LICIACube Explorer Imaging for Asteroid (LEIA) and LICIACube Unit Key Explorer (LUKE) Calibration Pipeline Description

Technical Content Approval

<u>Prepared/Approved by</u>:

Vincenzo Della Corte
LICIACube Instrument Team Lead

Angelo Zinzi
LICIACube SOC Lead

<u>Reviewed by</u>:

Simone Pirrotta
LICIACube Project Manager

Marilena Amoroso
LICIACube Science Operations Center Coordination Lead

Elisabetta Dotto
LICIACube Science Team Lead

Revision Log

Version	By	Description	Date
1	V. Della Corte	Release to accompany PDS delivery	October 2023

Table of Contents

1. Introduction

This document defines and describes how the LICIACube Science Operations Center (SOC) will calibrate images taken by the LICIACube Explorer Imaging for Asteroid (LEIA) and LICIACube Unit Key Explorer (LUKE). The pipeline is implemented by INAF and installed into the SOC pipeline hosted at the ASI-SSDC premises. This document also enumerates the input files to the calibration pipeline and their required formats.

This document focuses on the specific steps that the SOC takes to produce calibrated images. This document does not discuss at length any calibration activities or results. These topics will be treated in the paper by Della Corte et al., with expected publication dates in 2023 or 2024.

1.1. Relevance to mission level 1 requirements

The Investigation Team is using calibrated LEIA and LUKE images to meet LICIACube Level 2 requirements:

- **LCC-1:** Testify the impact with a time resolution of 5s
- **LCC-2**: Multiple (at least 3) images of the ejecta plume taken over a span of time and phase angle, that, with reasonable expectations concerning the ejecta mass and particle size distribution, can potentially:
    - **2a** Allow measurement of the motion of the slow (< 5 m/s) ejecta
    - **2b** Allow estimation of the density structure of the plume
- **LCC-3:** Multiple (at least 3) images of the DART impact site having sufficient resolution (< 2 m/pixel) to allow measurements of the size and morphology of the crater, and taken sufficiently late after impact that the plume can be reasonably expected to have cleared
- **LCC-4:** Multiple (at least 3) images of Dimorphos showing the non-impact hemisphere, which can potentially increase the accuracy of the shape and volume determination.

The LICIACube observations will aid in identifying the impact point and will improve the estimate of the shape of Dimorphos needed for a more accurate estimate of the volume of the satellite. This volume estimate reduces the uncertainty of the momentum transferred to Dimorphos during the impact. Finally, LICIACube will provide information on the plume properties of the ejecta excavated that can constrain the strength attributes of the asteroid surface during impact, and also affects estimates of the momentum transferred.

This document describes only the SOC calibration pipeline.

1.2. Responsibility and change authority

The LICIACube LEIA/LUKE Instrument Lead Scientist (IS) or Deputy IS (hereafter referred to simply as IS) is responsible for making changes to this document. Requests for changes will be made to the IS, who will incorporate changes and publish an updated version.

2. Related documents

- LICIACube LEIA/LUKE Uncalibrated/Calibrated Data Software Interface Specification (SIS)
- Dotto et al., 2021. LICIACube - The Light Italian Cubesat for Imaging of Asteroids In support of the NASA DART mission towards asteroid (65803) Didymos, *Planetary and Space Science*, 199, https://doi.org/10.1016/j.pss.2021.105185

- Zinzi et al., 2022. The SSDC Role in the LICIACube Mission: Data Management and the MATISSE Tool, The Planetary Science Journal, 3:126, https://doi.org/10.3847/PSJ/ac6509

In the event of a conflict between the LICIACube LEIA/LUKE Uncalibrated/Calibrated SIS and this document, the SIS takes precedence.

3. Calibration pipeline inputs

3.1. LEIA images

LEIA images that enter the calibration pipeline will be 16-bit 2048x2048 FITS files. Keywords in the FITS header describe the location of the window, if applicable. For additional details on these images, see the SIS.

