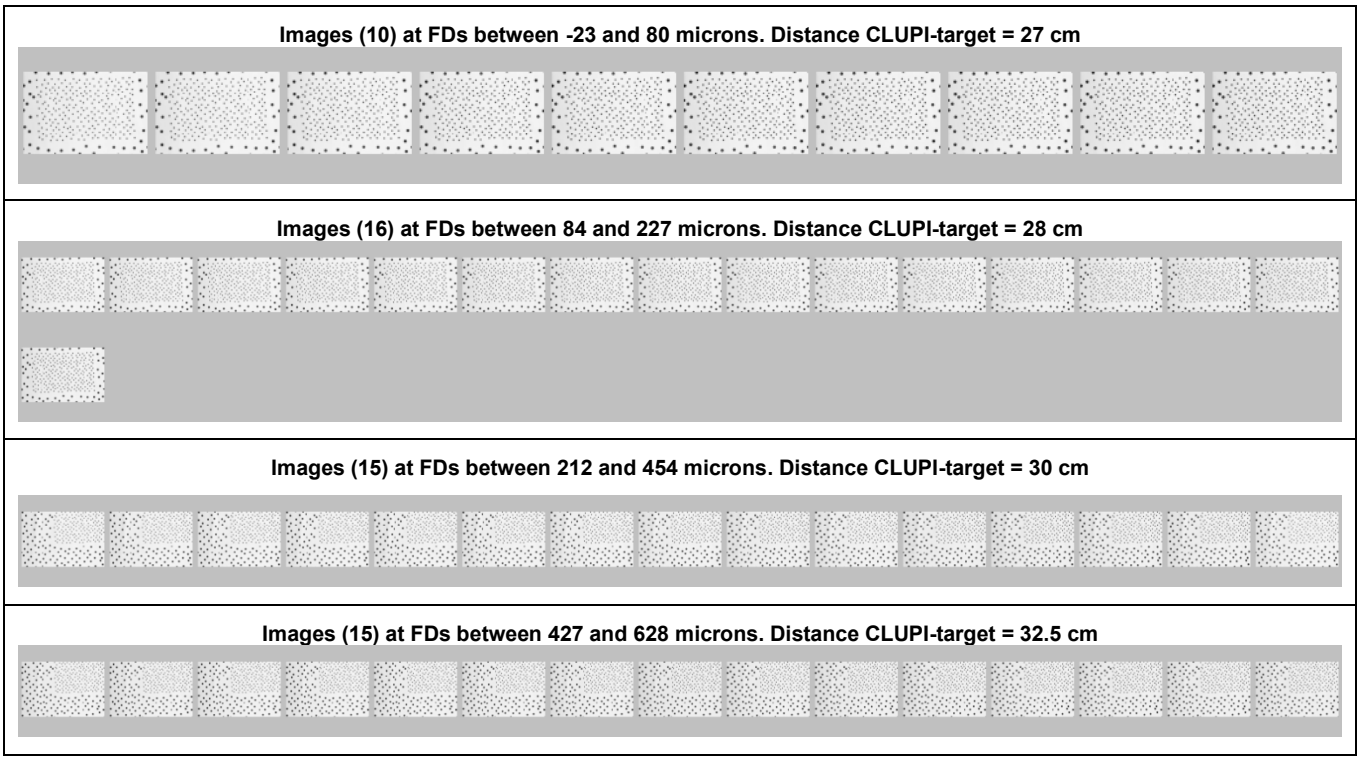


Figure 6.-Images of the JR calibration target taken with CLUPI at FDs between -24 and 628 microns FD motor setting.

The images taken with FDs between 1496 and 2009 microns are displayed below (Figure 7). The calibration target was placed at 59, 68 and 80 cm from CLUPI.

