MASTCAM MULTISPECTRAL IMAGING ON THE MARS SCIENCE LABORATORY ROVER: WAVELENGTH COVERAGE AND IMAGING STRATEGIES AT THE GALE CRATER FIELD SITE.

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Introduction: The Mars Science Laboratory (MSL) rover "Curiosity" will land in Gale crater on 6 August 2012 UT to begin a mission to investigate the habitability of an ancient aqueous sedimentary environment on Mars. MSL carries a comprehensive payload of remote sensing and *in situ* instruments designed to characterize the geology, elemental composition, mineralogy, and geochemistry of materials encountered along a traverse from the landing site crater floor plains and up into at least several hundred meters of section within a 5 km tall mound of layered sedimentary rocks [1-4]. An important payload element is the Mastcam imaging system [5], a pair of CCD cameras mounted on the rover's mast about 2 m above the surface and capable of obtaining high resolution visible to short-wave near-IR images of the scene. The left Mastcam (M-34) has a 34-mm focal length and a 18.4°x15° field of view (FOV) over the 1600x1200 pixels of its Kodak KAI-2020 interline transfer CCD. The right Mastcam (M-100) has a 100-mm focal length and uses the same kind of HD-format CCD to image a FOV of 6.3°x5.1°.

Mastcam Multispectral Filters. Each Mastcam obtains images through a Bayer pattern of RGB filters and telecentric microlenses bonded onto the CCD (Figure 1; [6]) for nominal "human color" imaging, and an 8-position filter wheel in front of each camera's optics that provides the ability to obtain additional narrowband images through visible, near-IR, and solar neutral denstity filters. Three of the ten wavelengths of the narrowband "science filters" were selected to provide potentially-diagnostic information on iron-bearing minerals (*e.g.,* Fe^{3+} oxides like hematite, Fe^{2+} silicates like pyroxene) and are similar to wavelengths used for the multispectral CCD imagers on the Mars Pathfinder lander [7], the Mars Exploration Rovers (MER) [8], and the Phoenix lander [9].

The effective band centers and band widths of the Mastcam broadband RGB and narrowband science filters were characterized using a monochromator during pre-flight calibration of the cameras, for comparison with design and component-level vendor specifications [5]. Table 1 provides a summary of the as-built system-level (CCD + optics + filter) effective wavelengths (λ_{eff}) and half-width at half-maximum bandwidths (HWHM) of the Mastcam filters; normalized bandpass profile curves are shown in Figure 2. Filters in wheel positions 1 through 6, plus the three RGB Bayer filters imaged through filter wheel position 0 (a broadband IR cutoff filter) provide the ability to image in 13 distinct wavelength bands for regions imaged with both Mastcams (but only over an imaging area of about 1/3 of the M-34's field of view because of the different focal lengths of the two cameras). Filter position 7 is a combination of a narrowband filter plus a 10^{-5} attenuating neutral density filter for direct "solar filter" imaging of the Sun in two wavelengths designed to distinguish between dust versus water ice cloud sources of opacity [10].

Table 1. MSL/Mastcam Filter Wavelengths & Bandpasses

Left (M-34)		Right (M-100)	
Filter	$\lambda_{eff} \pm$ HWHM (nm)	Filter	$\lambda_{eff} \pm$ HWHM (nm)
L0[a]	590 ± 88	R0[a]	575 ± 90
L0R	640 ± 44	R0R	638 ± 44
L0G[b]	554 ± 38	R0G[b]	551 ± 39
L0B	495 ± 37	R0B	493 ± 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
L7	880 ± 10, ND5[c]	R7	440 ± 20, ND5[c]

Notes: [a]Broadband near-IR cut-off filter for Bayer filter RGB imaging. [b]There are two green filters per 2x2 Bayer unit cell (Fig. 1), with essentially identical characteristics. [c]ND5 means 10^{-5} neutral density coating for solar imaging. See text for explanation of shaded cells.

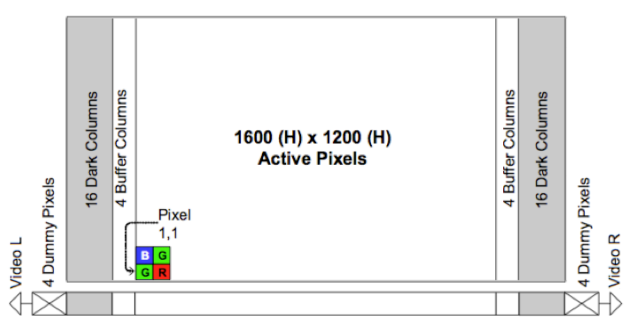

Figure 1. Simplified schematic of the Kodak KAI-2020 interline transfer CCD used in the MSL Mastcams [6], along with a graphical representation of each of the 2x2 Bayer RGB filter unit cells bonded directly onto the CCD's active pixels.

