MASTCAM-Z IMAGE PRODUCTS IN MARS 2020 PERSEVERANCE AND INGENUITY OPERATIONS.

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Introduction: The Mastcam-Z cameras are among the scientific eyes of the *Perseverance* rover, with their zoomable, focusable, and multispectral stereo imaging capabilities [1]. Mastcam-Z is used for science and engineering purposes for daily coordinated surface tactical operations between multiple instruments as well as support of the *Ingenuity* helicopter technology demonstration. Mastcam-Z has also contributed to the scouting of potential landing areas for NASA's Mars Sample Return mission (MSR). This abstract summarizes the use of Mastcam-Z products in science and engineering operations during the Mars 2020 Prime Mission, providing insight into instrument operations, data reduction, and data analysis.

Daily Mastcam-Z Operations:

Source Images. The Mastcam-Z downlink team at Arizona State University (ASU) oversees processing and data reduction of images received from the rover via each orbiter downlink pass. Images come down as low-resolution "thumbnails" (typically 192x144 pixels) that sample the high-resolution images (typically 1648x1200 pixels) which come down later when there is room in the downlink budget. Raw data products are first processed by NASA's Jet Propulsion Laboratory (JPL) into Experiment Data Records (EDR) in a NASA Planetary Data System (PDS) compliant format. EDRs are the Level 1 derived products that undergo radiance (RAD) and radiance factor (IOF) calibration by the Mastcam-Z team [2]. RADs and IOFs are used by scientists and operations engineers as inputs for other derived products, detailed below.

Panoramic Mosaics. Using RADs, each image in a mosaic sequence is stitched together by the team using custom-designed software to make a panoramic mosaic that is used in tactical science planning. Depending on the timing and data volume of a downlink pass, thumbnail mosaics might need to be used before full-resolution mosaics are available to assist in fast-paced tactical planning. The tactical mosaic routines also create stereo mosaics that combine left and right camera images of the same regions when applicable. Stereo mosaics can be helpful to rover planners to support and/or enhance navigation and hazard avoidance camera images [3]. Mastcam-Z mosaics are generally acquired at the maximum possible zoom that will enable the sequence to fit within resource constraints (time and data volume), and mosaics are almost always acquired in stereo to enable an understanding of 3-D context for science or to help in engineering assessment prior to deploying time- or power-intensive contact measurements (*e.g.,* SuperCam, SHERLOC, PIXL) and/or sampling [4]. The Mastcam-Z team generates enhanced color and natural color versions of mosaics, as described in Table 1.

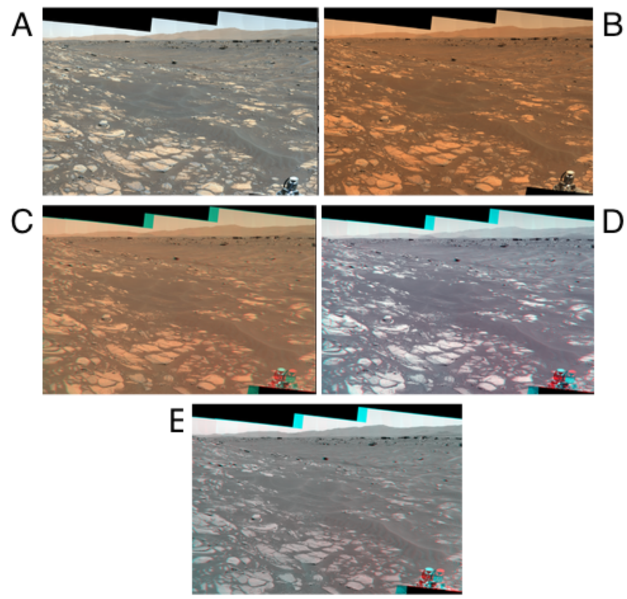

Figure 1: Examples of common mosaic types used in daily rover operations, using the sol 214-215 "Village" outcrop at Séítah. (A) Enhanced color, (B) Natural color, (C) Stereo anaglyph in natural color ("colorglyph"), (D) Blue channel stereo anaglyph, and (E) Red channel stereo anaglyph. The analgyphs are for viewing by standard red/blue stereo glasses.