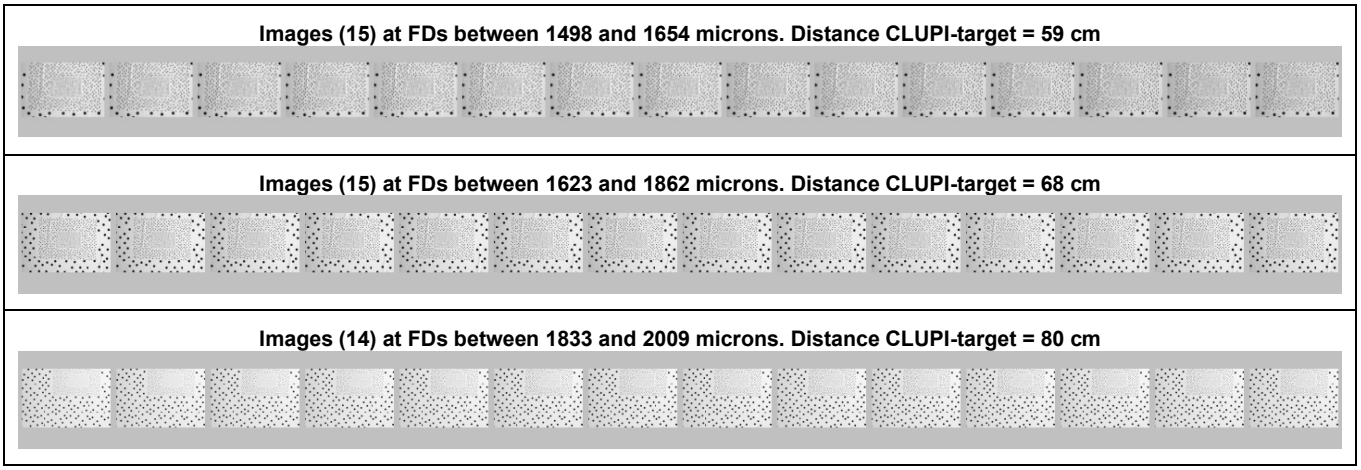


Figure 7.- Images of the JR calibration target taken with CLUPI at FDs between 1498 and 2009 microns.

The images taken at FDs between 1998 and 2484 microns are displayed in Figure 8. The calibration target was placed at 100, 120 and 150 cm from CLUPI.

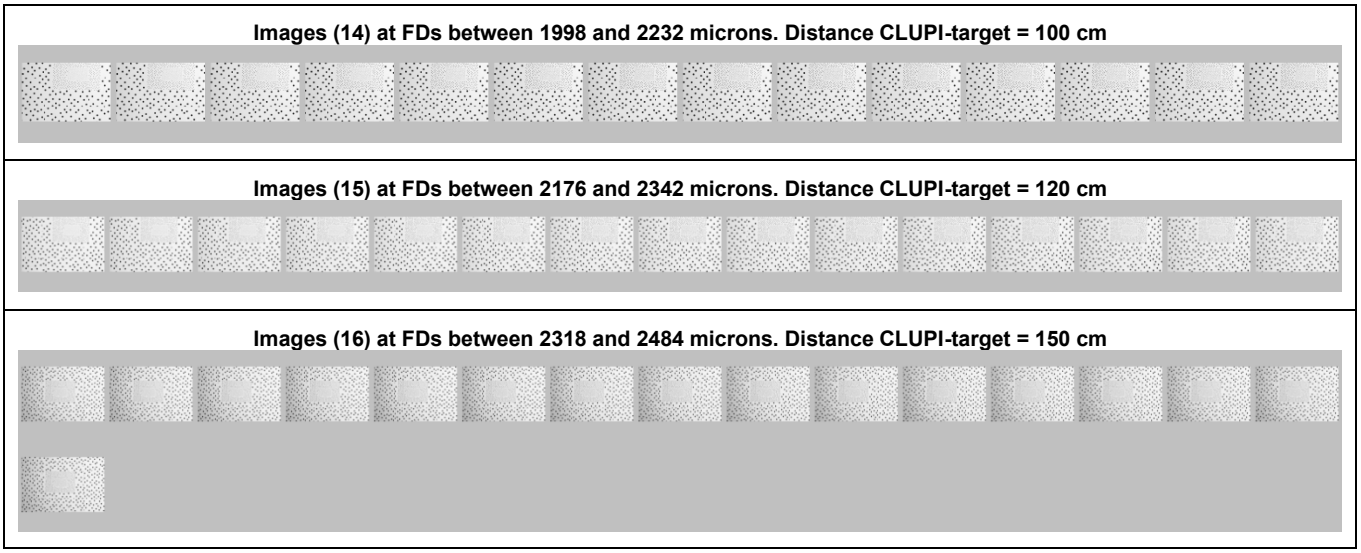


Figure 8.-Images of the JR calibration target taken with CLUPI at FDs between 1998 and 2484 microns.

4 GEOMETRIC CALIBRATION RESULTS

Following Table 2 displays the obtained CLUPI FM intrinsic camera parameters for each focus distance (28, 100 and 250 cm). The intrinsic camera parameters are namely: the focal length (pixels), the coordinates of the principal point (pixels) and the lens distortion coefficients. The resulting RMS errors can also be seen in this table.