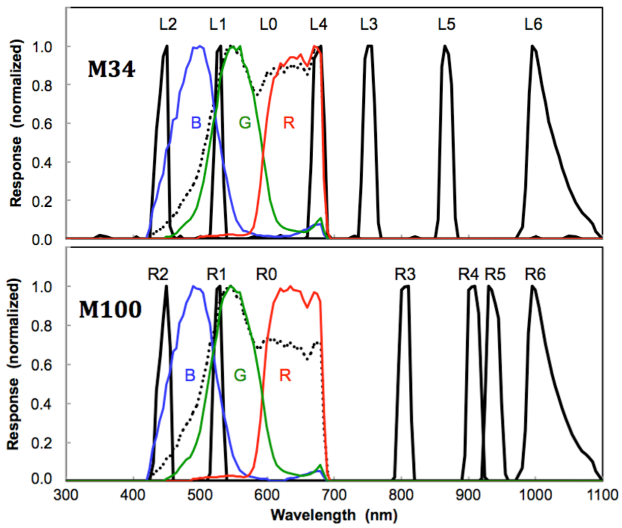

Figure 2. Normalized MSL/Mastcam system-level spectral response profiles for the left eye M-34 camera (top panel) and the right eye M-100 camera (bottom panel). When the filter wheel is set to Filter 0 (broadband IR cutoff; dashed profiles shown here), the resulting Bayer filter RGB response profiles are as shown here in red, green, and blue. When the filter wheel is set to a nonzero number, however, the response profiles of the Bayer filters are as shown in [5].

Mastcam Multispectral Imaging Strategies. As shown in [5], all three of the Bayer filters covering each pixel are essentially transparent above 850 nm, meaning they will have no effect on imaging at and longward of that wavelength. However, for the science filters with wavelengths below 850 nm, the throughput in some pixels of each Bayer RGB 2x2 unit cell will be poorer than in other pixels. For example, images through the L2 or R2 filters will only illuminate the blue-filtered Bayer pixels of each unit cell, because the green and red Bayer filter response is ~0 at the L2 and R2 filter's bandpass of ~445±10 nm. Thus, L2 and R2 images will end up having an effectively lower spatial resolution by a factor of 2. Other unique variable Bayer throughput situations will be encountered when using other Mastcam science filters below 850 nm (shaded entries in Table 1). For those filters, special strategies may need to be developed to deal with their effectively lower spatial resolutions.

Data volume is also always an operational concern. Extensive multispectral imaging with the Mastcams could easily overwhelm the available downlink data volume from the mission, and so thoughtful strategies must be developed for the use of this capability. For example, a strategy often employed with the MER Pancam instruments [8] is to acquire 3-filter multispectral images only in the shortest (432 nm), middle (532 nm), and longest (1009 nm) wavelengths, to maximize the amount of potential spectral contrast that can be discerned among typical Martian rocks and soils [*e.g.,* 11,12]. An analogous "survey mode" strategy for Mastcam might be to acquire four-band images using just Filter 0 for RGB Bayer color plus Filter 6 for the longest possible wavelength (~1012 nm) imaging. Such a strategy could be employed on either Mastcam, depending on the spatial resolution and scene coverage needed for a particular observation.

Other strategies can be implemented based on past Mars surface imaging experience and the goals and needs of specific imaging sequences. For example, "true color" images approximating what humans would perceive on Mars [*e.g.,* 13] can be obtained just using the Filter 0, Bayer RGB mode for either camera. Sequences (possibly in stereo) using just the shortest-wavelength violet (~445 nm) filters could provide images where brightness variations are almost completely due to shading/shadowing rather than albedo variations, maximizing sensitivity to texture and topography. Limited assessment of the presence of hydrated minerals can also be obtained by using the longest wavelength filters in the M-100 camera and the "hydration index" recently developed from MER/Pancam imaging in Gusev crater and Meridiani Planum at similar wavelengths [14,15]. The most robust investigations of the detailed spectral characteristics of Gale crater materials can of course be obtained by acquiring a full (13-wavelengths) set of images from all of the non-solar filter wheel positions, but only for one small 6.8°x5.1° FOV at a time, and at the most expensive "cost" in terms of imaging time, power, and stored/downlinked data bits. Ultimately, the multispectral imaging strategies that will be adopted by the MSL science team will depend on both available resources as well as the specific kinds of spectral signatures exhibited by the as-yet unknown materials to be encountered in the Gale crater field site.

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