Multispectral Imaging. Mastcam-Z takes observations in 11 unique narrowband filters from the near-UV to near-IR to help detect specific iron-bearing minerals in scenes of interest [1]. The Mastcam-Z calibration targets are usually imaged in tandem, allowing scientists to use this well-understood target to provide "ground truth" calibration of the derived IOF in each filter [5] After undergoing IOF processing, calibrated multispectral images are used by the science team to map different materials across the landscape [*e.g.,* 6]. Small multispectral mosaics are commanded when two or more multispectral targets are in close proximity.

Atmospheric Opacity. Observations used to measure atmospheric opacity (also known as "tau" because opacity ~$e^{-\tau}$) are taken using the Mastcam-Z solar (neutral density) filters [1]. These provide scientists a way to monitor dust and ice cloud behavior and to estimate particle size [7]. Taus also enable comparison to comparable concurrent and longer-term atmospheric observations acquired from other Mars rovers/landers.

Table 1. Common Mastcam-Z Mosaic Types

Name	Image Processing	Description/Purpose
Enhanced Color	±3-sigma from the median stretch[a] of RAD values in each red/green/blue (RGB) channel; separate left and right camera mosaics generated	Improves visual contrast and accentuates color differences. Most common type of post-processing used for science planning
Natural Color	Stretch of RAD values in red channel from a minimum of 0.0 to a maximum of 3-sigma above the median, then same stretch as the red channel applied to green and blue channels; separate left and right camera mosaics generated	Provides an approximation of what the human eye would see on Mars
Red Channel Anaglyph	Monochromatic red channel RAD values typically stretched by ±3-sigma from the median; single combined left and right camera stereo mosaic generated with left eye data in the output red channel, and right eye data in the output green and blue channels.	Accentuates topographic features and albedo contrasts prominently seen in the red channel in stereo/3-D
Blue Channel Anaglyph[b]	Monochromatic blue channel RAD values typically stretched by ±3-sigma from the median; single combined left and right camera stereo mosaic generated with left eye data in the output red channel, and right eye data in the output green and blue channels.	Because almost all surfaces on Mars have uniformly low albedo in the blue, this analglyph primarily accentuates just topographic variations, rather than albedo variations, in stereo/3-D
Enhanced Color Colorglyph[b]	±3-sigma from the median stretch of RAD values in each red/green/blue (RGB) channel for both cameras; single combined stereo mosaic generated with left eye red data used for the output red channel, right eye green data used for the output green channel, and right eye blue data used for the output blue channel.	Improves visual contrast, accentuates color differences and topography in stereo/3-D
Natural Color Colorglyph[b]	Stretch of RAD values in red channel from a minimum of 0.0 to a maximum of 3-sigma above the median, then same stretch as the red channel applied to the right eye green and blue channels; single combined stereo mosaic generated with left eye red data used for the output red channel, right eye green data used for the output green channel, and right eye blue data used for the output blue channel.	Provides an approximation of the color and topography that the human eye would see on Mars in stereo/3-D

[a]"stretch" here means scaling of floating-point numbers to a new 8-bit dynamic range (0-255 Data Numbers) based on calculated min and max values from the original floating-point data. "sigma" here denotes the standard deviation of the values in each color channel.
[b]Indicates a stereo/3-D product generated using simultaneous images from both the left and right Mastcam-Z cameras and intended to be viewed with standard red/blue 3-D glasses.

Ingenuity: Before the inaugural takeoff in April 2021, Mastcam-Z helped scout a suitable drop-off location to deploy *Ingenuity* (Fig. 2) by providing stereo products that helped gauge surficial topography and hazards. Using high spatial resolution and video capabilities, Mastcam-Z has documented 6 Ingenuity flights so far, including the first 5 historic flights [8]. The first few flights were baseline tests to understand the specific effects of the Mars environment and establish vehicle health [9]. The Mastcam-Z videos helped visually assess the performance of the tests from ~70 m away, which was closer to Ingenuity than originally predicted (~120 m), and as a consequence allowed higher resolution videos [8]. Mastcam-Z videos reveal natural and rotor-induced dust lifting, leading to "bonus science" about the behavior of dust on Mars using precise measurements from *Ingenuity's* ascents, traverses, and descents [10]. This is a novel addition to Mars atmospheric studies enabled by Mastcam-Z.

