Description of the Pancam Photometry Cube PDS Archive

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1. Data Set Overview

The Pancam Photometry Cube data set contains derived data from the Pancam instrument on the Mars Exploration Rovers (MER) Spirit and Opportunity. Pancam is a high resolution, multispectral and stereo imaging system. Each of the two Pancam "eyes" has an eight-position filter wheel that provides data for surface mineralogic, photometric, and topographic studies (Bell et al., 2003). Filter positions and wavelengths for the “geology” filters are shown in Table 1.

Table 1. Pancam geology filters

Name	*Center λ (nm)*	*Bandpass (nm)*		*Name*	*Center λ (nm)*	*Bandpass (nm)*
L1	739	338		R1	436	37
L2	753	20		R2	754	20
L3	673	16		R3	803	20
L4	601	17		R4	864	17
L5	535	20		R5	904	26
L6	482	30		R6	934	25
L7	432	32		R7	1009	38

Stereographic data from Pancam image sequences were used to generate three-dimensional cubes containing multispectral images and geometric information. The core bands of the cubes include left-eye and warped right-eye multispectral images calibrated to radiance factor (IOF*,* described below). The backplanes contain the following geometric information: calibrated right-eye images, disparity images, range images, XYZ images, surface normal images, and incidence, emission, and phase angle images. These image cubes have been used to study the photometric properties of materials visited by the Spirit and Opportunity rovers (Johnson et al., 2006a; Johnson et al., 2006b; Johnson et al., 2015). The data set is being archived with the Planetary Data System (PDS) for use in future photometric and multispectral research. Note that the current collection of Pancam cubes is only a subset of Pancam multi-filter, stereo observations that could be turned into cube products. If in the future additional photometry cubes are generated from Pancam observations, these 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, 2015) and the standards are specified in the PDS4 Standards References (PDS4 Standards Reference, 2015).

2. Photometry Cube Processing

Photometry cubes were created using a modified version of the MER image processing pipeline of Alexander et al. (2006). Pancam stereo pairs were correlated to produce a disparity map, using an algorithm described by Deen and Lorre (2005). When both red (L2/R2 filters) and blue (L1/R1) stereo pairs were available, the correlation algorithm would use the blue stereo pair. The disparity map derived from the stereo correlation provides, for each pixel in the left eye image, the coordinates of the matching pixel in the right eye image by correlating a small patch around the pixel using a two-dimensional search (Alexander et al., 2006). Further, both left-eye to right-eye and right-eye to left-eye correlations were performed. The matching points between images were projected into 3-D space by using camera models that describe the relationship between line and sample in the image and a view ray in the rover (XYZ) Cartesian coordinate space. The point where the left-eye and right-eye rays come closest to intersecting were selected as the XYZ coordinate of the pixel. The Cartesian distance from the camera to that coordinate is stored in the range image. Next, the surface normal (UVW) was determined for each pixel. A patch of XYZ coordinates around each pixel was analyzed to determine the best fit for a plane, as described by Leger et al. (2005), and the normal to the plane was expressed as a unit vector. The incidence, emission, and phase (IEP) angles were computed for each pixel by using the camera and solar locations and the XYZ and UVW values of the pixel. Finally, the right-eye images were back-projected through the disparity map to create a warped image product, with the advantage that features were co-registered with the left-eye. All of these data (original and warped images in all available filters, right and left disparity, XYZ, range, UVW, and raw and approximated lighting and viewing angles) were collected together to form the photometry cube for a given scene. The XYZ images and especially the UVW images typically contain several holes where correlations and plane fits can be unsuccessful. To fill in these gaps, the IEP products were also interpolated to produce "approximated" products.

