Mars2020/Mastcam-Z

Derived Product SIS
M2020_MCZ_SIS_0001



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~~2~~	~~Sec 1.1 & 3.3~~	~~Caveats and artifacts (may or may not be applicable)~~	~~Alyssa/MCZ~~	~~7/15/2021~~
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~~12~~		~~Update RDR derived image definitions~~	~~Alyssa/MCZ~~	~~7/28/2021~~

Acronyms and Abbreviations

ASU	Arizona State University
CCD	Charge-Coupled Device
CDPID	Camera Data Product Identifier
CDR	Calibrated Data Record
DC	Dark Current
DEA	Digital Elect Assembly
DN	Data Number
DQI	Data Quality ID
EDR	Experimental Data Record
FPA	Filter Plane Array
GOP	Group of Pictures
HWHM	Half Width at Half Maximum
I/F	Radiance factor calibrated
IDS	Instrument Data Systems
JPEG	Joint Photographic Experts Group (Compressed image file)

LIDVID	Logical Identifier, Version Identifier
LUT	Lookup Table
MCU	Minimum Coded Unit
MSSS	Malin Space Science Systems
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
ODL	Object Description Language
PDS	Planetary Data System
RAD	Radiance calibrated
RDR	Reduced Data Record
RGB	Red, Green, Blue
ROI	Region Of Interest
RSM	Remote Sensing Mast
SCLK	Spacecraft Clock
SIS	Software Interface Specification
TBD	To Be Determined
TBR	To Be Read
XML	eXtensible Markup Language
ZCAM/MCZ	Mastcam-Z

Words That May Be Used Synonymously

Because variations in terminology used for the cameras and data values can be confusing, the following are some common groups of terms that are often used to mean the same thing:

- Mastcam-Z, Mast Cameras Zoom, Mastcam-Z instrument suite, MCZ, ZCAM, MCAMZ.
- Mastcam-Z calibration target, “caltarget” or “cal target”
- Bayer pattern, Bayer microfilters, Bayer color filter array Bayer/RGB color filter, filter 0, L0 and/or R0, broadband near-IR cutoff filter.
- Narrow-band science filters, geology filters, (specifically) L1-L6 and/or R1-R6, LALLRALL,
- Solar imaging filter(s), filter 7, L7 or R7, (10^{-5})-neutral-density-coated filters
- I/F, radiance factor, “reflectance”, “Relative reflectance”

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1 Introduction

1.1 Overview

The goal of this data archive is to provide a complete set of radiometrically calibrated Mastcam-Z data products. These data products are appropriate for quantitative use by the scientific community for investigations relating to reflectance and scattering properties of Jezero crater material. The calibrated data products, produced from Mastcam-Z Experimental Data Records (EDRs), are publicly available in NASA's Planetary Data System (PDS). The calibrated data records are calibrated to two different radiometric quantities; spectral radiance (RAD) and radiance factor (I/F). The Mastcam-Z instrument is a pair of color-capable focusable stereo cameras ("eyes") mounted on the rover's Remote Sensing Mast (RSM). Each camera has identical zoom/focus capabilities but different sets of multispectral filters. Together, they can acquire images of up to 1648 x 1200 pixels and are capable of video. They acquire color via Bayer-pattern filters on the CCD, but also have selectable filters for science/geology applications. To learn more about the Mastcam-Z instrument see Bell et al. (2020) and Hayes et al. (2020).

1.2 Contents

This document describes the archive contents and calibration pipeline used to produce the radiometrically calibrated data products. The Mastcam-Z archive consists of seven collections; documents, calibration, miscellaneous, browse_asu, browse_ids, data_asu, and data_ids. The Mastcam-Z team at Arizona State University (ASU) is responsible for the contents of the browse_asu and data_asu collections, which are the recommended highest-fidelity, best-calibrated data products for scientific analysis. The Mars 2020 Instrument Data System (IDS) group at JPL is responsible for the browse_ids and data_ids collections, which are the quick-look versions of the Mastcam-Z data products that were used for tactical operations and initial assessment during the mission. This document focuses on those ASU collections. The data and browse collections are broken down by file type (e.g., RAD) and then by sol. The calibration collection contains supplementary information with respect to calibration, including details of the calibration target scattering model that underlies the I/F calibration, as well as version notes for the calibration software. The browse collection has thumbnail products for easy "browsing" of the available images. Users should start in the documentation collection, which contains documentation that was used to build this archive and holds important details for data users to understand the mission scope and goals. The documents collection contains material for understanding the Mastcam-Z instrument, including copies of journal articles that describe both their capabilities and operation and pre-flight (and eventually, in-flight) calibration efforts. The structure and contents of the bundle is described in more detail in Section 2.

The calibration pipeline employed for the data in this archive converts the raw DN counts recorded by the CCDs to one or both of two meaningful physical quantities—radiance (in $W/m^2/nm/sr$), and/or "reflectance" (otherwise known as I/F or radiance factor). Radiance is a measurement of the light reaching the detector. Radiance factor is a unitless ratio defined as the amount of light measured by the sensor relative to what would be received from observing a normally illuminated, perfectly reflecting Lambertian surface. The dataset and pipeline for the generation of these products is described in Section 3.

Radiance-calibrated products may be appropriate for users who do not want or need a correction for surface-incident solar spectral irradiance. As an example, users interested in sky imaging observations (for radiative transfer, atmospheric dust particle size retrievals, etc.) should use the radiance products.

Calibrated I/F products are provided for surface imaging observations. These products depend on accompanying observations of the Mastcam-Z calibration target, located on the rover deck, to accurately characterize the surface illumination. The accuracy of the calibration can vary, but is best when the difference in time between an observation and its nearest calibration target ("caltarget") observation is small. Imaging observations acquired with the intention to be used for quantitative surface reflectance (in particular, imaging sequences taken through multiple filters for spectral analysis) usually have an associated calibration target sequence that was acquired immediately before or after the surface observation, when not precluded by operational constraints. These multispectral products are intended to allow for comparison with spectral features documented in spectral libraries and in publications on the optical properties of natural and synthetic materials.

Users interested in using any of these calibrated products should consult Section 3.4 for a discussion of caveats and artifacts that may occur within the image data and when interpreting the quantitative values.