Mars Sample Return: Mastcam-Z mosaics provide important geologic context for MSR by helping to characterize and evaluate possible sampling locations from a distance, and then by supporting sampling workspace localization and science observations [*e.g.,* 6]. As of this writing, the rover team is building the contingency Sampling Depot Construction Campaign ahead of the traverse to the top of the Jezero delta. Mastcam-Z imaging will also help characterize the locations and status of the sample tubes, for further scientific assessment when future researchers are processing samples on Earth.

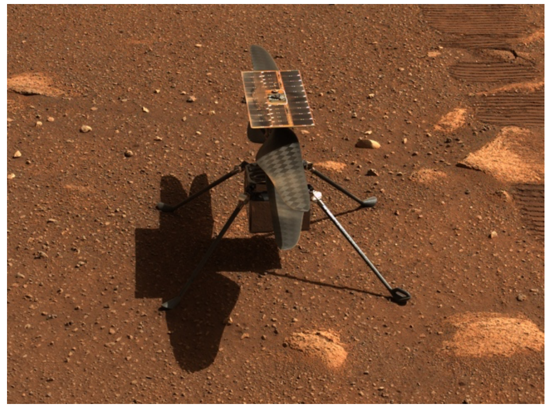

Figure 2: Natural Color Mastcam-Z image of *Ingenuity*, taken on sol 45 of the mission with the left camera at 34 mm.

Publicly Released Products: Images taken by Mastcam-Z are released to the public through the NASA/JPL Perseverance Raw Images website (in PNG format; [11]) and through the PDS on a quarterly basis [12,13]. Mastcam-Z EDR, IOF, and RAD IMGs are archived in the PDS, along with browse products, videos, associated metadata, documentation, and release notes [12]. Images are also processed into Education and Public Outreach (EPO) products that are meant for general public view and use. For example, individual RAD-calibrated natural and enhanced color images taken through the RGB filters are hosted on the Mastcam-Z website [14], where a growing collection of Mastcam-Z mosaics is also publicly available [15].

References: [1] Bell J.F. et al. (2020) *Space Sci. Rev., 217*, doi:10.1007/s11214-020-00755-x. [2] Hayes, A.G. *et al.* (2020) *Space Sci. Rev., 217,* doi:10.1007/s11214-021-00795-x. [3] Maki, J.N. *et al., Space Sci. Rev., 217,* doi:10.1007/s11214-020-00765-9. [4] Yingst R.A. *et al.* (2017) LPSC, #1162. [5] Kinch K. *et al.* (2020) *Space Sci. Rev., 216,* doi: 10.1007/s11214-020-00774-8. [6] Bell J.F. *et al.* (2022) *Sci. Adv., 8,* doi:10.1126/sciadv.abo4856. [7] Wolff M.J. *et al.* (2021) AGU Fall Meeting, P32C-03. [8] https://mastcamz.asu.edu/mars-helicopter-flights-caught-on-video. [9] Balaram J. *et al.* (2021) *Space Sci. Rev., 217*, doi: 10.1007/s11214-021-00815-w. [10] Lemmon M. *et al.* (2022) *JGR Planets, 32*, doi:10.1029/2022JE007605. [11] https://mars.nasa.gov/mars2020/multimedia/raw-images. [12] Bailey, A. *et al.* (2021) 5th Planetary Data and PSIDA, #2549. [13] https://mastcamz.asu.edu/mastcam-z-data-for-all. [14] https://mastcamz.asu.edu/mars-images/images-videos. [15] https://mastcamz.asu.edu/mars-images/panoramas-mosaics.