3.2. LUKE images

LUKE images that enter the calibration pipeline will be 8-bit 2048x1088 FITS files. Keywords in the FITS header describe the location of the window, if applicable. For additional details on these images, see the SIS.

3.3. Additional calibration pipeline inputs

3.3.1. Bad pixel map

At most, the bad pixel map will include a handful of pixels that do not exhibit a good dark or photoresponse for the 2 payloads. For purposes of the calibration pipeline, the bad pixel map is provided as a plane of the calibration FITS file. As of July 2023, no bad pixels have been flagged in the bad pixel map.

Pixels in the bad pixel map are unitless.

3.3.2. Bias frames

The pipeline includes a bias subtraction for both payloads. Bias frames for both payloads are produced using dark images acquired on ground. The bias frame uses for each pixel the intercept value of the dark current trend.

3.3.3. Dark current frames

The LICIACube payloads dark current is corrected using the curves fit to each pixel retrieved by during on-ground calibrations in the dark. Using the integration time of the images and the actual detector temperature, the dark current is evaluated for each pixel. The calibration pipeline removes the dark current contribution by subtracting the resulting dark frame obtained for each pixel.

3.3.4. Radiometric calibration

Radiometric calibration involves conversion of raw signals in engineering units (DN) to physical units. Radiometrically calibrated images provide useful information to the Investigation Team and the science community. LICIACube payloads images have been radiometrically calibrated on a best-effort basis using images acquired on the ground with a calibrated integrating sphere.

The conversion from DN to physical units requires knowledge of the spectral properties of the source, the target, and the instrument. The LICIACube LEIA payload is a broadband imager. The detector response has been evaluated pixel by pixel.

The calibration team retrieved for each pixel an analytical function linking the DN obtained by the telemetry to the Radiance [W/(m^2*sr*nm)] for each pixel

3.4. Required formats for calibration pipeline inputs

The SIS lists the naming convention and file formats for calibration pipeline inputs.

3.5. Inputs of calibration process

Tables 1 and 2 list the planes in the calibration FITS files used as inputs in the calibration process. The data producers are responsible for complying with the file format, naming conventions, and metadata requirements specified in the LICIACube SIS.

Table 1. Teams responsible for producing calibration pipeline inputs

FITS keyword	Description	Produced by	Notes
BIAS	Bias plane	Instrument Team [Vincenzo Della Corte]	–
BAD PIXEL MAP	Bad pixel map plane	Instrument Team [Vincenzo Della Corte]	–
DARK1	Dark current plane 1	Instrument Team [Vincenzo Della Corte]	-
DARK2	Dark current plane 1	Instrument Team [Vincenzo Della Corte]	-

Table 2. Teams responsible for producing calibration pipeline inputs

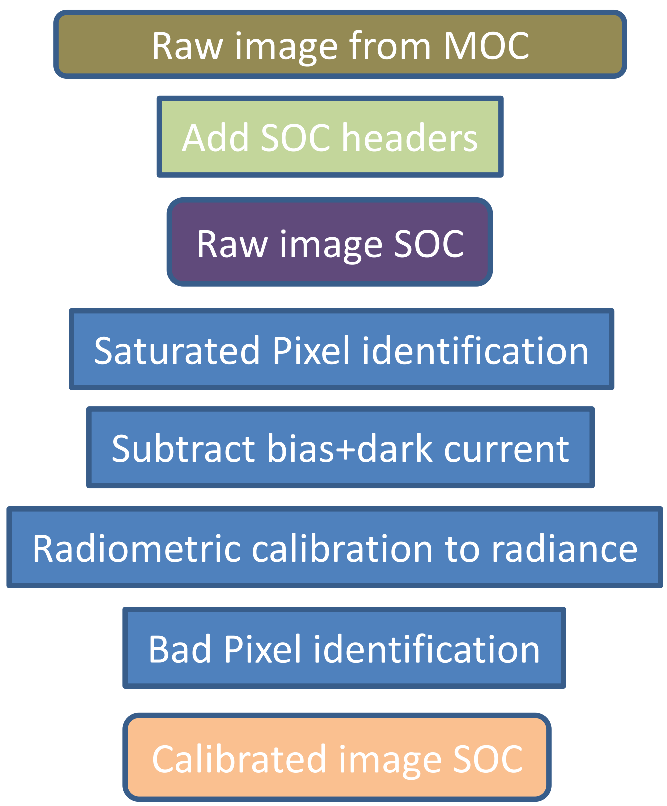
FITS keyword	Description	Produced by	Notes
SPLINE PARAMS	Parameters for the spline curves	Instrument Team [Vincenzo Della Corte]	–