CLUPI_FM_FD_028_Ceres_2iter_RD.xml

```
<?xml version="1.0" encoding="utf-8"?>
<calibration_file version="2">
    <camera type="CLUPI_FM" device_uid="FD_028">
        <image_size>2652 1768</image_size>
        <components>1</components>
        <minimum>0</minimum>
        <maximum>255</maximum>
    </camera>
    <monocular_calib device_uid="FD_028">
        <time>2019-Jul-03 09:52:58</time>
        <focal_length>13616.126338849 13616.126338849</focal_length>
        <principal_point>1048.9536340664 693.43003744259</principal_point>
        <distortion>0.90795278846644 -0.81549917806834 -0.015467154966426 -0.024081314487023 -0.021714843651652 0 0 0 </distortion>
        <n_images>82</n_images>
        <rms_err>0.57800891212241</rms_err>
    </monocular_calib>
</calibration_file>
```

CLUPI_FM_FD_100_Ceres_2iter_RD.xml

```
<?xml version="1.0" encoding="utf-8"?>
<calibration_file version="2">
    <camera type="CLUPI_FM" device_uid="FD_100">
        <image_size>2652 1768</image_size>
        <components>1</components>
        <minimum>0</minimum>
        <maximum>255</maximum>
    </camera>
    <monocular_calib device_uid="FD_100">
        <time>2019-Jul-03 11:31:38</time>
        <focal_length>12979.313699206 12979.313699206</focal_length>
        <principal_point>1059.0009439107 716.27511432891</principal_point>
        <distortion>0.82640045036451 -0.80990580903775 -0.013565578400063 -0.024481529915831 -0.020481752564741 0 0 0 </distortion>
        <n_images>94</n_images>
        <rms_err>0.31021374148287</rms_err>
    </monocular_calib>
</calibration_file>
```

CLUPI_FM_FD_250_Ceres_2iter_RD.xml

```
<?xml version="1.0" encoding="utf-8"?>
<calibration_file version="2">
    <camera type="CLUPI_FM" device_uid="FD_250">
        <image_size>2652 1768</image_size>
        <components>1</components>
        <minimum>0</minimum>
        <maximum>255</maximum>
    </camera>
    <monocular_calib device_uid="FD_250">
        <time>2019-Jul-03 11:59:51</time>
        <focal_length>13167.381556084 13167.381556084</focal_length>
        <principal_point>1488.0073428712 1090.7177140844</principal_point>
        <distortion>0.84478595905046 -0.77452686325751 0.016311335023569 0.013922403608605 0.040406969232604 0 0 0 </distortion>
        <n_images>82</n_images>
        <rms_err>0.31153269805449</rms_err>
    </monocular_calib>
</calibration_file>
```

Table 2.- Obtained CLUPI FM intrinsic parameters for the focus distances 28 (top), 100 (centre) and 250 (bottom) cm. The resulting RMS error (pixels) is also displayed.

The five distortion coefficients correspond to the radial and tangential lenses distortion as in the formula below [RD-1]:

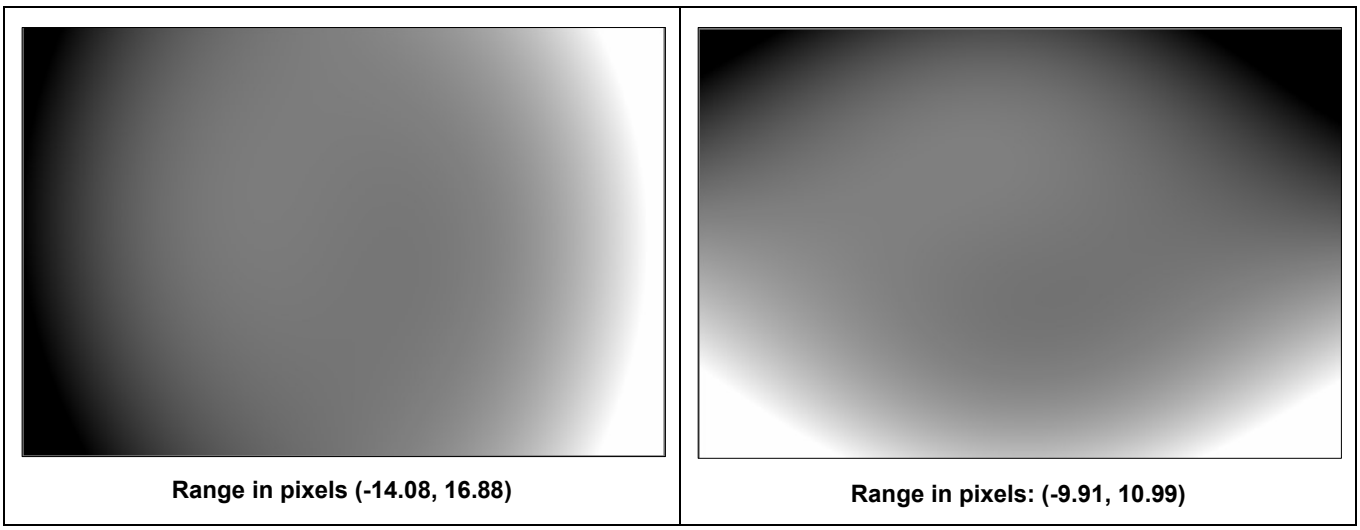
$$Distortion\_Coefficients = (k_1, k_2, p_1, p_2, k_3),$$

where: k_1, k_2, k_3 are the coefficients of the radial distortion and p_1, p_2 of the tangential one.