The image data is accompanied by metadata in two formats: an ODL3 format label attached to the binary data, and a PDS4-compliant XML detached image label.

This archiving project does not include any associated software tools for opening, reading, displaying, or manipulating the data files. Users may find what they need within NASA's PDS Tool Registry, although we are not able to guarantee that these products are or will continue to be supported by any particular software packages. Section 5 contains some suggestions for users who encounter difficulty using the data files.

1.3 Instrument Overview

Mastcam-Z is comprised of a pair of color, focusable, zoomable stereo cameras ("eyes") mounted on the rover's Remote Sensing Mast (RSM). Each camera has identical zoom/focus capabilities but each has a different set of color filters. The camera heads are capable of zoom with focal lengths from 26 mm to 110 mm with a rotating, eight- position filter wheel. Their position on the RSM allows a large range of pointing in azimuth and elevation. Each eye can acquire images of up to 1648 x 1200 pixels and is capable of high frame rate acquisition (video) and on-board processing of focus stack images. They acquire color via Bayer-pattern filters on the CCD, but also have selectable superimposed narrowband filters for limited compositional applications. The cameras have a variety of commandable parameters including filter position, subframing, compression, focus, focal length, and exposure settings. The Mastcam-Z camera system is described in more detail by Bell et al. (2020) and Hayes et al. (2020). [Figure 1-1].



Figure1-1. The two Mastcam-Z flight cameras, shown with a pocket knife for scale, are assembled and ready for testing in this photo taken at Malin Space Science Systems, in San Diego, California. Photo credit: MSSS/ASU.

Image sequences are obtained as single or multiple pointings through one or more of the following filters on each camera: a broadband, IR-cutoff filter (for "RGB" imaging, filter position 0), six narrow-band filters (filters 1–6) selected to characterize surface reflectance for multispectral science imaging, and two solar imaging filters (filter 7), one with an 880 nm filter and a 10^{-5} neutral density (ND) coating (R eye) and the other with a broadband IR-cutoff filter and a 10^{-6} ND coating (L eye).

The camera heads are connected to the rover via a Digital Electronics Assembly (DEA) that provides some onboard image-processing capabilities, including 11-to-8-bit companding (a term for compression, then later expanding; *e.g.,* Bell *et al.,* 2017), horizontal sub-framing, and image compression using either lossless predictive (Huffman-encoded; Malin *et al.,* 2013) or lossy JPEG algorithms.

Uncompressed data have 11-bit (raw Data Numbers from 0 to 2047) dynamic range with no compression or color interpolation. Lossless compression typically yields ~1.7:1 compression and is not color interpolated. Lossy compression uses a Realtime JPEG algorithm with color interpolation or in grayscale, and with commandable color subsampling (4:4:4 or 4:2:2) and a commandable compression quality of 1 to 100. Lossy JPEG compression of the images is common, depending on downlink volume constraints, although in some cases some observations are retransmitted (as a recovered product) later losslessly. Video products can be commanded raw or as JPEG-compressed color-interpolated Groups of Pictures (GOPs; ≤ 2 MB file size and ≤ 16 frames/GOP), with commandable color subsampling and compression quality. Z stack products (for focus merges and range maps) can reduce as many as eight 1600x1200

raw images to a single 1600x1200 color JPEG and a grayscale JPEG range image. Lastly, companding performs 11-bit to 8-bit square-root encoding/decoding via lookup tables.

A summary of the filter set and the debayering methods used to generate the full-size images is shown below in Figures 1-2 and 1-3.

Table 3. Mastcam-Z Left (L) and Right (R) Filters[a]

Filter Number	$\lambda_{eff} \pm$ HWHM (nm)[b]	
L0/R0 (Red Bayer)	630 ± 43	631 ± 43
L0/R0 (Green Bayer)	544 ± 41	544 ± 42
L0/R0 (Blue Bayer)	480 ± 46	480 ± 46
L1 / R1	800 ± 9	800 ± 9
L2 / R2	754 ± 10	866 ± 10
L3 / R3	677 ± 11	910 ± 12
L4 / R4	605 ± 9	939 ± 12
L5 / R5	528 ± 11	978 ± 10
L6 / R6	442 ± 12	1022 ± 19
L7 / R7[c]	590 ± 88, ND6	880 ± 10, ND5

[a]Red text means new performance compared to MSL/Mastcam.
[b]λ_{eff} is the effective band center wavelength, calculated as the weighted average of the normalized system spectral response (including optics, filter, and CCD) and the solar radiance at the top of the Martian atmosphere. HWHM is the half-width of the bandpass at half-maximum for each filter.
[c]Filters L7 and R7 are for direct imaging of the Sun using Neutral Density (ND) coatings that attenuate the flux by factors of 10^6 and 10^5, respectively. Filter L7 enables 3-color (RGB) Bayer filter color imaging of the Sun at the same effective band center wavelengths as the L0 and R0 filters.
See Hayes *et al.* (2020) for details on these derived values.

Figure 1-2 Mastcam-Z filters and corresponding effective band center wavelengths (Bell et al. 2020)

Camera	Filter 0	Filter 1	Filter 2	Filter 3	Filter 4	Filter 5	Filter 6	Filter 7
Left	Malvar[a]	Red[b]	Red	Red	Red	Green[d]	Blue[e]	Malvar
Right	Malvar	Red	Identity[c]	Identity	Identity	Identity	Identity	Identity

[a]Malvar means that interpolation using the algorithm of Malvar *et al.* (2004) is performed.
[b]Red means that bilinear interpolation of red Bayer pixels is performed; blue and green pixels are discarded.
[c]Identity means that no interpolation is performed; image is returned as a monochrome JPEG that was compressed from raw data with as-is Bayer values (because the Bayer filters are transparent at near-IR wavelengths; see Bell *et al.* 2017, Figure 3).
[d]Green means that bilinear interpolation of green Bayer pixels is performed; red and blue pixels are discarded.
[e]Blue means that bilinear interpolation of blue Bayer pixels is performed; red and green pixels are discarded.

