MASTCAM-Z: A GEOLOGIC, STEREOSCOPIC, AND MULTISPECTRAL INVESTIGATION ON THE NASA MARS-2020 ROVER.

J. F. Bell III[1], J. N. Maki[2], G.L. Mehall[1] , M.A. Ravine[3], M.A. Caplinger[3], and the Mastcam-Z Science Team.
[1]Arizona State University, Tempe, AZ (Jim.Bell@asu.edu); [2]Jet Propulsion Laboratory/Caltech, Pasadena, CA;
[3]Malin Space Science Systems, Inc., San Diego, CA.

Introduction: The Mastcam-Z imaging investigation was recently selected by NASA to fly on the Mars 2020 Rover Mission. The "Z" denotes the > 3:1 Zoom lens component of the stereoscopic imaging system. Jim Bell (ASU) is the Mastcam-Z PI and Justin Maki (JPL) is the Deputy PI. Malin Space Science Systems, Inc. (MSSS), is our major industry partner, and will perform much of the construction and testing of the cameras under a contract with ASU.

Overview: The Mars-2020 mission is the next flagship mission in NASA's strategic program of exploring the Red Planet. The Mars-2020 Science Definition Team (SDT) report [1] called for observations to be made by a visible color, multispectral, and stereo context imaging system. The capability of such a system is required to conduct lateral and stratigraphic surveys and analyses at multiple spatial scales on many targets, for navigational purposes, to characterize the geological context, and to select locations from a distance for closer in-depth analyses by the rover. This imaging system will also help to characterize and document the results from the mast-mounted and arm-mounted *in-situ* investigations also selected for Mars 2020.

Mastcam-Z was selected to meet these science and operational objectives. Mastcam-Z is a multispectral, stereoscopic imaging instrument based directly on the successful MSL/Mastcam investigation [2-4]. Mastcam-Z will have all of the capabilities of the heritage MSL/Mastcam instruments, with the addition of a > 3:1 zoom capability that will significantly enhance stereoscopic imaging performance and efficiency for both science and rover navigation/operations support.

Mastcam-Z Goals and Objectives: The Mastcam-Z investigation goals and objectives respond directly to Objectives A-D of the Mars-2020 mission [1,5]. Specifically, the primary goals of Mastcam-Z are:

Goal 1: *Characterize the overall landscape geomorphology, processes, and the nature of the geologic record (mineralogy, texture, structure, and stratigraphy) at the rover field site.* Mastcam-Z observations will provide a full description of the topography, geomorphology, geologic setting, and the nature of past and present geologic processes of the Mars-2020 field site, especially as they pertain to habitability. This includes observations of rocks and outcrops to help determine morphology, texture, structure, mineralogy, stratigraphy, rock type, history/sequence, and associated depositional, diagenetic, and weathering characteristics. Meeting this goal also requires observations of regolith to help evaluate physical and chemical alteration, along with stratigraphy, texture, mineralogy, and depositional/erosional processes.

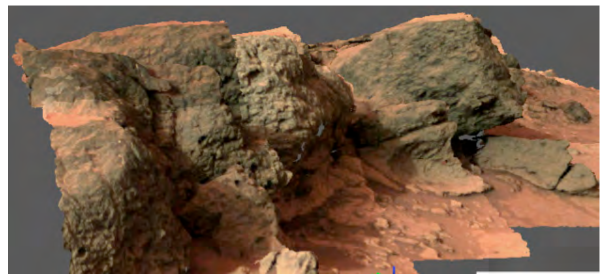

Figure 1: *Example MSL/Mastcam stereo image data products, generated using automated software developed for active MSL/Mastcam tactical operations. These stereo data were acquired on MSL sol 305, sequence mcam01262. Maximum relief is ~ 60 cm; Photo credit: NASA/JPL/MSSS.*

Goal 2: *Assess current atmospheric and astronomical conditions, events, and surface- atmosphere interactions and processes.* This will be achieved by Mastcam-Z observations of clouds, dust-raising events, properties of suspended aerosols (dust, ice crystals), astronomical phenomena, and aeolian transport of fines. This goal also encompasses characterization of potential ice- or frost-related (periglacial) geomorphic features, and even the characterization of frost or ice, if present, and its influence on rocks and fines.