This geometric data is derived from a stereo pair of images in the observation using software developed at Cornell University and the Multi-mission Image Processing Laboratory (MIPL) at JPL. Disparity values are calculated for pixel locations with successful stereo correlations. Uncertainties in the stereo correlation led to errors in the derived disparity images. During an observation the camera model is calculated on-board using knowledge of the rover's orientation derived from Inertial Measurement Unit (IMU) and the camera's orientation. Using the disparity maps derived from the stereo correlation, solar geometry derived from SPICE data (spacecraft and solar system body ephemerides and instrument field of view and pointing information), and the camera model calculated on-board, the range images, XYZ images, surface normal images and incidence, emission, and phase angle images of the observed surface are calculated.

The Pancam multispectral image data were first calibrated to units of radiance and then a quantity known as IOF was computed (Bell et al., 2006). IOF is defined as the ratio of the bidirectional reflectance of a surface to that of a normally illuminated perfectly diffuse surface. This ratio is also known as a radiance factor (Hapke, 1993). IOF is equal to I/(pi*F) where I is the measured scene radiance, and pi*F is the solar irradiance at the top of the Martian atmosphere. The image data (original and warped right-eye) in the cubes are IOF values.

3. Detail Data Product Structure

The PDS4 product for a Pancam 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 (*.qub) contains several multispectral filters of Pancam data and a number of backplanes including lighting and viewing geometry. The number of multispectral filters in a given image cube varies within the archive.

Tables 2 and 3 give a summary of the filters in each set of Pancam sequences. The specific Pancam filters for each image cube are described in the product's PDS4 label.

These cube products were originally generated during the MER mission, which used PDS3 archiving standards, but the products were never archived in the PDS before now. 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 Pancam image data in the cube is described in the Array_3D_Spectrum 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. IOF values for the image data are stored as scaled 2-byte integers with the most significant byte first. Scale and offset values are included in the label to convert the scaled integer numbers into floating point values. The right eye filters in the cube are warped using the disparity images so that they are registered with the left eye data. This enables one to easily extract multispectral spectra for a given feature. The Spectral_Characteristics section of the XML label provides the specific Pancam filters contained in each cube. The filter name, approximate center wavelength and bandpass are listed for each filter. The characteristics of the backplanes in the cube are described by a series of Array_2D_Image objects the PDS4 label. Thus, each backplane can be thought of as a separate 2D image. The Array_2D_Image object contains similar information as the Array_3D_Spectrum for the image cube. All backplanes are scaled 2-byte integers with the most significant byte first. Scale and offset values to convert these scaled number to floating point values are given for each backplane in the PDS4 label. A description of the backplanes is given below.

Original Right Eye Images:
These backplanes are the right eye images in their original frame, that is, the orientation of the data before it was warped. There are the same number of right eye backplanes as there are right eye bands in the 3D image portion of the file. The right eye backplanes are in scaled units of IOF. Scale and offset values to convert these scaled number to floating point values are given in the PDS4 label. These backplanes are named in the label with the form IOF_Rx, where x is the right eye filter number.

Disparity images:
Disparity images are derived from stereo images using a correlation algorithm developed at JPL's MIPL (Multi-mission Image Processing Laboratory). There are four disparity images included as four separate backplanes. The backplanes named disparity_l_eye_0 and disparity_l_eye_1 correspond to the line (row) and sample (column) disparity values in the left eye. Likewise, backplanes named disparity_r_eye_0 and disparity_r_eye_1 are the line (row) and sample (column) disparity values in the right eye. That is the 0 image is the line coordinate of the point in the other eye and the 1 image is sample coordinate of the other eye. Disparity values are given in units of pixels.

XYZ, Range, and Surface Normal Images:
The disparity images are 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 and a disparity was determined. 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 are calculated 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.

Approximated Incidence, Emission, and Phase Angle Images:
There are three separate backplanes with names of the form 'approx_*' in the PDS4 label. These are approximated lighting and viewing angle images made by interpolating data from the original incidence, emission, and phase angle images, attempting to fill in areas where the stereo correlation was not successful. These angles have units of degrees.