Figure 1-3 Mastcam-Z Bayer Pattern Interpolation Scheme used for Lossy JPEG Compressed Data (Bell et al. 2020)

Mastcam-Z optics characteristics that are useful in the analysis of EDR and RDR products are described in Figure 1-4 below:

Characteristic	Left Eye = Right Eye
Field of View (FOV)	Wide: ~25.5° x 19.1 ° Narrow: ~6.2° x 4.2 °
Baseline Stereo Separation	24.4 cm
Toe-in	1.6°
Spatial Resolution	~1 mm @ ~2 m range ~3–4 mm @ 100 m range
Angular Resolution	26 mm focal length: 280 µrad/pix 110 mm focal length: 66.7 µrad/pix
Focal Length	26 – 110 mm
f/number	26 mm focal length: f/7 110 mm focal length: f/9
Focus Range	0.5 – 1 m – infinity
Number of Spectral Filters	7 plus Bayer pattern

Figure 1-4 Mastcam-Z operational characteristics (Hayes et al. 2020)

2 Archive Structure and Contents

2.1 Mastcam-Z PDS Bundle Overview

The Mastcam-Z Bundle: `urn:nasa:pds:m2020_mastcamz`

See Figure 2-1 below for a breakdown of how a PDS4 bundle works. The Mastcam-Z bundle is linked to the Mars2020 Mission and Rover bundles. The terms “bundle” and “collection” are terminology referring to archive structure. See the PDS4 standards document for more information (PDS Standards Reference 2021).

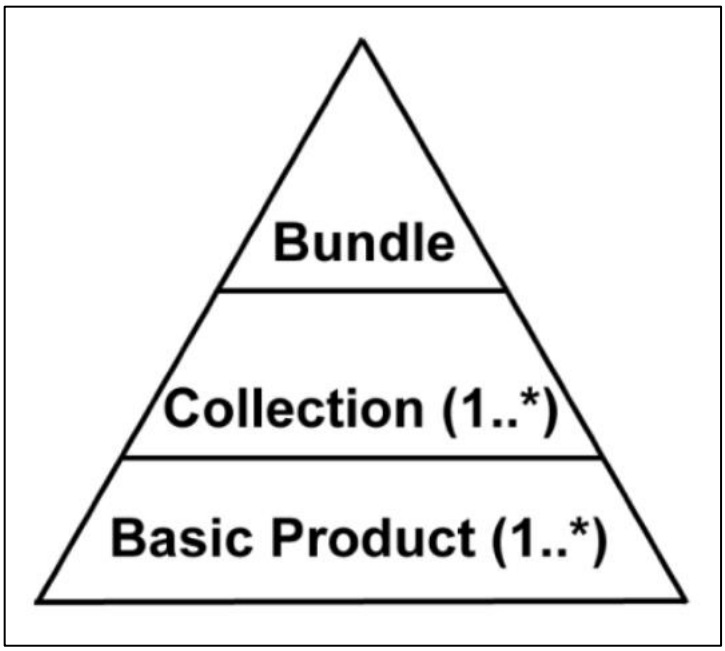


Figure 2-1 Basic PDS4 bundle/collection structure

The Mastcam-Z bundle consists of seven collections: data_asu, data_ids, calibration, documentation, browse_asu, browse_ids, and, miscellaneous. The data and browse collections are split into two (asu and ids) to differentiate the producers of this data.
The Collections:

```
urn:nasa:pds:m2020_mastcamz:browse_asu
urn:nasa:pds:m2020_mastcamz:browse_ids
urn:nasa:pds:m2020_mastcamz:calibration
urn:nasa:pds:m2020_mastcamz:data_asu
urn:nasa:pds:m2020_mastcamz:data_ids
urn:nasa:pds:m2020_mastcamz:document
urn:nasa:pds:m2020_mastcamz:miscellaneous
```

2.1.1 data_asu

The data_asu collection contains all the radiance-calibrated and radiance factor-calibrated products. The collection structure of data_asu is broken down by derived product type (RAD or IOF) and then by sol. These products are in the form of a .IMG file containing the image data, preceded by a plain text, ODL-format attached label. Each file also has a detached XML label that has the same filename before the .XML extension. All radiance calibrated products will have the product type “RAD” (video frames & images). All radiance factor calibrated data products will have the “IOF” product type (video frames & images).

The file naming convention as used with our archived calibrated products is as reported in the Mars2020 Camera EDR/RDR SIS (M2020 SIS 2021), as follows:

Table 2-1 Mastcam-Z Calibrated RDR 58-character Filename

```
IIB_PPPPVCCCCCCCCCC_TTTEEEGNLLLDDDDFFFFFFFFFSZZZOXXQRR.SSS
```

II:	Two-digit Instrument Identifier: "ZL"=Mastcam-Z left, "ZR"=Mastcam-Z Right
B:	One-digit Filter number: Value 0-7
PPPP:	Four-digit Primary Timestamp: Sol
V:	One-digit Mission Venue identifier (typically, "_" for surface or cruise venue)
CCCCCCCCCC:	Ten-digit Secondary Timestamp: SCLK
TTT:	Three-digit Tertiary timestamp: SCLK milliseconds
EEE:	Three-digit Product Type (ex. Standard "EDR", JPEG "EJP", Video "EVD", Depth Map "EDM", Recovered "ERD")
G:	One-digit Geometry identifier (ex. "_"=raw, "L"=linearized)
O:	One-digit Thumbnail flag : "T"=Thumbnail, "N"=Non-Thumbnail
LLL:	Three-digit Site location count from the RMC where the data were acquired
DDDD:	Four-digit Drive count position within a site location
FFFFFFFFF:	Nine-digit Sequence id where ZCAM is the first four digits followed by a five-digit sequence id (ex. ZCAM00000, setup sequence)
SZZZ:	Four-digit Camera Specific- SZZZ where S = Stereo partner counter and ZZZ = focal length (mm)
N:	One-digit Downsample resolution identifier where N= level of downsampling and resolution= 2^Nx 2^N (ex. If the level of downsampling applied to the image is N=1 then 2^1x2^1= an image resolution of 2x2)
XX:	Two-digit Compression flag (ex. "00"=JPEG lossy compressed thumbnail, "01-99"=JPEG lossy compressed quality level, "LU"=Losslessly uncompressed)
Q:	One-digit Producer of product (ex. "J"=JPL, "P"=made at ASU)
RR:	Two-digit Product Version number
SSS:	Three-digit extension (.IMG, .PNG etc..)