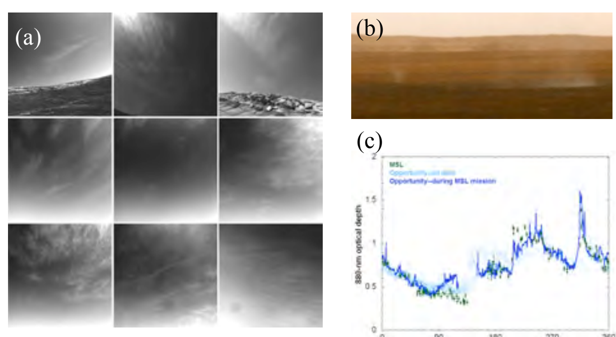

***Figure 2**. Examples of the types of atmospheric observations that Mastcam-Z can conduct for Mars-2020. (a) MER Navcam observations of high altitude water ice clouds [6], (b) MER Pancam Observations of dust devils [e.g., 7,8], and (c) MER Pancam/MSL Mastcam dust optical depth meas-*

urements from direct solar imaging observations [e.g., 6,7]. Photo credits: NASA/JPL/Cornell/ASU/Texas A&M.

Goal 3: *Provide operational support and scientific context for rover navigation, contact science, sample selection, extraction, and caching, and the other selected Mars-2020 investigations.* Mastcam-Z images will assist rover navigation by determining the location of the Sun and of horizon features, and by providing information pertinent to rover traversability (*e.g.*, distant hazards, terrain meshes, etc.). This goal also includes observations enabling other Mars-2020 science instruments to identify and characterize materials to be collected for in situ analyses, coring, and caching, or other purposes (*e.g.*, hardware monitoring).

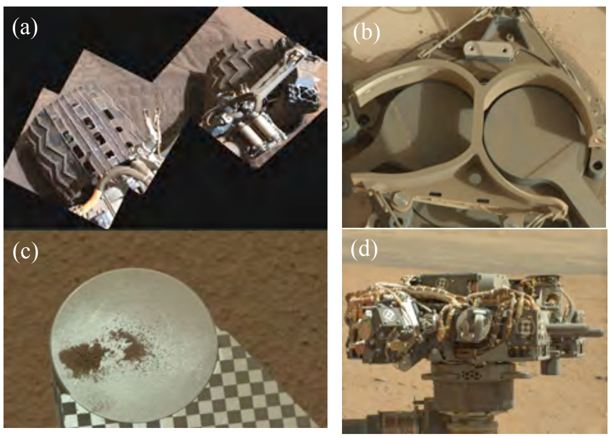

Figure 3: *Examples of operational support imaging from MSL Mastcam. Mastcam-Z will provide the kind of operational support the Mars 2020 surface mission, as well as enhanced support for stereo imaging that will aid in tactical decisions about driving, coring, arm placement, etc. Photo credits: NASA/JPL/MSSS.*

Instrument Description: Mastcam-Z consists of an identical pair of zoom-lens cameras that each provide broad-band red/green/blue (RGB), narrow-band visible/near-infrared (VNIR) color, and direct solar images with fields of view (FOV) from ~ 5° to ~ 15°. The cameras have the ability to resolve (across 4-5 pixels) features ~ 1 mm in size in the near field and ~ 3-4 cm in size at 100 m distance. Each Mastcam-Z camera consists of optics and associated focus, zoom, and filter wheel mechanisms, a CCD detector assembly, digital electronics assembly, and power supply. An external passive color/grayscale calibration target is mounted on the rover deck. Mastcam-Z is a direct descendant of the successful MSL Mastcams (with the same size, detectors, electronics interface, firmware, and operations protocols), augmented by a > 3:1 zoom capability that will significantly enhance stereoscopic imaging performance. The two Mastcam-Z cameras will be mounted on the Mars-2020 rover's Remote Sensing Mast (RSM), which sits approximately 2 meters above the local surface. From this vantage point Mastcam-Z will observe textural, mineralogical, structural, and morphologic details in rocks and fines at the rover's field site.