The above lighting and viewing angles were computed with the Sun position at the time that the stereo pair filters were acquired. The elapsed time while the other filters were acquired means that the Sun moved 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. The accuracy of the rover attitude can also add uncertainty to the computed emission and phase angles. The rover attitude is determined from its Inertia Measurement Unit (IMU), which can drift over time. The IMU determined attitude is periodically checked and updated by imaging the position of the Sun to minimize any attitude error from drift.

4. Archive Structure

The Pancam photometry cube archive uses the PDS4 archiving standard (PDS4 Concepts, 2015; PDS4 Standards Reference, 2015) 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 Pancam photometry cubes and documents. Basic products of similar types are aggregated into collections. In this archive the collections include the MER1 (Opportunity) cubes and MER2 (Spirit) cubes where the name is based on the Spacecraft_ID as is done for other MER PDS archives. Note that the Spirit mission is also known as MERA and Opportunity mission as MERB. There is also a collection for documents and one for ancillary tables (named MISCELLANEOUS). 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 two photometry cube collections is broken down into subdirectories based on the Sol that the original data were acquired because each collection has a large number of products. The collection product and member products for the DOCUMENT and MISC collections 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.

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 LID for a basic product, i.e., a Pancam photometry cube, has the form of:

urn:nasa:pds:<bundle_id>:<collection_id>:<product_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.

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

urn:nasa:pds:mer_pancam_photometry:mer1:b0029_p257501_01_01v02

where:

mer_pancam_photometry is the bundle_id
mer1 is the collection_id
b0029_p257501_01_01v02 is the product_id and is the cube file name without its extension.

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.

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

<rover><sol>_<seqid><seqver>_<run_id>_<frame_num>V<version>.QUB

where:

<rover> has a value of A for Spirit and B for Opportunity
<sol> is the Sol number on which the original data were acquired
<seqid> is the Pancam sequence number for the observation
<seqver> is the version number of that sequence
<run_id> indicates which time the sequence was run
<frame_num> identifies individual pointings with a sequence
<version> indicates the processing version of the cube. There are a few cases where multiple versions of a cube generated with different parameter settings are included in the archive.

An example cube file name is: A013_P236402_01_01V01.QUB. The product PDS4 label file has the same name but with XML for the file extension. Note that the A and B values for the <rover> token refers to the mission with MERA referring to Spirit and MERB referring to Opportunity. The spacecraft_id is used in the PDS archives delivered by the MER project. This convention is followed in this data set for the collection names when referring to the rovers with MER1 being Opportunity and MER2 being Spirit.

5. Cube Sequences Included in Archive and Data Quality

The following table summarizes the products in the Spirit rover (MERA / MER2) 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 2. Spirit Photometric Sequences

Sols	*Area*	*Filters*	*Phase Angle Range (°)*	*No. of Cubes*
13	Landing site	L247R27	30-120	12
87-88	Bonneville rim	L247R27	25-120	10
102-103	NW of Missoula crater	L247R17	0-125	36
212-225	Cahokia	L247R27	0-125	21
284-286	Palenque 1	L247R27	0-100	13
291-295	Palenque 2	L247R27	0-100	6
401-404	Paso Robles 1	L247R27	0-70	9
425-426	Paso Robles 2	L247R27	10-110	9
564	Voltaire	L247R27	40-95	12
606-610	Cliffhanger	L247R27	5-147	35
708-710	El Dorado	L247R27	32-150	12
930-935	Low Ridge/McMurdo	L247R27	9-150	12
1142-1148	Torquas	L247R27	15-137	23
1240-1245	Eileen Dean	L247R27	13-151	40

Below are data quality notes about cube products in the Spirit rover (MERA / MER2) collection:

1) Sol 102-103 cubes contained some data dropouts (missing packets never recovered) for the following data sets:

L4 filter in A103_P238203_01_02V03.QUB
R7 filter in A102_P238003_02_03V03.QUB
R7 filter in A103_P238003_01_01V03.QUB
L7 and R1 filters in A103_P237903_01_01V03.QUB
L7 filter in A103_P238103_01_03V03.QUB.