ASU calibrated products have a similar filename to the IDS generated EDRs, with differences only in the product type & one character producer code (A for ASU). The version number is incremented for re-releases to reflect an updated product, which should supersede all prior product versions. The Camera SIS (M2020 SIS 2021) is the controlling document for the filename schema. It has been repeated in this document for convenience.

The data values in ASU produced RAD and IOF products are stored as 16-bit signed MSB integers, in band-sequential format. Products have scaling factor and offset keywords that allow data values to be recast to physical values. Values within either the ODL or XML label provide information to allow the user to properly parse and convert the stored integer values to floating point radiance values in W/m^2/nm/sr (for RAD files) or unitless floating point radiance factor values (for IOF files).

2.1.2 browse_asu

The browse_asu collection contains all the radiance-calibrated and radiance factor-calibrated products. The collection structure of browse_asu is broken down by derived product type (RAD or IOF) and then by sol. These products are in the form of a browse .png file with the same filename as the corresponding image in the data_asu collection. Each file also has a detached XML label that has the same filename before the .XML extension. All radiance

calibrated products will have the product type “RAD” (video frames & images). All radiance factor calibrated data products will have the “IOF” product type (video frames & images).

This collection consists of reduced resolution images, stored in the PNG graphics format, that are created for easy viewing. The products are stored in the similar directory structure as the data collection, to facilitate users finding the browse product to a PDS product. Filename follows the same naming schema for data_asu collection products; the only difference is the extension (PNG for browse products) and lack of an attached ODL label. Browse products are a lossy compressed file format and are generated at the same pixel size as the original image. Browse products are best used to quickly check the images for desired features before downloading the higher-fidelity image product from the data_asu collection.

2.1.3 Calibration Collection

This collection contains calibration data files and their associated metadata, used during the radiometric calibration of an EDR product. Included files are as follows (see Hayes et al. 2020 for a detailed description of each filter type):

- Flat fields (including pre-flight and in-flight sky flats)
- LUT tables (companding tables)
- Bias Files
- Radiometric coefficients
- Effective F-number LUT tables (provides effective F-number for each zoom-level)
- System transmission profiles for each filter
- Bad Pixel Maps

2.1.4 Document Collection

This collection contains copies of published papers that provide additional information of the instrument, data processing and other ancillary information. Documents are stored in Archive PDF (PDF/A) format with a detached PDS4 XML label.

mastcamz_img_inv.pdf Bell III, J.F., J.N. Maki, G.L. Mehall et al. The Mars 2020 Rover Mast Camera Zoom (Mastcam-Z) Multispectral, Stereoscopic Imaging Investigation. Space Sci Rev, https://link.springer.com/article/10.1007/s11214-020-00755-x, 2020.

The “The Mars 2020 Rover Mast Camera Zoom (Mastcam-Z) Multispectral, Stereoscopic Imaging Investigation” paper is an overview of the Mastcam-Z instrument and goes into detail about its features and capabilities.

mastcamz_preflight_cal.pdf Hayes, A.G., Corlies, P., Tate, C. *et al.* Pre-Flight Calibration of the Mars 2020 Rover Mastcam Zoom (Mastcam-Z) Multispectral, Stereoscopic Imager. *Space Sci Rev* **217,** 29 (2021). https://doi.org/10.1007/s11214-021-00795-x

The "Pre-Flight Calibration of the Mars 2020 Rover Mastcam Zoom (Mastcam-Z) Multispectral, Stereoscopic Imager" paper describes the calibration process, including an overview of the calibration pipeline.

mastcamz_radiometric_cal.pdf Kinch, K.M., M.B. Madsen, J.F. Bell III et al. Radiometric Calibration Targets for the Mastcam-Z Camera on the Mars 2020 Rover Mission. Space Sci. Rev., https://doi.org/10.1007/s11214-020-00774-8, 2020.

The "Radiometric Calibration Targets for the Mastcam-Z Camera on the Mars 2020 Rover Mission" paper goes into detail about the Mastcam-Z calibration targets and their use in radiometric calibration.

3 Mastcam-Z Calibration Processing

3.1 Calibration processing Steps

Mastcam-Z products are acquired and downlinked as one of several different product types, which are described in Section 4 of the Mastcam-Z Camera SIS (M2020 SIS 2021).

All products are calibrated to radiance (in the processing parameters section of the ODL label, RADIOMETRIC_CORRECTION_TYPE = RADIANCE). A subset of these products are also calibrated to I/F (RADIOMETRIC_CORRECTION_TYPE = RADIANCE_FACTOR). For I/F products specifically, users should be aware that the reliability of the calibration varies with time and time-of-day differences between the product and its associated caltarget. This is indicated in a coarse manner within the calibrated product metadata by a data quality id or DQI keyword (see Section 4.2.2 for more information).

