Description of the Mastcam Photometry Cube PDS Archive

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TABLE OF CONTENTS

1 DATA SET OVERVIEW

The Mastcam Photometry Cube data set contains derived data from the Mastcam and Navcam instruments on the Mars Science Laboratory Curiosity rover. Mastcam is a high resolution, multispectral imaging system. Each of the two Mastcam "eyes" has an eight-position filter wheel that provides data for surface mineralogic, photometric, and topographic studies (Bell et al., 2017). Filter positions and wavelengths for the "geology" filters are shown in Table 1, which includes Bayer filters. The Navcam stereo images use red/near-infrared bandpass filters centered at 650 nm (Maki et al., 2012). Their stereo images were used to enable calculation of terrain measurements necessary to compute local incidence and emission angles, as described further below.

Table 1. Mastcam geology filters

Name	*Center λ (nm)*	*Bandpass (nm)*		*Name*	*Center λ (nm)*	*Bandpass (nm)*
L0R	640	44		R0R	638	44
L0G	544	38		R0G	544	39
L0B	480	37		R0B	480	38
L1	527	7		R1	527	7
L2	445	10		R2	447	10
L3	751	10		R3	805	10
L4	676	10		R4	908	11
L5	867	10		R5	937	11
L6	1012	21		R6	1013	21

Because the Left (M34) and Right (M100) cameras comprising the Mastcam imaging system have different focal lengths, it was more efficient to generate stereographic data from Navcam image sequences taken at the same time as the Mastcam imaging sequences. Navcam stereo images were used to generate three-dimensional cubes containing multispectral images and geometric information. The core bands of the cubes include Mastcam multispectral images calibrated to radiance and radiance factor (IOF, as described in Bell et al., 2017). 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 observations could be added to this data set.

This archive was produced using the PDS4 archiving standards. An overview of PDS4 is provided in the PDS4 Concepts document (PDS4 Concepts, 2021), and the standards are specified in the PDS4 Standards References (PDS4 Standards Reference, 2021).

2 PHOTOMETRY CUBE PROCESSING

The Photometry products were created with techniques similar to those used by Johnson et al. (2006a,b; 2015, 2021), but instead of using MER Pancam stereo images, MSL Navcam stereo images were geometrically correlated to provide digital terrain models. Based on an algorithm from Deen and Lorre (2005), disparity maps were made from a given Navcam stereo pair that encompassed the region in which the Mastcam M34 images were acquired. Each pixel in the Navcam left eye was correlated to the matching feature in the right eye. These matched points were projected using camera models for both Navcam and Mastcam M34 into rover Cartesian coordinate space (XYZ). This enabled calculation of range (distance) and surface normal (UVW) (cf. Leger et al, 2005). 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 M34 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 M34 images from each time of sol.

3 DETAIL DATA PRODUCT STRUCTURE

The PDS4 product for a Mastcam 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 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. The number of multispectral filters in a given image cube varies within the archive. Table 3 gives a summary of the filters in each set of Mastcam sequences. The specific Mastcam filters for each image cube are described in the product's PDS4 label. Band-specific identifying information is included in the Array_3D_Image description.

Table 2. General order of bands in photometry cubes

Name	*Comment*
Reference IOF Image	band 1 of multispectral sequence (or bands 1-3 if RGB image)
Incidence angle	for the 1st sequence acquired
Emission angle	same map for all times of day
Phase angle	for the 1st time of sol acquired
NaN mask	invalid pixels (lacking stereo correlation)
Range	(meters)
XYZ-1,2,3	X, Y, Z coordinates (digital terrain)
UVS-1,2,3	U, V, S (surface normal) coordinates
IOF images	remaining IOF images from each filter and time of sol acquired
RAD images	RAD images from each filter and time of sol acquired
Incidence, Phase angle	sequential Incidence/Phase angle maps from other times of sol (Incidence 2, Phase 2, Incidence 3, Phase 3, etc.)

The images to create these photometry cube products were originally generated during the MSL mission, which used PDS3 archiving standards. Thus, the cube files have attached PDS3-like labels. The PDS3 label is described in the PDS4 xml label as a Header object. The PDS3 label may contain some information of interest to the science user. So, it was left as is in the archived cube product.

The structure of the Mastcam image data in the cube are described in the Array_3D_Image section of the PDS4 XML label. 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 Navcam 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 photometry cube archive uses the PDS4 archiving standard (PDS4 Concepts, 2021; PDS4 Standards Reference, 2021) 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 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 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:msl_mastcam_photometry:data:0060ml0002730040102315d01_a1i1_photometry::1.0

where:

msl_mastcam_photometry is the bundle_id
data is the collection_id
0060ml0002730040102315d01_a1i1_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:

<sol><camera_name><seqid><imageid><file_type><version>_<filter><calibration_version>_photometry.img

where:

<sol> is the 4 numeric digit value for Sol number on which the original data were first acquired
<camera_name> abbreviated name of camera (ML for Mastcam Left)
<seqid> is the 6 numeric digit value for the Mastcam sequence number for the first observation
<imageid> is the 10 numeric digit value for the image identifier
<file_type> indicates file type identifier based on source product (c=Losslessly Compressed 8 Bit Image; d=JPEG Gray Image)
<version> is the 2 digit alphanumeric code to indicate the sequential processing version of the first file used in the cube
<filter> is the 2 digit alphanumber code to indicate the filter number of the first file in the cube (e.g., A1)

<calibration version> is the 2 digit alphanumeric code to indicate the sequential processing version of the first file in the cube (e.g., i1)

An example cube file name is **0060ml0002730040102315d01_a1i1_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 MSL collection. Note that the sol range in the table below spans the full range of sols over which data were acquired for each area. In some cases data were not acquired on all sols within the range.

Table 3. MSL Photometric Sequences

Sols	*Area*	*Filters*	*Phase Angle Range (noted for center of frames only)*	*No. of Cubes*
20	Bradbury Landing	Bayer L0RGB	32-143°	63
60-78	Rocknest	L1236	10-145°	4
171-184	John Klein	L1236	8-127°	4
397	Darwin	L1236	9-139°	3
441-443	Cooperstown	L1236	4-139°	4

Below are data quality notes about cube products in the collection:

1) Sol 20: The photometry cube for scene 53 (out of of 64) was not produced owing to issues with its stereo correlation. Note that the Sol 20 data was acquired specifically for Mastcam calibration purposes, resulting in the acquisition of 64 frames (16 in each of four quadrants).

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