4. Calibration pipeline procedure

Figure 1. in Section 4.1 illustrates the steps used by the LICIACube calibration pipeline. Section 4.2 enumerates the FITS keywords the calibration pipeline queries. Section 4.3 details each step in the pipeline. Section 4.4 lists the keywords added by the calibration pipeline. Keywords are copied from raw to calibrated so user do not have to refer to the original Raw image ones.

4.1. Graphical depiction

Figure 1. Schematic of LICIAcube Payloads image calibration pipeline.



4.2. Fits keywords used in the calibration process

The pipeline processes images acquired as full-frame. The steps in the pipeline are almost always the same, but the particular files used to calibrate an image may vary depending on the calibration file indicated in the calibrated image FITS header. The pipeline selects the bias files, dark current frames, and the calibration parameters that match the state of the image. In order to correctly calibrate a particular image, the pipeline parses the following keywords from the FITS header of the LICIACube image.

Table 3. Fits keywords queried by pipeline.

Keyword	Brief description	Use in pipeline
DETTEMP	Temperature of the LEIA/LUKE detector, in degrees Celsius.	This is the temperature that would be used for temperature-dependent dark current corrections.
EXPTIME	Integration time of the image, in seconds	Used in dark current subtraction and radiometric calibration
CALFILE	Name of file uploaded for LEIA/LUKE calibration file.	Used to ensure that the correct calibration file is used for each image.

4.3. Description of calibration pipeline steps

4.3.1. Subtract a bias frame.

Select the bias frame: the image is calibrated and the bias subtracted. In-flight data will also be used to monitor temperature stability of LICIACube Payloads.

output1 = raw – bias

output1 is in units of DN.

4.3.2. Subtract a dark current frame.

Evaluate the dark signal for each pixel at the actual detector temperature and considering the integration time.
The dark current vs temperature is computed by means of an exponential fit as follows:

dark current = dark1*exp(-dark2/dettemp)

dark current is in units of DN/sec.

Where dark1 (in DN/s) and dark2 (in °C) are the corresponding planes of the calibration FITS file. The obtained value is the actual dark current for each pixel the obtained value are in units of DN sec^{-1}. To obtain the DARK signal the obtained matrix is multiplied by the integration time

Output2 = output1 – (dark current frame)*EXPTIME

output2 is in units of DN.

4.3.3. Convert to radiance.

Output4 = f_rad(output_3)/t_exp

output4 is in units of $W\ m^{-2}\ nm^{-1}\ sr^{-1}$

.

For LEIA payload a single function of conversion of corrected DN to integrated radiance, was retrieved from the calibration measurements. The value for each pixel is obtained applying this function on the output2.

In case of LUKE each acquisition provides 3 different images after a de-bayerization process (see reference and description provided in the SIS for how this is done). Recall that the LUKE detector is a color filter array with an RGGB configuration. For each image the same conversion is applied, using the relevant calibration function obtained for the 3 different camera colors. This conversion is applied before the application of de-bayerization process, so that only the effective pixels have calibration curves.