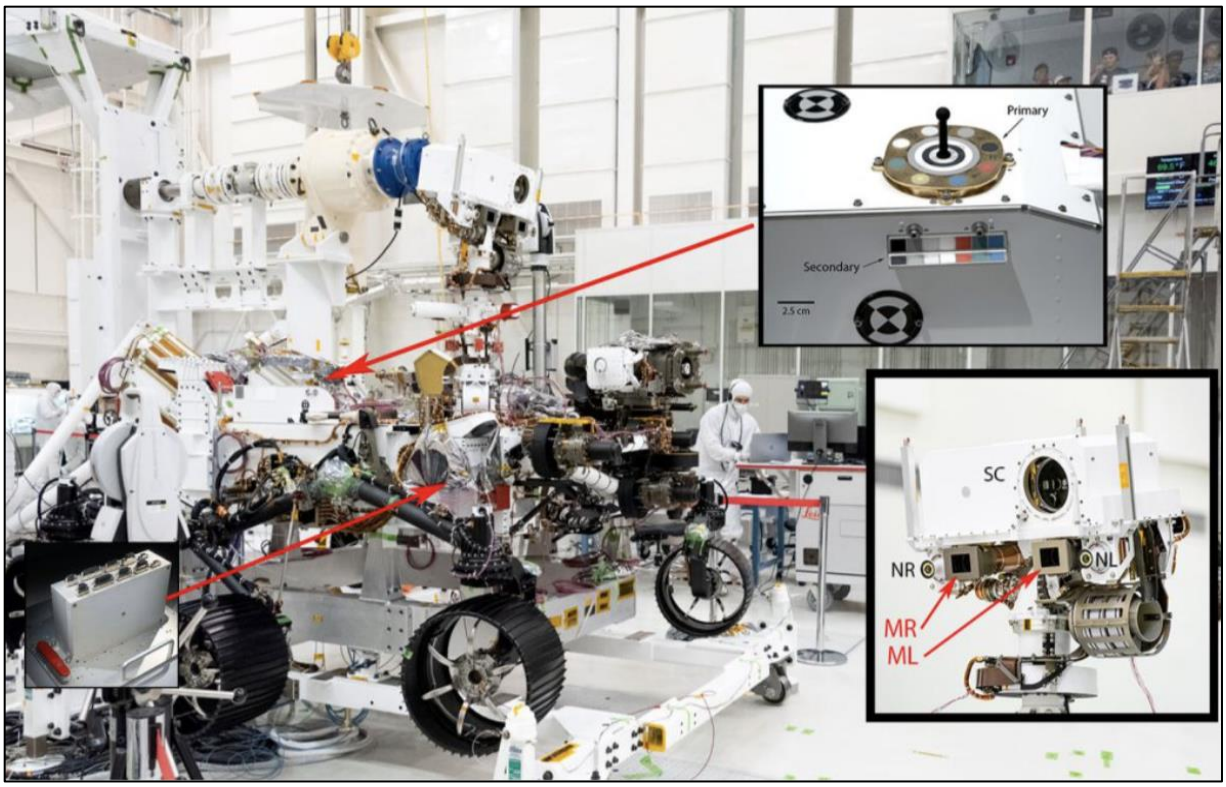


Figure 3-1 Mastcam-Z Primary and Secondary caltarget onboard the rover pre-launch

There are two caltargets mounted on the rover deck for ZCAM. The primary target and secondary target are featured in Figure 3-1. To learn more about these see Kinch et al 2020.

3.2 Product Generation

The ASU calibrated products are derived from Mastcam-Z EDRs obtained from the IDS. IDS generates EDRs from the raw .dat and .emd files as downlinked from the rover. The following sections describe the calibration pipeline steps implemented to generate the calibrated files provided in this bundle. These steps are summarized graphically in Figure 3-2. Processing-specific keywords are added to the metadata for each product, and are summarized in Section 4.2.4.

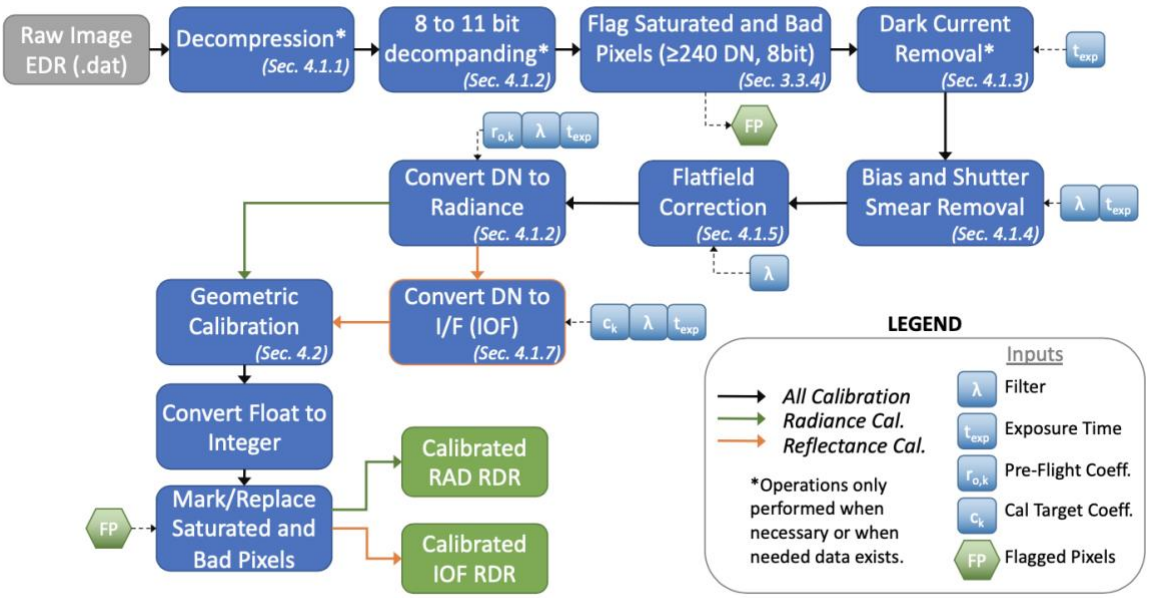


Figure 3-2 The Mastcam-Z radiometric calibration pipeline used to generate the products of this archive (Hayes et. al 2021)

3.2.1 Radiance Calibration (RAD)

The RAD radiance calibration pipeline (Hayes et al., 2020) converts raw images (IDSO generated EDR files) in units of Digital Number (DN) to calibrated files that describe the observed radiance in $W/m^2/sr/nm$. Processing steps, in order, include; bias subtraction, shutter and transfer smear correction, flat field correction, bad pixel removal, and radiance calibration to produce RAD files. The RAD files are then converted to IOF by multiplying by a conversion coefficient determined using the calibration target.

The RAD calibration process remove the effects of the camera optics (e.g., vignetting) and electronics (e.g., transfer smear) to convert the image into a true representation of the observed scene in physical units. Radiance calibrated images create better mosaics which are not only more seamless but also more scientifically useful for tactical rover planning and morphologic and multispectral analyses.

RAD calibration is performed on all images except 0-second exposure shutter frames, which are sometimes acquired and subtracted from the actual images when high radiometric fidelity is required. Otherwise, the shutter frames are simulated using pre-flight calibration data.

