Description of the Mars 2020 Mastcam-Z Photometry Cube PDS Archive

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1 DATA SET OVERVIEW

The Mastcam-Z Photometry Cube data set contains derived data from the Mastcam-Z instrument on the Mars 2020 Perseverance rover. Mastcam-Z is a stereoscopic multispectral imaging system. Each of the two Mastcam-Z "eyes" has an eight-position filter wheel that provides data for surface mineralogic, photometric, and topographic studies [1]. Filter positions and wavelengths for the "geology" filters are shown in Table 1, which includes Bayer filters. Mastcam-Z is a zoomable camera system, providing focal lengths from 100 mm to 26 mm. Images acquired for the photometry experiments shown here used the 34 mm ("Z34") focal length, which has a Field-of-View (FOV) of 20°x15° and an Instantaneous Field-of-View (IFOV) of 0.22 mrad/pixel.

Table 1. Mastcam-Z geology filters

Name	*Center λ (nm)*	*Bandpass (nm)*		*Name*	*Center λ (nm)*	*Bandpass (nm)*
L0R	630	43		R0R	630	43
L0G	544	41		R0G	544	42
L0B	480	46		R0B	480	46
L1	800	9		R1	800	9
L2	754	10		R2	866	10
L3	677	11		R3	910	12
L4	605	9		R4	939	12
L5	528	11		R5	978	10
L6	442	12		R6	1022	19

Mastcam-Z images were acquired at different times of sol over several sols at the same rover location to sample sufficient incidence, emission, and phase angles to enable radiative transfer modeling (e.g., using Hapke theory) (e.g.,[4]). Stereo images were used to generate three-dimensional cubes containing multispectral images and geometric information. The core bands of the cubes include Mastcam-Z multispectral images calibrated to radiance ($W/m^2/nm/sr$) and radiance factor (IOF) ([1][3]). The backplanes contain the following geometric information: range images, XYZ images, surface normal images, and incidence, emission, and phase angle images. Note that future additional photometry cubes generated from Mastcam-Z observations will be added to this data set (e.g., [9][10]).

This archive was produced using the PDS4 archiving standards. An overview of PDS4 is provided in the PDS4 Concepts document [14], and the standards are specified in the PDS4 Standards References [13].

2 PHOTOMETRY CUBE PROCESSING

The Photometry products were created with techniques similar to those used by[4][5][6][7], in this case using Mastcam-Z Z34 stereo image pairs to create digital terrain models. Based on an algorithm from [2], disparity maps were made from a given Mastcam-Z stereo pair using the 800 nm (L1, R1) filters in each eye. Each pixel in the Mastcam-Z left eye was correlated to the matching feature in the right eye. These matched points were projected using Mastcam-Z camera models into rover Cartesian coordinate space (XYZ). This enabled calculation of range (distance) and surface normal (UVW) (cf.[11]). Values for incidence, emission, and phase (IEP) angles were computed for each pixel by integrating the positions of the sun and camera. The combination of these products (registered Z34 images in both radiance factor (I/F) and radiance, XYZ positions, range, UVW, and IEP) formed the photometric information for a scene acquired at a particular time of sol. The final Photometry products for a given scene included all Z34 images from each time of sol.

3 DETAIL DATA PRODUCT STRUCTURE

The PDS4 product for a Mastcam-Z photometry cube consists of two files: the PDS4 label and the image cube. The PDS4 label (*.xml) is a XML file that contains metadata about how the data in the image cube were acquired and information on the physical structure of the image cube. Each image cube file contains multispectral filters of Mastcam-Z data for all times of sol acquired for a given scene and a number of geometry backplanes including lighting and viewing geometry. Table 2 shows the order of the bands within a photometry cube product. Table 3 gives a summary of the filters in the Mastcam-Z sequence. The specific Mastcam-Z filters for each image cube are described in the product's PDS4 label. The attached headers in the files also include information copied from the first original image used to create the Photometry cube (users are directed to the Mastcam-Z Software Interface Specification document [12]). Also contained are the lists of filenames used in the photometry cube (see Table 2).