The parameters to be used with the PchipInterpolator Scipy Python function are those present in the calibration FITS file and they can be extracted using the following approach:

1. After opening the FITS file in Python assuring of using it as LSB, instead of MSB (i.e., perform a byte swap)
2. For every LUKE color, or for the whole LEIA image, starting a loop scrolling once pixel at a time
3. The data extracted from the calibration file, for every pixel has to be divided in 3 different arrays, differentiating on the last Python index
4. For every array so created it is needed to reshape it as a list (i.e., flattening it) and then selecting only data with valid number (i.e., not 1e32 flag)
5. The 3 flattened arrays generated in this way have to be merged in a single list-of-lists and then converted in a Numpy array of dtype = object
6. To this array the Pchipinterpolator has to be applied and to its output function (the spline) computed at the background removed DN value

These steps are summarized in the following lines of Python code, that show an example of how to proceed for every plane to be calibrated.

Opening the FITS file:

```
with fits.open(<calfile>) as cal:
 caldata=cal[0].data
if caldata.dtype.byteorder == '>': caldata=caldata.byteswap().newbyteorder()
par_list_orig=np.reshape(caldata,(nparam,naxis2,naxis1,3))
```

Converting the FITS data to numpy array dtype=object to be used by PchipInterpolator (i and j are the indexes of the pixel):

```
par_list_0=np.reshape(par_list_orig[:,i,j,0],-1)
par_list_0=par_list_0[np.isfinite(par_list_0)]
par_list_1=np.reshape(par_list_orig[:,i,j,1],-1)
par_list_1=par_list_1[np.isfinite(par_list_1)]
par_list_2=np.reshape(par_list_orig[:,i,j,2],-1)
par_list_2=int(par_list_2[np.isfinite(par_list_2)])
par_list=[par_list_0,par_list_1,par_list_2]
tck=np.array(par_list, dtype=object)
tckp=scipy.interpolate.PchipInterpolator.from_spline(tck)
calibrated_data[i,j]=tckp(background_removed_DN[i,j])
```

LUKE pixels will be processed as non-saturated if their background-removed DN value is less than 210. For LEIA no saturation DN value is applied.
The values coming from the PchipInterpolator processing need to be further processed, by multiplying them by a factor to rescale the values to radiance from optical power taking into consideration the power at the entrance pupil. These values have been inferred by empirical image analysis of in-flight images and are set to the following:

- LEIA: 0.44263
- LUKE Red: 3.445
- LUKE Green: 4.793
- LUKE Blue: 4.437

All the values so computed shall be then divided by a factor (resulting to be 102.1522 for LUKE and 1 for LEIA) to correct for radiance of the real exposure time of the on-ground calibration source and for the exposure time (in seconds) in order to be output as radiances at the following wavelengths:

- LEIA: 612 nm
- LUKE Red: 630 nm
- LUKE Green: 530 nmLUKE Blue: 460 nm

It is worthy to note that, due to the intrinsic characteristics of the LUKE detector (coming as a Commercial off the Shelf – COTS), the accuracy of this calibration is estimated to be around 30% in radiance. Furthermore, since it was computed using stars, we make no promises that it is correct for an extended body, such as an asteroid, and may require other additional correction processes.

4.3.4. Change the values of bad pixels to -1E09.

The pipeline will identify bad pixels in raw images thanks to the corresponding calibration FITS plane and changes the values of those pixels in the calibrated images to BADMASKV = -1E09. To date, no bad pixels have been flagged by the bad pixel map.

4.3.5. Change the values of saturated pixels to 1E30.

The pipeline will identify saturated pixels in raw images and changes the values of those pixels in the calibrated images to BADMASKV = -1E09. For LUKE these pixels are those with DN > 210 in the raw images, after background removal; for LEIA no saturated pixels have been identified.

4.4. Fits keywords added or modified by calibration pipeline

In order to track what was done in the calibration process, the pipeline will modify or add the keywords listed below to the FITS header of the calibrated images. For description of these keywords, see the SIS.

- BITPIX
- RADCONV
- CALFILE
- BADMASKV

- MISPXVAL
- SATPXVAL

For LUKE calibrated images, apart from these listed here, also the following keywords are added or modified into the FITS header

- NAXIS
- NAXIS3
- PLANE1
- PLANE2
- PLANE3