Various aspects of the RAD pipeline are updated to reflect changes in the camera system periodically measured during in-flight calibration. An example are sky flats, which are flat field modifications obtained by looking at the uniform sky on Mars. These changes can be caused by dust collecting on the optics, by radiation damage to the detector, or by the long-term effects of thermal cycles of the detector array.

3.2.2 Radiance Factor Calibration (IOF)

The IOF calibration pipeline (Kinch et al., 2020) converts a RAD image to an I/F using the calibrated radiance (RAD) images of the primary and/or secondary caltarget. Almost all RAD calibrated images get converted to IOF, excluding solar filter (L7/R7) and post-sunset/pre-sunrise observations.

3.3 Product Generation

3.3.1 Decompression

Mastcam-Z data products can be compressed for downlink. If applicable, the pipeline will perform decompression into the proper spatial domain format depending on the compression. For more information see Section 4.1.1 in Hayes et al. (2020).

3.3.2 Decompanding

The EDR image data values, which are typically downlinked and stored as 8-bit DN, are decompanded using the appropriate Look-Up Table (LUT) to transform the data into 11-bit values that represent raw linear pixel response. The most commonly used LUT uses a square root LUT that avoids the encoding of photon arrival ("shot") noise. This LUT minimize the loss of data by compressing in steps with magnitudes proportional to the magnitude of noise expected. There are 32 LUTs, all with different application and appropriate scenarios. See Section 4.1.2. of Hayes et al. (2020) for more details.

3.3.3 Handling of Bad Pixels

So-called "bad" pixels (non-responsive, non-linear, or always saturated) were characterized in the Mastcam-Z cameras during pre-flight testing, as described in Hayes et al. (2020). Additional saturated pixels can occur in parts of images with very high signal levels, such as glints off metallic parts of the rover or shiny parts of rocks. We track these bad pixels with a bad pixel map for each image during the calibration process. These bad pixel values are replaced by the value of the INVALID_CONSTANT keyword in the label and are excluded in the calibration process. Bad pixels can cause questionable or peculiar features in calibrated RAD or IOF images, and such potential issues are flagged in the DQI (Section 4.2.2) to notify users of the issue areas and allow them to exclude the values from their own data analyses. To learn more about bad pixels see Hayes et al. (2020).

3.3.4 Bias and Dark Current Correction

Dark current results from thermally generated electron-hole pairs. These pairs are impossible to distinguish from photo-generated electrons in the detector. Dark current typically has an exponential thermal dependance and occurs regardless of illumination of the field of view. See section 3.3.2 on dark current in Hayes et al. (2020) to learn more.

Bias is independent of exposure time and present in all Mastcam-Z images. This bias, which has both static and dynamic (i.e., scene dependent) parameters can be singled out by commanding a zero-second exposure (called "bias frame" images), which are sometimes acquired along with caltarget images. See Section 3.3.3 in Hayes et al. (2020) to learn more.

To combat the inherent bias we apply a correction in the calibration pipeline that subtracts estimates of the static and dynamic bias components. The static bias was measured during pre-flight calibration, while the dynamic bias, which includes transfer smear effects, is modeled using best-fit coefficients generated from in-flight calibration activities.

3.3.5 Shutter Smear Correction

Mastcam-Z does not have a mechanical shutter, and the shielded CCD shift registers transmit a small fraction of the incident illumination, resulting in an effect known as "electronic shutter smear". This additional bias signal is part of the dynamic bias and is dependent on the observed scene (see Figure 3 in Hayes et al., 2020 and additional discussion of this effect in Bell et al., 2017).

3.3.6 Flatfield Correction

A standard way to remove pixel to pixel responsivity differences is by scaling pixel values by a normalized array created from an evenly illuminated or “flat” target. These differences come from variations in detector responsivity, optical effects like vignetting, filter imperfections, and/or dust on the lens or CCD surfaces. Bias and dark current corrected images are multiplied by normalized flatfield maps to attempt to cancel the effects of these variations and make every pixel react the same as an average pixel. See Section 3.6 in Hayes et al. (2020) to learn more.

3.3.7 Convert DN to Radiance

Once images have been dark current subtracted, bias corrected, and flat fielded, Mastcam-Z images can be converted to units of photon flux. The output is a calibrated product with the average in-band radiance incidence upon the CCD sensor. To learn more about the algorithms involved, see Hayes et al. (2020), Section 4.1.6.

3.3.8 Convert from RAD to IOF

During surface operations, multispectral caltarget images are nominally acquired near-in-time to multispectral imaging sequences of Mars. The primary caltarget is used for converting RAD to IOF and the secondary caltarget is used to verify and validate the calibration. Radiance values are first derived from the caltarget images for all applicable observations, and then average radiances from specific Regions of Interest (ROIs) on the caltargets are extracted. For each ROI a plot of observed radiance vs. model reflectance is generated, and a straight-line fit is derived. The slope of this linear fit is a measure of the instantaneous irradiance and provides a direct conversion factor from units of radiance to units of radiance factor (I/F or IOF). The value of the radiance factor scaling coefficient that was used to create each IOF image is included in the label, among the processing parameters, as RADIOMETRIC_COEFFICIENT, in units of $(W/m^2/nm/sr)/(DN/s)$. DN values are normalized by exposure time to DN/s using the label value of EXPOSURE_DURATION within the group INSTRUMENT_STATE_PARMS. Unsaturated DN/s values are linearly related to either radiometric quantity (radiance or radiance factor) by a scaling coefficient. **To learn more about this process and the derivation of radiance factor scaling coefficients from RAD-calibrated caltarget images, see Kinch et al.**

(2020), Sections 3.3.3 and 4.1.7 of Hayes et al. (2020), and the MSL/Mastcam heritage process discussion in Section 5.3.6 of Bell et al. (2017).

3.4 Caveats and Known Issues

3.4.1 Bad Pixels

The left and right Mastcam-Z camera have 1600 x 1200 active pixels. There are 14 known left camera bad pixels and 17 known right camera bad pixels (Hayes et al., 2020). Bad pixels can be “hot”, “gray” or “dead”. A hot pixel is saturated, which we define as 2033 DN or above. A gray pixel is responsive but only at a higher or lower value than the average detector element. A dead pixel is non-responsive. Of the 14 left bad pixels 1 is hot, 5 are gray, and 8 are dead pixels. Of the 17 right bad pixels 4 are gray, and 13 are dead. To learn more about these pixels and their location see Hayes et al. (2020), Section 3.3.4.