The distortion correcting images for each focus distance can be seen in Figure 9. The images represent the warping values (pixels, in horizontal and vertical direction) to be applied to the

acquired images in order to correct them from lens distortion. Dark values correspond to negative values and vice versa.

Horizontal distortion correcting image	Vertical distortion correcting image
FD= 28 cm	
	
Range in pixels (-16,76, 11.61)	**Range in pixels (-10,82, 10.52)**
FD= 100 cm	
	
Range in pixels (-11.33, 10.89)	**Range in pixels (-17.51, 10.45)**
FD= 250 cm	



Range in pixels (-14.08, 16.88)

Range in pixels: (-9.91, 10.99)

Figure 9.- CLUPI FM distortion correcting images for focus distances 28 cm (top), 100 cm (centre) and 250cm (bottom) for the horizontal and vertical directions.

Figure 10 shows an example where original and corrected images are superposed. The difference of the pixel coordinates of target dots in the images can be recognised.

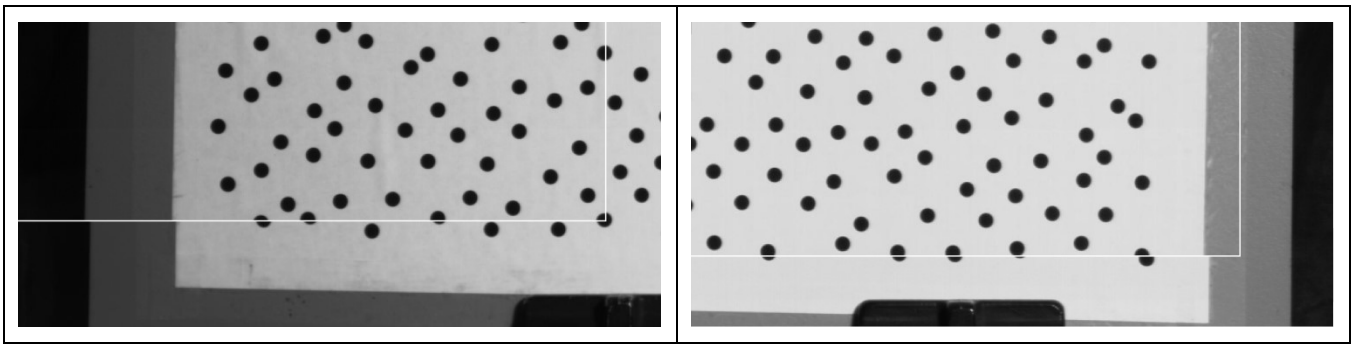


Figure 10.- Comparison between the original CLUPI FM image "20190630_153328_RPMCL005_100ms_+2653um_Red.jpg" and the same image corrected from distortion "20190630_153328_RPMCL005_100ms_+2653um_Red_dist_corr.jpg", set as background.

5 FOCUS STACKING RESULTS

The resulting affine transformations were saved in *.t2d files. An example of the affine transformation between 1645 and 1499 microns can be seen on the left side of Table 3:

1645_um_1499_um.t2d [method] mt=Affine2D [tiltmatrix] c00=1.003087 c10=-0.000017 c20=-4.137172 c01=0.000001 c11=1.003054 c21=-2.557282	$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} a1 & a2 \\ a3 & a4 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} b1 \\ b2 \end{bmatrix}$ c00 = a1 c10 = a2 c20 = b1 c01 = a3 c11 = a4 c21 = b2

Table 3.- Left: file example of an affine transformation between FDs 1645 and 1499. Right: affine transformation formula and equivalences to *.t2d file parameters.

Figure 11 (right side) displays the calculated changes in the 2d coordinates of a hypothetical principal point (red cross, centred in the image) along the modifications of the FD, i.e.; between 1643 and 1863 microns. On the left side of Figure 11, the steady increment (almost linear) of the calculated values of the x/y translation in the affine transformations between 1643 and 1863 microns can be seen.