2) Sol 212-225 West-looking photometry cubes (sequence P2401) include two files labeled with both a "*V02.QUB" and "*V03.QUB" suffix in the filename. These employed a slightly different algorithm designed to emphasize correlations of distant targets. The V02 QUBs were used for analysis far-field targets (nominally the "ripple soils" from that data set). The V03 QUBs were normal versions used for near-field and mid-field targets.

3) Sol 284-286: Full sequences of two far field scenes were not acquired in the late afternoon in the southeast sector, which would have matched these two taken on Sol 284:

A284_P241604_01_05V03.QUB
A284_P241604_01_06V03.QUB

4) The A295_P242304_01_02V03.QUB (a 13-filter observation) has the R567 filters offset from the others in the warped images.

5) The A610_P284706_01_01V01.QUB file does not contain R2 image data.

6) The P2763 west-looking sequences were not acquired on sol 1148 as part of the Torquas experiment.

The following table summarizes the products in the Opportunity rover (MERB / MER1) 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. Opportunity Photometric Sequences

Sols	*Area*	*Filters**	*Phase Angle Range (°)*	*No. of cubes*
11	Eagle crater (landing site)	L247R27	40-115	15
29-33	Eagle crater (McKittrick, Guadalupe, Tamannend Park)	All	30-90	7
38-39	Eagle crater (Last Chance)	L247R27	20-105	11
42-45	Eagle crater (Berrybowl)	All	30-125	4
89-91	Plains NW of Endurance crater	L247R17	0-150	48
261-262	Endurance: Wopmay	L27R17	20-80	3
306-307	Endurance: Tipuna	L247R17	25-75	5
328-329	Westpoint (Heat Shield)	L247R17	0-75	13
335-336	Heat Shield	L247R17	0-150	24
339-352	Heat Shield rock	L247R17	40-100	6
363	Plains (near Alvin crater)	L247R17	25-110	4
367-374	Trench site (near Alvin crater)	L247R17	0-150	50
403-404	Valentina (Vostok crater)	L247R17	30-90	5
437-439	Plains S of Voyager crater	L247R17	5-140	16
449-455	Purgatory Ripple	L247R27	0-135	64
473	Purgatory Ripple	L247R27	52-115	12
573-577	N Erebus crater	L247R27	1-151	34
665-703	Olympia	L247R27	5-161	69
716-717	Overgaard	L7R1	16-103	4
736-739	Bellemont	L247R27	12-153	25
920-925	Victoria crater Annulus	L247R27	4-157	28
1134-1136	Outside dark streak	L247R27	7-144	16
1138-1151	Inside dark streak	L247R27	5-144	29
1510-1522	Duck Bay	L247R27	32-152	30
*All means all 13 multispectral Pancam filters				

Below are data quality notes about cube products in the Opportunity rover (MERB / MER1) collection:

1) Cubes not constructed for upper two rows of 4-row North-facing mosaics from Sols 38-39 data set.

2) Filters R3-R7 were not acquired for the 2nd instance of the Sol 43 P2552 sequence.

3) The warped R7 filter is misaligned in the following QUB files:

B328_P236003_01_03V01.QUB
B336_P236503_02_02V02.QUB
B336_P236503_02_03V02.QUB
B335_P236603_01_01V02.QUB
B336_P236603_01_01V02.QUB
B368_P237205_01_03V01.QUB
B370_P237305_01_03V01.QUB
B370_P237305_02_03V01.QUB
B437_P240305_01_02V01.QUB.

4) Cubes were not used for the Sol 673 early morning observations owing to a problem with the filter wheel.

5) The following cubes from sequence P2763 on Sols 737 and 739 were not created owing to non-convergence of the disparity algorithm:

B737_P276306_02_02V01.QUB
B739_P276306_03_01V01.QUB
B739_P276306_03_02V01.QUB

6) Filters L2 and L7 have missing packets in B920_P236708_01_02V01.QUB.

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