3.4.2 Optical Distortion – Vignetting

The Mastcam-Z filters are rectangular, and introduce a small and known amount of vignetting in the raw images, mostly on the left side of the field of view. The effect decreases at longer focal lengths as the field of view contracts. This is expected behavior, and flatfield correction allows us to remove this effect from calibrated images. For additional details and examples, see Hayes et al. (2020), Section 3.6.

4 Product Labels

4.1 PDS4/XML

NASA’s Planetary Data System (PDS) maintains standards for the structure and format of metadata information submitted by data providers to the PDS. PDS4 has accompanying XML labels, which are nested entries of the form <tag>value</tag>. However, we provide ODL labels prepended to the binary image data for compatibility with software developed to support ODL labels, and for better human readability. For image data products, the accompanying XML metadata files are populated directly from the ODL values, and contain approximately the same information, although particular keywords related especially to data processing may be grouped differently in the XML. For other files, such as document or calibration materials, we provide only XML- format metadata.

4.1.1 Detached XML Labels for the Calibrated Image Data Products

The separate XML files contain the same information as within the attached ODL labels, but in a different format and with a different organization. In PDS4, keywords are defined in different data dictionaries, organized by discipline or mission. Our labels use the following dictionaries: Display (disp), Geometry (geom), Imaging (img), Surface Imaging (img_surf), Mission Information (msn), Surface Mission Information (msn_surface), and Processing Information (proc), in addition to the core PDS dictionary (pds).

Identification data elements from the ODL labels can be found either in the <Observation_Area> outside of the specific discipline data dictionaries, within the Mission Information, Surface Imaging, or Surface Mission Information dictionaries. The Surface Mission

Information dictionaries also contains telemetry information. Rover device articulation, camera model, and coordinate system definitions are within <Geometry>.

The <Imaging> section contains commanding, instrument state, data product, and some processing information. It is important to note that some information within the <Commanded_Parameters> group has a subtly different meaning than identical keywords that appear outside of this group. Keywords that describe the data product, rather than the observation itself, apply to the original data request when appearing in this group. For example, an observation that was originally downlinked via lossy compression will reflect that in the <Onboard_ Compression> group; outside of <Commanded_Parameters>, these same keywords describe the actual data product, and for a retransmit, may differ.

Much of the processing information from PROCESSING_PARMS in the ODL label can be found in the <proc:Processing_Information> section which describe the processing history applied to the data product.

The <Reference_List> section does not have an analog in the ODL label. These keyword groups link the data product to the associated source data product and ancillary calibration files.

4.2 Attached ODL Labels for the Calibrated Image Data Products

To a significant degree, the ODL labels for the calibrated data products in this archive reproduce the information contained in the EDR labels of their source products, with the addition of processing information specific to our calibration procedure (see section 4.2.2 below).

4.2.1 ODL Image Label

The ODL3 attached image label contains keywords with information about the image product. The label has telemetry information, commanding, processing, and rover information.

Telemetry information is captured the FILE DATA ELEMENTS group in addition to other key image information like source product, size, and image acquisition time.

The HISTORY DATA ELEMENTS – PDS History group details the software version, name and processing level (ex. EDR to RAD).

CAMERA_MODEL DATA ELEMENTS, COORDINATE SYSTEM STATE: ROVER, COORDINATE SYSTEM STATE: REMOTE SENSING MAST, COORDINATE SYSTEM STATE: TURRET, COORDINATE SYSTEM STATE: TOOL, ARTICULATION DEVICE STATE: REMOTE SENSING MAST, ARTICULATION DEVICE STATE: ROBOTIC ARM, ARTICULATION DEVICE STATE: MOBILITY CHASSIS, ARTICULATION DEVICE STATE: HIGH GAIN ANTENNA,

The OBSERVATION REQUEST, IMAGE REQUEST, SUBFRAME REQUEST, THUMBNAIL REQUEST groups detail what was commanded. INSTRUMENT STATE RESULTS, COMPRESSION RESULTS, MINI_HEADER DATA ELEMENTS, IMAGE DATA ELEMENTS, IMAGE HEADER DATA ELEMENT groups detail what actually occurred during acquisition.

The remaining groups; DERIVED GEOMETRY DATA ELEMENTS: ROVER FRAME, DERIVED GEOMETRY DATA ELEMENTS: SITE FRAME, DERIVED IMAGE DATA ELEMENTS, DRILL

ARTICULATION STATE, SCS ARTICULATION STATE, and SHA ARTICULATION STATE have rover information as it relates to the acquisition of the image.

4.2.2 Label Keywords Pertaining to File Structure and Primary Data products

Mars 2020 Project Mastcam-Z EDRs are published with detached labels containing data object descriptors for the associated file, the observation data, and the camera mini-header. The corresponding Mastcam-Z RDRs are uncompressed, with detached labels pointing to the binary data file. Our ODL product labels are attached to and include an internal file pointer to the binary image data contained within the same file. Our labels begin with an ODL_VERSION_ID keyword that should equal “ODL3” as a proper PDS4 ODL label. It includes a LABEL_RECORDS keyword that gives the length of the label data, and an ^IMAGE pointer that points internally within the file, in units of “records” of size RECORD_BYTES.

The data contained within the OBJECT = IMAGE subsection is likewise different, in order to be appropriate to our data structure and format. These keywords give the size and structure of the image data array; it is stored as 16-bit integer data, with bad data values flagged as INVALID_CONSTANT and MISSING_ CONSTANT.