Table 2. General order of bands in photometry cubes

Name	*Band number(s)*	*Comment*
Reference IOF Image	1	band 1 of multispectral sequence (or bands 1-3 if RGB image)
Incidence angle	2	for the sequence acquired
Emission angle	3	same map for all times of day
Phase angle	4	for the 1st time of sol acquired
NaN mask	5	invalid pixels (lacking stereo correlation). Invalid/missing pixels in other bands are flagged with the exact value 0; the NaN-mask is bivalued (0 valid, 1 invalid). Treat pixels as valid only when NaN mask = 0 and band ≠ 0.
Range	6	(meters)
XYZ-1,2,3	7-9	X, Y, Z coordinates (digital terrain)
UVS-1,2,3	10-12	U, V, S (surface normal) coordinates
IOF images	13-17, 24-29,36-41,48-53,60-65,72-77,84-89	remaining IOF images from each filter and 7 times of sol acquired
RAD images	18-23,30-35,42-47,54-59,66-71,78-83,90-95	RAD images from each filter and7 times of sol acquired
Incidence, Phase angle	96-107	sequential Incidence/Phase angle maps from other times of sol (Incidence 2, Phase 2, Incidence 3, Phase 3, etc.)

The structure of the Mastcam-Z image data in the cube are described in the Array_3D_Image section of the PDS4 XML label, including band-specific identifying information. The size of each axis in the 3D cube (i.e., number of lines, samples, and bands) are defined, along with the storage order, which is band sequential. A description of key backplanes is given above (cf. Table 2).

XYZ, Range, and Surface Normal Images:

The disparity calculations were used in combination with camera models calculated onboard to compute the XYZ location, range, and surface normal values for each pixel location where stereo correlation was successful. The reference frame for X, Y, and Z data is called site frame, which is a right-handed Cartesian system with the positive X-axis aligned with north, positive Y-axis aligned with east, positive Z-axis pointed down. There are a total of seven backplanes for these quantities, three for XYZ, one for range, and another three for the three components of the surface normal unit vector. X, Y, Z, and range data are in units of meters, whereas the surface normal components are unitless and have values between 0.0 and 1.0.

Incidence, Emission, and Phase Angle Maps:
The incidence, emission, and phase angle images were calculated from Mastcam-Z Z34 stereo images using the surface normal geometry products described above in combination with knowledge of the solar geometry derived from SPICE data. The incidence angle is the angle between a feature's surface normal and the Sun. The emission angle is the angle between a feature's surface normal and the boresight of the camera. The phase angle is the angle between the boresight of the camera and the Sun, whose vertex is located at the feature. These backplanes only have real values for pixels where a surface normal exists. The angles have units of degrees.

The lighting and viewing angles were computed with the Sun position at the time that the images were acquired. The elapsed time while the other filters were acquired means that the Sun moved slightly while these other images were taken. This does not have a large effect for most geometries, but can be more noticeable for small phase angles.

Users should note that regions where the stereo correlation did not converge are marked by NaN values (see Table 2). However, some non-physical values (incidence angles > 90, etc.) may still occur that were not designated by NaN values.

4 ARCHIVE STRUCTURE

The Mastcam-Z photometry cube archive uses the PDS4 archiving standard [13][14] for the archive structure and product labels. In PDS4 every object in the archive is a product, meaning that it has a detached PDS4 label expressed in XML and for most product types an associated data object. The logical structure of a PDS4 archive is hierarchical. The physical archive structure usually follows a similar pattern. At the base of the hierarchy are basic products, such as individual Mastcam-Z photometry cubes and documents. Basic products of similar types are aggregated into collections.

4.1 Bundle and Collections

There are two collections in this archive: **data** and **document**. The photometry cubes are in the **data** collection, while bundle documentation is in the **document** collection. Each collection has a collection product, which consists of an XML label and an inventory table that lists the members of the collection. The physical storage for the photometry cube collection is broken down into subdirectories based on the first Sol that the original data were acquired. The collection product and member products for the **document** collection are stored in the same directory because these collections only have a few products. In PDS4, related collections are logically and often physically collated together into a bundle. The bundle product is an XML file, which serves as both a label and the bundle inventory, i.e., a list of included collections. The bundle product for this archive is located in the root directory of the archive. There are also subdirectories under the bundle root directory for each collection.