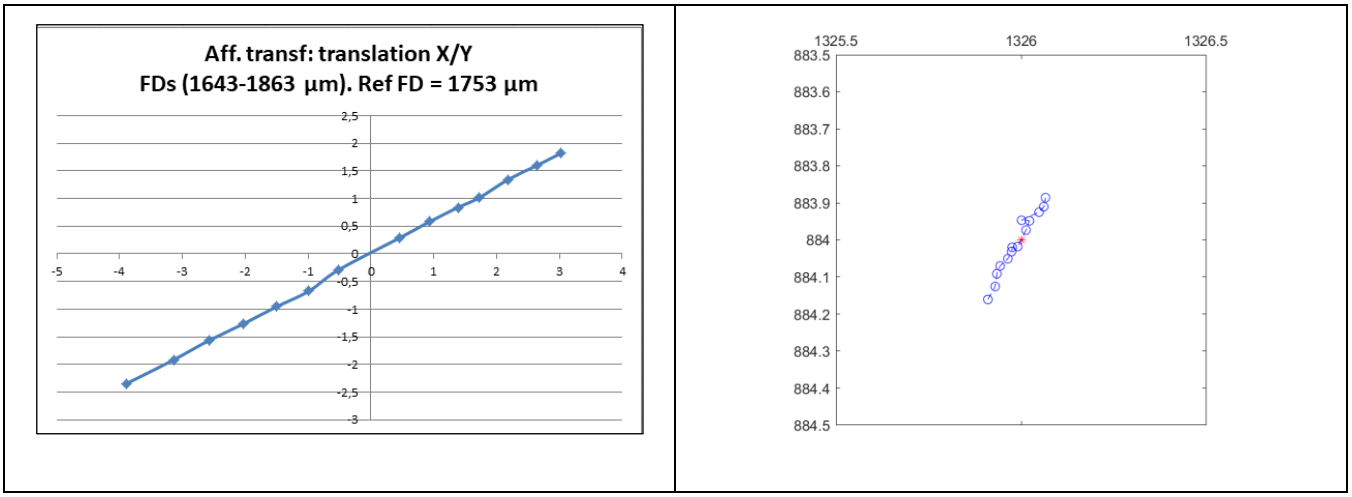


Figure 11.-Left: changes in the x/y translation values of the affine transformations between FDs: 1643-1863 microns. Right: modification of the coordinates (blue circles) of a hypothetical principal point centred in the image (red cross) along the FDs (1643-1863 microns).

Table 4, Table 5 and Table 6 represent all affine transformations calculated between CLUPI FDs, where several stacks between affine transformations were required. The transformations for the working distances 26.5-33.9 cm transform each FD into the one taken as reference, i.e. FD= 152 microns (28 cm), where the distortion parameters are known. In the same way, the transformations for the working distances 86.0-171.0 cm transform each

FD into FD= 2126 microns (100 cm) where the distortion parameters were also computed. However, the transformations for the working distances 55.5-87.0 cm transform the FDs into FD= 1753 microns (approximately 70 cm) where the distortion parameters are **unknown** because no full calibration was carried out. Interpolation using surrounding data sets will be subject of future analysis not immediately bound to the campaign exploitation & data validation as described here and contained in the initial data acquisition campaign[2].

152_um_000_um.t2d	152_um_004_um.t2d	152_um_-012_um.t2d	152_um_016_um.t2d
152_um_-023_um.t2d	152_um_035_um.t2d	152_um_055_um.t2d	152_um_062_um.t2d
152_um_071_um.t2d	152_um_084_um.t2d	152_um_096_um.t2d	152_um_105_um.t2d
152_um_112_um.t2d	152_um_119_um.t2d	152_um_131_um.t2d	152_um_141_um.t2d
152_um_163_um.t2d	152_um_175_um.t2d	152_um_184_um.t2d	152_um_194_um.t2d
152_um_199_um.t2d	152_um_213_um.t2d	152_um_218_um.t2d	152_um_227_um.t2d
152_um_245_um.t2d	152_um_270_um.t2d	152_um_287_um.t2d	152_um_304_um.t2d
152_um_323_um.t2d	152_um_337_um.t2d	152_um_347_um.t2d	152_um_372_um.t2d
152_um_392_um.t2d	152_um_404_um.t2d	152_um_428_um.t2d	152_um_443_um.t2d
152_um_454_um.t2d	152_um_476_um.t2d	152_um_490_um.t2d	152_um_500_um.t2d
152_um_519_um.t2d	152_um_535_um.t2d	152_um_546_um.t2d	152_um_548_um.t2d
152_um_572_um.t2d	152_um_590_um.t2d	152_um_602_um.t2d	152_um_615_um.t2d
152_um_629_um.t2d			

Table 4.-Resulting affine transformations (49) between FDs -23 and 615 microns. The reference image is the one taken with FD= 152 microns, i.e. 28 cm.