4.2.3 Data Quality ID (DQI)

The data quality id is addressed in three label keywords. See table below

Keyword	Type	Description
DATA_QUALITY_ID	Integer	This represents the bits associated with the bit names that are present in this image product. If the product is saturated then bit position 0 is flipped making this value equal to "1".
DATA_QUALITY_NAME	String array	This value lists out what the bits represent associated with Data Quality Id. ex. Saturated, Zero-Value Pixels,... etc..
DATA_QUALITY_VALUE	String array	This value is a string array of 0's and 1's indicating which bit position has been flipped. ex, 0,0,0,1,0,0,1,0,0,0

The DATA_QUALITY_ID is an integer representing flipped bits of a 16bit array. This number is unique to the recorded issues and can only represent one value at any given time. These bits are flipped based on tracked issues starting the moment the data is downlinked to our filesystem. The DQI is meant to help data users determine the accuracy and trust ability of any given image product and help with further analysis. See table below for bit position, DQI value, and description.

Bit Position	DQI Value	Description
0	1	image saturation is more than 10% of the pixels (DN = 255)
1	2	image has zero-value pixels (DN = 0)
2	4	image is BELOW the Allowable Flight Temperature range +/- 40°C
3	8	image is ABOVE the Allowable Flight Temperature range +/- 40°C

4	16	image is missing ancillary temperature data
5	32	Image is out of focus
6	64	Image is at the wrong pointing (not as commanded)
7	128	Image is at the wrong zoom (not as commanded)
8	256	Image used the wrong filter (not as commanded)
9	512	Image sequence was cut short by rover before completion
10	1024	Image has raw DN (as downlinked) values above 90% full well
11	2048	Reserved for future use
12	4096	Reserved for future use
13	8192	Reserved for future use
14	16384	Reserved for future use
15	32768	Reserved for future use

4.2.4 Processing Keywords

Processing information for our radiance and I/F calibration is included in the metadata within both of the provided labels (the attached ODL label and the detached XML label), as shown in the table below. As such, all of these keyword values are specific to our calibrated products, and are not present in uncalibrated image files. Some processing keywords are applicable only to the I/F products, as noted in the table. In the ODL label, all of this information is contained within the DERIVED_IMAGE_PARMS group.

To see the scaling factor for Rad products, you will see the RADIANCE_SCALING_FACTOR keyword in the derived image data elements group, only present in our RDR derived data products. The PROCESSING_HISTORY_**TEXT will** tell you the level of calibration. You should see EDR TO RAD or RAD TO IOF in RADs or IOFs respectively.

KEYWORD	TYPE	DEFINITION
UNITS	string	String keyword defining the units of the values in the file
RADIOMETRIC_COEFF	float array	Radiometric coefficient to convert DN (bias subtracted) to radiance units of W/m^2/sr/nm
EFFECTIVE_WAVELENGTH	float array	Weighted average of the system response and solar spectrum
FSUN	float array	In-band spectral irradiance at the top of the Martian atmosphere at perihelion
HOT_PIXEL_COUNT	integer	Number of identified hot pixels
HOT_PIXEL_THRESH_FACTOR	integer	Factor used to define hot pixels. Refers to multiplicative factor used to isolate pixels that are X times greater than their nearest neighbors.
SATURATED_PIXEL_COUNT	integer	Number of saturated pixels

SATURATED_PIXEL_THRESH	float array	DN Value used to define pixel saturation
SATURATED_THRESH	float array	Derived value (radiance or IOF) used to define pixel saturation for center of array
NONLINEAR_PIXEL_COUNT	integer	Number of potentially non-linear pixels
NONLINEAR_PIXEL_THRESH	float	DN Value used to define onset of potential non-linear behavior
NONLINEAR_THRESH	float array	Derived values (radiance or IOF) used to define the onset of non-linear behavior.
NOSSIGNAL_PIXEL_COUNT	integer	Number of pixels that received no signal above bias.
RADIOMETRIC_COEFF_STD	float array	1-sigma standard deviation in radiometric coefficient
DYNAMIC_BIAS_FILE_NAME	string	Filename used for the dynamic bias correction
STATIC_BIAS_FILE_NAME	string	Source file containing the static bias that was subtracted during calibration
CONTINUOUS_FLAT2_FILE_NAME	string	Source file containing the second continuous flat values used during calibration
CONTINUOUS_FLAT1_FILE_NAME	string	Source file containing the first continuous flat values used during calibration
SKY_FLAT_FIELD_FILE_NAME	string	Source file containing the sky flat values that were used calibration
BAD_PIXEL_FILE_NAME	string	Source file containing the map of bad pixels used during calibration of this image
IOF_CONV_COEFF	float array	IOF Conversion coefficient
IOF_CONV_COEFF_STD	float array	1-sigma standard deviation in IOF conversion coefficient

4.3 XML Metadata for Other Products in the Archive

PDS4 follows the principle of “Everything is a product.” As such, other files in addition to data products also have XML metadata, including documentations and ancillary calibration files. For delimited text files in this archive such as those that store information on calibration parameters, the XML provides descriptions of the different fields in each record; the files themselves do not contain a header line. For documents, the XML contains file information, internal references, and citation data. Each collection also has an inventory table in the form of a .csv file; the associated metadata contains identification and citation information.

5 Reading Image Data Files

We do not provide software to read, display, or manipulate data values as any part of this or subsequent releases. The PDS provides a registry of software tools for working with data following PDS standards, available online; however, we do not provide any guarantees that these tools will operate on our products free of error. A change with PDS4 is the PDS_VERSION_ID was updated to ODL_VERSION_ID which may make PDS3 made tools fail when trying to parse a PDS4 data product.

Many programming languages provide library functions designed to parse binary files. Both the XML and ODL labels contain keyword values that communicate the file structure and data storage type such that the user could read the file into a data structure by correctly applying this information. In ODL, the file structure is described by RECORD_TYPE, RECORD_BYTES, FILE_RECORDS, and LABEL_RECORDS keywords, as well as ^IMAGE, a pointer to the start of the binary image data. Users will also need the data provided in the OBJECT = IMAGE group, which describes the structure of the image array.

If the image values were successfully read, the data structure should contain an m × n or m × n × 3 array of 16-bit integer values (float values if by a tool that has automatically unscaled the data), depending on the product type. To convert integers to radiometric floating-point values, the integer array should first be multiplied by the value given by the SCALING_FACTOR keyword, then added to the value given by the OFFSET keyword. Pixels corresponding to the integer value given by either of INVALID_CONSTANT or MISSING_CONSTANT need to be flagged and excluded from analysis.

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