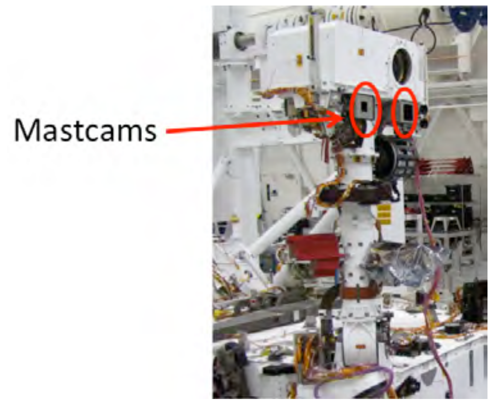

Figure 4. *Location of the Mastcams on the MSL Remote Sensing Mast (RSM). The Mastcam-Z cameras will be mounted in a similar location on the Mars 2020 rover. Photo credit: NASA/JPL*

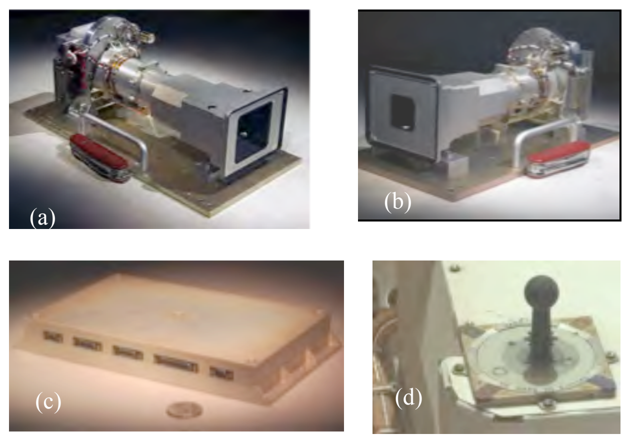

***Figure 5**. MSL/Mastcam flight fixed-focus (a) 34 mm and (b) 100-mm cameras [2]; (c) digital electronics asembly, and (d) 8x8 cm calibration target. The Mars 2020 Mastcam-Z cameras are based on the MSL Mastcam designs. Photo credits: MSSS.*

The 2020 Mastcam-Z flight hardware consists of five elements: two zoom camera heads with high MSL heritage from the MSL Mastcams (Figures 5a,5b), to be mounted on the bottom of the plate on the RSM (Figure 4), two copies of the MSL Mastcam digital electronics assembly (DEA, Figure 5c) with minor modifications from MSL, to be located inside the rover chassis, and an MSL flight-spare calibration target or its equivalent (Figure 5d), to be mounted at a location visible to the cameras via RSM pointing (*e.g.*, at the same location on the rover deck as the MSL Mastcam calibration target).

Optics	*Description*	
Focus	Adjustable; Working distances 1-2 m to ∞	
Filter bandpasses	Two 8 position filter wheels	
Zoom-dependent param.	*Widest Field*	*Narrowest Field*
FOV (1600×1200 pix)	~ 23°×18.0°	~ 6°×5°
IFOV	266 μrad	74 μrad
Focal ratio	*f*/8	*f*/10
Effective focal length	28 mm	100 mm
Detector	*Description*	
CCD	Truesense (Kodak) KAI-2020CM interline transfer	
Color	Red, Green, Blue microfilters, Bayer pattern	
Array size	1600 × 1200 photoactive pixels	
Pixel size	7.4 μm (square pixels)	
Gain, read noise, full well	16.2 e⁻/DN; 17.9 e⁻; 29000 e⁻	
Exposure	*Description*	
Duration	0 to 838.8 sec; commanded in units of 0.1 msec	
Auto-exposure	Uses MSL and MER auto-exposure algorithm	
Onboard Compression	*Description*	
Uncompressed	• 11-bit data; No compression; No color interpolation	
Lossless	• ~1.7:1 lossless compression; no color interpolation	
Lossy	• Realtime JPEG; color interpolation or grayscale; commandable color subsampling Y:C_R:C_B (4:4:4 or 4:2:2); commandable compression quality (1–100)	
Video Group of Pictures (GOP)	• JPEG-compressed color-interpolated GOPs, up to 2 MB file size and up to 16 frames/GOP; commandable color subsampling and compression quality	
Deferred compression	• Image can be stored onboard Mastcam-Z DEA uncompressed; specified compression can be performed at a later time for transmission to Earth	
Companding	• 11-bit to 8-bit square-root encoding	

Table 1. *Mastcam-Z instrument characteristics.*

Filter Position	λ_{eff} ± HWHM (nm)	
	Left (M34)	Right (M100)
0 (broadband)	590 ± 88	590 ± 88
0 (Red Bayer)	640 ± 44	640 ± 44
0 (Green Bayer)	554 ± 38	554 ± 38
0 (Blue Bayer)	495 ± 37	495 ± 37
L1 / R1	**600 ± 10**	527 ± 7
L2 / R2	445 ± 10	867 ± 10
L3 / R3	751 ± 10	805 ± 10
L4 / R4	676 ± 10	**965 ± 11**
L5 / R5	805 ± 10	937 ± 11
L6 / R6	908 ± 11	1013 ± 21
L7 / R7	880 ± 10, ND5	440 ± 20, ND5