4.2 Data Product Logical Identifiers

All PDS4 products are uniquely identified by a combination of a logical identifier (LID) and a version identifier (VID). The LID and VID are separate attributes in a PDS4 label. However, they can be combined together into a versioned identifier (LIDVID) to uniquely identify and locate a particular version of a particular product throughout the entire PDS inventory. A LIDVID for a basic product, i.e., a Mastcam-Z photometry cube, has the form of:

urn:nasa:pds:<bundle_id>:<collection_id>:<product_id>::<version_id>

where:

urn:nasa:pds notes that this is a PDS4 product
<bundle_id> is taken from the bundle LID
<collection_id> is taken from the collection LID
<product_id> is a string to uniquely identify the product within its collection
<version_id> is a version identifier.

An example LIDVID for a photometry cube product is as follows:

**urn:nasa:pds:mars2020_mastcamz_photometry:data:
zl1_0063_0672518756_943iof_n0032046zcam03117_034085a03_photometry::1.0**

where:

mars2020_mastcamz_photometry is the bundle_id
data is the collection_id
zl1_0063_0672518756_943iof_n0032046zcam03117_034085a03_photometry is the product_id and is the cube file name without its extension
1.0 is the version identifier.

Version identifiers have the form M.n where M and n are both integers. The first version of a product has a VID of 1.0. Minor changes to the product or its label cause the n to increment and major changes, like recalibration, cause the M to increment.

4.3 File Names

File names for photometry cube products have the following formation rule:

<camera_name>_<sol>_<sclk>_<sclk-tertiary><product-type>_<thumbnail-flag><site><drive><seqid>_<focal-length><downsampling><compression><producer><product counter><extension>_photometry.<extention>

where:

<camera_name> abbreviated name of camera (zl1 for Mastcam-Z Left filter 1 is used because that was the first filter acquired in a given sequence)
<sol> is the 4 numeric digit value for Sol number on which the original data were first acquired
<**sclk**> is the 10 numeric digit spacecraft clock time associated with the first image in seconds
<**sclk-tertiary**> is the 3 numeric digit tertiary spacecraft clock time in milliseconds
<**product-type**> is the 3 character product type of the originating image; always "iof" for these products
<**thumbnail-flag**> is the 1 character identifier "n" for "non-thumbnail" image
<**site**> is the 3 numeric digit Site location count from where the data were acquired
<**drive**> is the 4 numeric digit Drive count position within a Site location
<seqid> is the 9 numeric digit value for the Mastcam-Z sequence number for the first observation
<**focal-length**> is the 3 numeric digit value for the camera focal length setting in millimeters (always 034 here)
<**downsampling**> is the 1 numeric digit value for any image downsampling, where 0 = no downsampling
<**compression**> is the 2 numeric digit value for jpeg compression (85 for images used here)
<**producer**> is the 1 numeric digit Producer of the original product ("a" = made at Arizona State University)
<**product counter**> is the 2 numeric digit Product Process Counter (versioning used by Arizona State University)
<**extension**> is the 3 numeric digit filename extension (.img)

An example cube file name is:

zl1_0063_0672518756_943iof_n0032046zcam03117_034085a03_photometry.img. The product's PDS4 label file has the same name but with XML for the file extension.

5 CUBE SEQUENCES INCLUDED IN ARCHIVE AND DATA QUALITY

The following table summarizes the products in the current Mars 2020 collection. Note that the sol range in the table below spans the full range of sols over which data were acquired for each area.

Table 3. Mars2020 Mastcam-Z Photometric Sequences					
Sols	*Area*	*Filters*	*Phase Angle Range (noted for center of frames only)*	*No. of Cubes*	*Reference*
63-65	Van Zyl Overlook	L156R126	~7-150°	4	[8]

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