1753_um_1499_um.t2d	1753_um_1507_um.t2d	1753_um_1523_um.t2d	1753_um_1535_um.t2d
1753_um_1545_um.t2d	1753_um_1559_um.t2d	1753_um_1565_um.t2d	1753_um_1582_um.t2d
1753_um_1594_um.t2d	1753_um_1601_um.t2d	1753_um_1614_um.t2d	1753_um_1622_um.t2d
1753_um_1630_um.t2d	1753_um_1643_um.t2d	1753_um_1665_um.t2d	1753_um_1682_um.t2d
1753_um_1703_um.t2d	1753_um_1719_um.t2d	1753_um_1738_um.t2d	1753_um_1772_um.t2d
1753_um_1786_um.t2d	1753_um_1803_um.t2d	1753_um_1814_um.t2d	1753_um_1830_um.t2d
1753_um_1846_um.t2d	1753_um_1863_um.t2d	1753_um_1876_um.t2d	1753_um_1887_um.t2d
1753_um_1898_um.t2d	1753_um_1927_um.t2d	1753_um_1941_um.t2d	1753_um_1954_um.t2d
1753_um_1960_um.t2d	1753_um_1977_um.t2d	1753_um_1987_um.t2d	1753_um_1991_um.t2d
1753_um_2006_um.t2d			

Table 5.- Resulting affine transformations (37) between FDs 1499 and 1991 microns. The reference image is the one taken with FD= 1753 microns, i.e. approximately 70 cm.

2126_um_2018_um.t2d	2126_um_2035_um.t2d	2126_um_2058_um.t2d	2126_um_2077_um.t2d
2126_um_2094_um.t2d	2126_um_2112_um.t2d	2126_um_2143_um.t2d	2126_um_2154_um.t2d
2126_um_2178_um.t2d	2126_um_2193_um.t2d	2126_um_2197_um.t2d	2126_um_2212_um.t2d
2126_um_2225_um.t2d	2126_um_2238_um.t2d	2126_um_2252_um.t2d	2126_um_2266_um.t2d
2126_um_2279_um.t2d	2126_um_2291_um.t2d	2126_um_2301_um.t2d	2126_um_2312_um.t2d
2126_um_2317_um.t2d	2126_um_2329_um.t2d	2126_um_2343_um.t2d	2126_um_2345_um.t2d
2126_um_2355_um.t2d	2126_um_2370_um.t2d	2126_um_2381_um.t2d	2126_um_2394_um.t2d
2126_um_2405_um.t2d	2126_um_2416_um.t2d	2126_um_2432_um.t2d	2126_um_2441_um.t2d
2126_um_2451_um.t2d	2126_um_2463_um.t2d	2126_um_2473_um.t2d	2126_um_2482_um.t2d

Table 6.- Resulting affine transformations (36) between FDs 2018 and 2482 microns. The reference image is the one taken with FD= 2126 microns, i.e. 100 cm.

[2] Further information supporting information about the missing range may be obtained from an additional test that captured a well-textured object (Mars meteorite) that covered the mentioned range.

6 MARTIAN METEORITE DATA

16 images of a real Martian meteorite were taken with CLUPI at ESTEC on 1st July 2019. The images were acquired with different focus distances (478-1001 microns) and are represented in Figure 12:

FD= 478 µm	**FD= 758 µm**
	
FD= 507 µm	**FD= 787 µm**
	
FD= 548 µm	**FD= 829 µm**
	
FD= 575 µm	**FD= 856 µm**

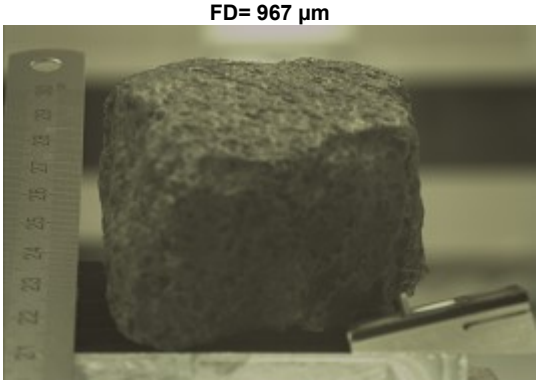
	
FD= 618 µm	**FD= 897 µm**
	
FD= 646 µm	**FD= 925 µm**
	
FD= 686 µm	**FD= 967 µm**
	
FD= 715 µm	**FD= 1001 µm**

Figure 12.- Images taken from a real Martian meteorite with 16 different CLUPI focus distances.

Since not all CLUPI FDs used during the acquisition of the Martian meteorite (Figure 12) were previously calibrated (according to Table 1, the near calibrated range is from -24 until 628 microns), and some of them within the calibrated range did not exactly coincide with the calibrated FDs, two different approaches were carried out:

- For the images taken in a non-calibrated FD range (i.e.; images taken with FDs=646-1001 microns), the FDs affine parameters were calculated using a feature matching procedure between homologue points in the corresponding images. An example can be seen in Figure 13.
- For the images taken with a FD within the calibrated range (i.e.; images taken with FD 478-628 microns) but not in coincidence with the calibrated FD (images with FDs= 507, 575 and 618 microns), interpolation of the affine transformations parameters was done.