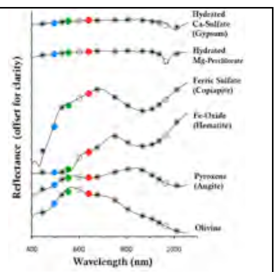

Table 2. *Left: Mastcam-Z multispectral filter band centers and widths, with proposed new filters listed in red. Right: Lab spectra [9,10] of hydrated minerals convolved to the Mastcam-Z narrowband and RGB filters (open circles are Mastcam-Z filters, solid circles are MSL Mastcam filters).*

Each 1.25 kg Mastcam-Z camera head (Figure 6) consists of an optomechanical lens assembly, a focal plane assembly and its electronics, and a filter wheel. The camera head electronics are laid out as a single rigid-flex printed circuit board (PCB) with three rigid sections. The sections are sandwiched between housings that provide mechanical support and radiation shielding; the interconnecting flexible cables are enclosed in metal covers. Camera head functions are supervised by a single Actel RTSX field-programmable gate array (FPGA). In response to commands from the DEA, the FPGA generates the CCD clocks, reads samples from the analog-to-digital converter (ADC) and performs digital CDS, and transmits the pixels to the DEA. The FPGA is also responsible for operating the motors that drive the focus, zoom and filter wheel mechanisms.

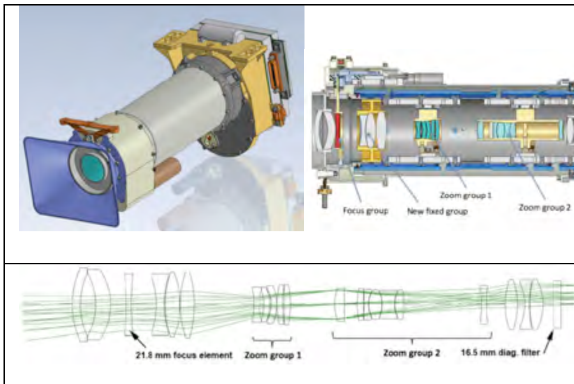

Figure 6. *Mastcam-Z camera head (top left, isometric view, top right, cross section). Bottom, optical ray-trace diagram. Credit: MSSS.*

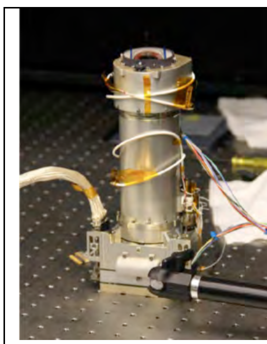

Figure 7. *Integrated MSL/Mastcam zoom camera lens (TRL 6). Photo credit: MSSS.*

The Mastcam-Z zoom mechanism (Figure 7) was developed as part of the original MSL/Mastcam instrument design, which had zoom capability when the instrument was selected, although it was ultimately not implemented for flight on MSL. The Mars-2020 Mastcam-Z implementation of zoom covers a much smaller zoom range, however (nominally 3.6:1 instead of MSL/Mastcam's planned 15:1) and leverages the fact that because of prior MSL development and testing work, the zoom mechanisms have already been qualified to the Mars-2020 life requirements (> 2x mission life cycles)..

The electronics architecture is the same as MSL/Mastcam. The Mastcam-Z focal plane assembly (FPA) and electronics are build-to-print, identical to the corresponding flight MSL Mastcam camera head subassembly. The FPA is designed around an On Semiconductor (formerly Truesense and Kodak) KAI-2020CM interline transfer CCD. The sensor has 1600x1200 photoactive pixels of 7.4 x 7.4 μm size. The sensor has red, green, blue (RGB) filtered microlenses arranged in a Bayer pattern. The microlenses improve detector quantum efficiency, which is about 40% on average. The output signal from the CCD is AC-coupled and then amplified. The amplified signal is digitized to 12 bits at a maximum rate of 10 Mpixels/s. For each pixel, both reset and video levels are digitized and then subtracted in the digital domain to perform correlated double sampling (CDS), resulting in a typical 11 bits of dynamic range.