Finally several transformation stacks were calculated to set the image taken at FD=476 microns as the reference one. A total number of 15 affine transformations were computed, as shown in Table 7. The output image obtained after applying these transformations along all FDs is displayed in Figure 14.

476_507.t2d	18.07.2019 13:29	T2D-Datei	1 KB
476_548.t2d	18.07.2019 13:26	T2D-Datei	1 KB
476_575.t2d	18.07.2019 13:31	T2D-Datei	1 KB
476_618.t2d	18.07.2019 13:31	T2D-Datei	1 KB
476_646.t2d	05.08.2019 11:07	T2D-Datei	1 KB
476_686.t2d	05.08.2019 11:08	T2D-Datei	1 KB
476_715.t2d	05.08.2019 11:08	T2D-Datei	1 KB
476_758.t2d	05.08.2019 11:16	T2D-Datei	1 KB
476_787.t2d	05.08.2019 11:08	T2D-Datei	1 KB
476_829.t2d	05.08.2019 11:08	T2D-Datei	1 KB
476_856.t2d	05.08.2019 11:08	T2D-Datei	1 KB
476_897.t2d	05.08.2019 11:08	T2D-Datei	1 KB
476_925.t2d	05.08.2019 11:08	T2D-Datei	1 KB
476_967.t2d	05.08.2019 11:08	T2D-Datei	1 KB
476_1001.t2d	05.08.2019 11:08	T2D-Datei	1 KB

Table 7.- Resulting affine transformations (15) between FDs 476 and 1001 microns. The reference image is the one taken with FD= 476 microns.