Test and Calibration: The Mastcam-Z assembly, integration, test, and validation flow will leverage significant relevant experience with geometric and radiometric testing and calibration from the MER/Pancam and MSL/Mastcam imaging investigations. This includes separate acceptance testing on various subassemblies (electronics, optics/mechanisms, and software) prior to the integration of the camera, followed by the standard flow of random vibration testing, thermal vacuum (TV) testing and instrument calibration.

Calibration will measure, as a function of temperature where appropriate: (1) absolute radiometric response, (2) system noise, (3) geometric distortion, (4) system MTF over field, (5) spectral response, (6) stray light susceptibility, (7) focus stepper motor count as a function of focus distance, and (8) zoom stepper motor count with image scale. The calibration effort will rely on procedures and software developed by the PI, DPI, and Co-Is for MER/Pancam and MSL/Mastcam, fine-tuned to the specific requirements of the Mars-2020 Mastcam-Z investigation.

Initial room temperature radiometric (flat field, spectral responsivity, dark current), focus, and zoom calibration will be performed using the same techniques and equipment used for MSL/Mastcam calibration. A more extensive standalone TV calibration campaign will then be performed to characterize instrument performance over a range of Mars-relevant temperatures, using the same facility used for MER/Pancam calibration [11]. The cameras will undergo standalone outgassing, planetary protection bioassay, and functional testing upon delivery to JPL, prior to integration with the rover.

During ATLO, additional geometric calibration will be conducted for target distances > ~10 m using the same techniques and equipment used for the Navcam, Hazcam, Pancam, and Mastcam geometric calibration on MER and MSL [12,13]. As part of this calibration, Mastcam-Z will take images of stereo dot targets at varying distances from the cameras. These images will be used to verify the stereo accuracy of the Mastcam-Z system over the full range of zoom and focus settings at distances from ~ 2 to 60 m. The resultant geometric camera models derived from these data will have sub-pixel accuracies of ≤ 0.25 pixels.

Operations and Data Plan: Operation of Mastcam-Z will be coordinated from a Science Data Center at ASU, which will oversee the creation and archiving of raw NASA Planetary Data System (PDS) Level 0 Experiment Data Records, as well as the implementation of the team's radiometric, geometric, and stereoscopic pipeline processing algorithms required to generate Level 1 and Level 2 PDS Reduced Data Records. Non-validated, preliminary forms of these EDR and RDR products in PDS format will be produced immediately and made available to the Project and Science Team for planning and analysis. We will make all images rapidly available to other investigators and Project personnel during the mission for shared analysis. The procedures to rapidly reduce and calibrate images are well established from the MER/Pancam and MSL/Mastcam Payload downlink experiences. Images will be provided in PDS format, and in a form that can be used within the Project's activity planning and sequencing tools (*e.g.*, MSLICE on MSL).

Mastcam-Z science data consist of full-frame and sub-framed images, thumbnail images (about 1/64th size), and compressed video Groups of Pictures (GOPs) stored in DEA flash memory. Raw data can be returned in four formats: (1) Color JPEG images and thumbnails, (2) Losslessly-compressed images, (3) Compressed color videos, and (4) Raw 11-bit images. All images will include instrument and spacecraft headers. Based on MSL experience, we expect most Mastcam-Z data products to be Color JPEG images, compressed to JPEG quality factors between about 65 to 95, which have been shown to meet similar MSL/Mastcam science requirements. We will PDS archive our EDR and RDR products in the same format accepted by the PDS for the MSL/Mastcam, data [14]. Raw and processed Mastcam-Z data and calibration records will be maintained in a "bested" form throughout the investigation.

E/PO: As part of our active and engaging Education and Public Outreach program, Mastcam-Z investigation scientists and engineers will team with the JPL Mars Program and The Planetary Society, the world's largest public space education organization, to stream all raw Mastcam-Z images to the Web within minutes of their downlink, and to maintain a dynamic and informative web site consisting of instrument background, Mars science information for educators, students, and the public, as well as the latest Mastcam-Z mosaics, blogs, Tweets, and other updated information on the status and progress of the investigation, and the Mars-2020 mission as a whole.

Schedule: The selection of Mastcam-Z as a Mars 2020 science payload was announced on July 31st, 2014, and we are presently proceeding with Phase A trades and analyses. We are planning for a Preliminary Design Review in the third quarter of FY15, a Critical Design Review in the fourth quarter of FY16, and the nominal delivery of the hardware to ATLO is scheduled for early FY19. Launch of the Mars 2020 rover is nominally scheduled for mid- to late-2020, followed by a Mars landing in early- to mid-2021.

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