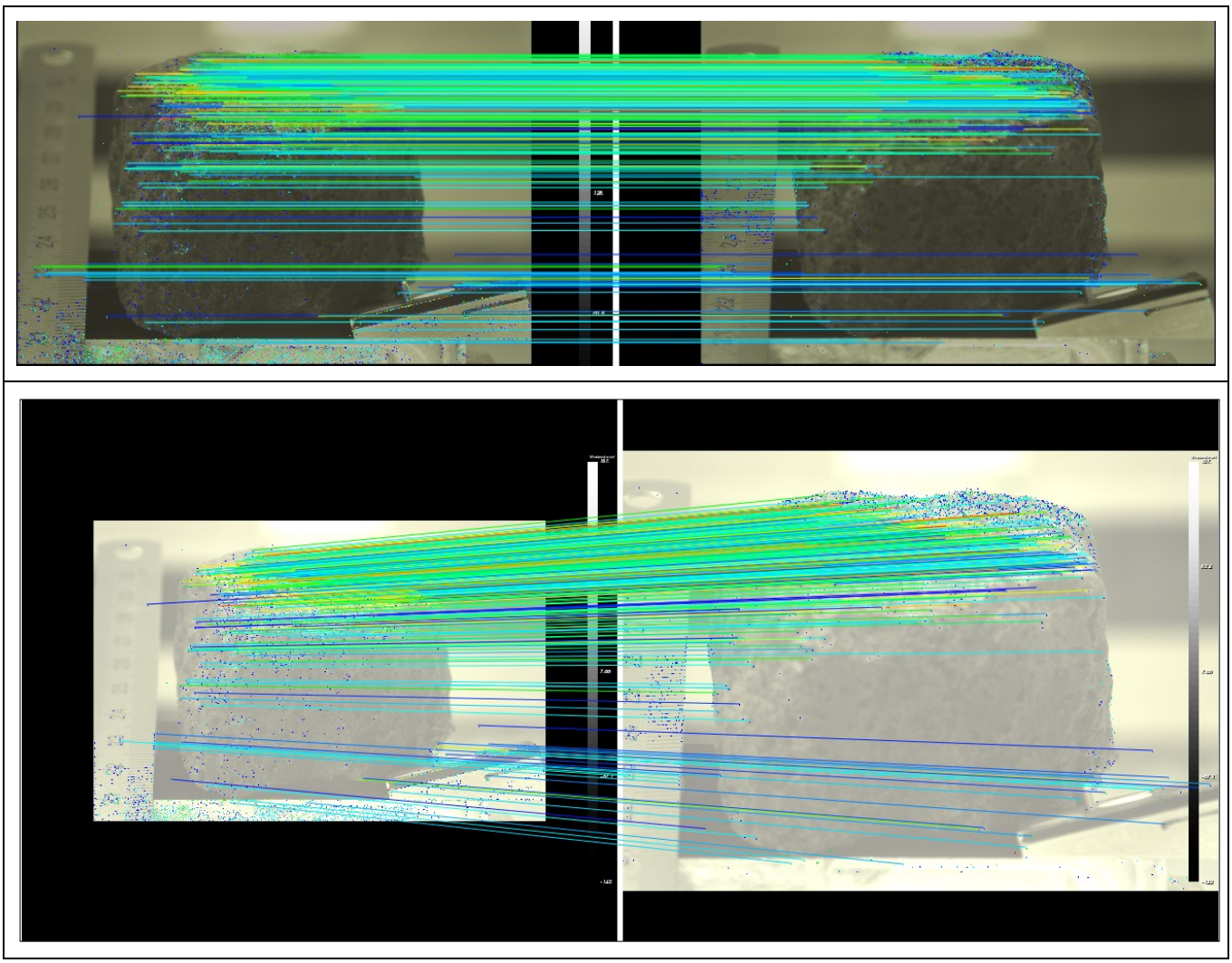


Figure 13.- Top: Feature Matching between images taken with FDs= 646 (left) and 897 (right) microns. Bottom: Image on the right side was zoomed in for better distinction of matched points.

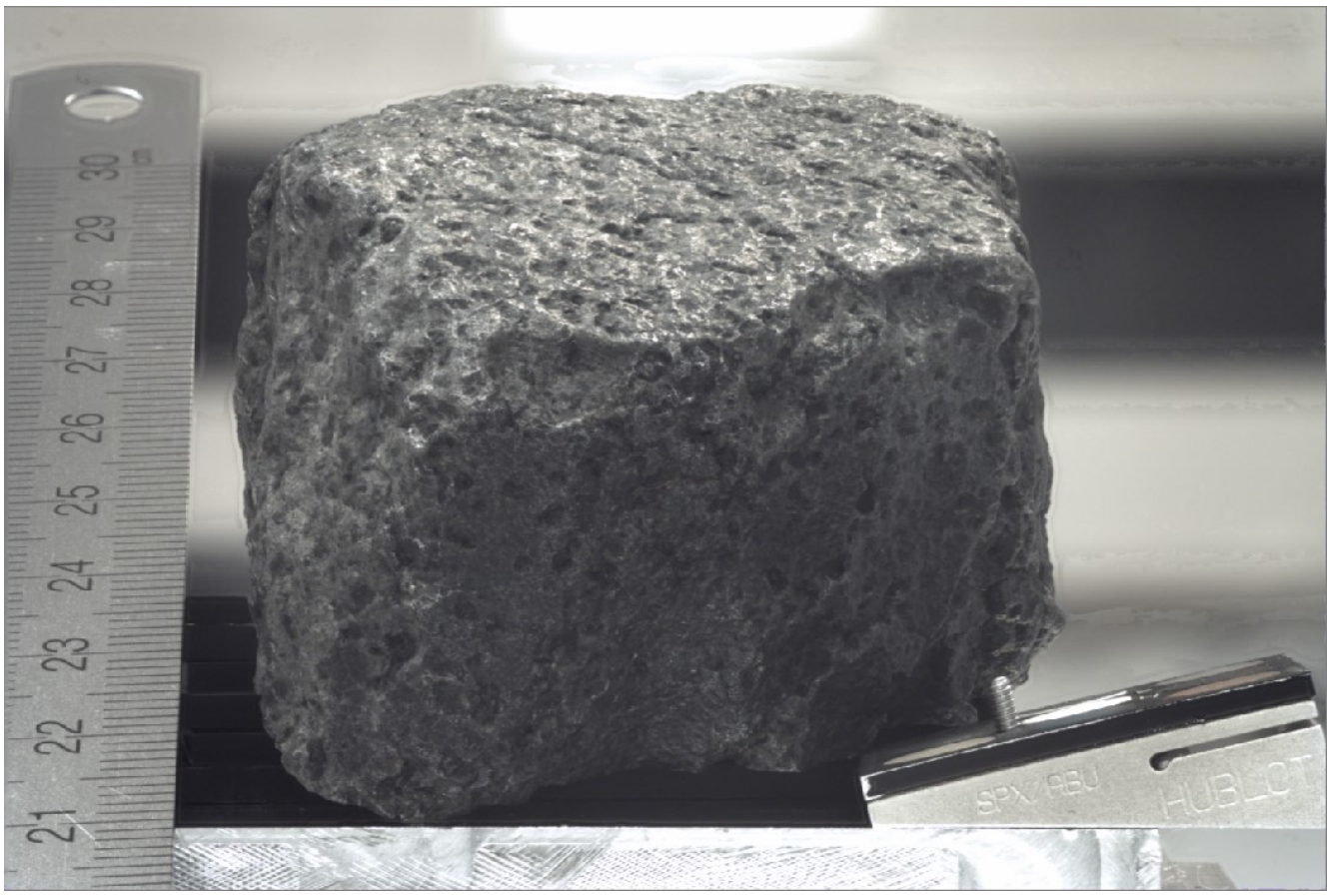


Figure 14.- Resulting FDs stacking image (focussed) from the real Martian meteorite, obtained from 16 different FDs.

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