1. Focus Stack Acquisition and Merge

1.1 Description

Owing to limitations in depth of field, some percentage of a MAHLI or Mastcam scene may be in focus while the rest is not. Sometimes a technical goal will require that all or most parts of an image be viewed in focus. A focus stack (also known as a z-stack, in which z refers to the camera's optic axis) is a composite of multiple images focused at different distances within a given scene.

Focus stack images are acquired at different focus positions that span a range greater than the depth of field of any one of the individual images. These images are then merged using software to form a single best-focus product. A byproduct of this technique is a second image, known as a range map, which identifies the portions of each image—acquired at a different z-axis distance—that were incorporated into the best-focus product.

The MAHLI and Mastcam focus stacks can be acquired and the individual images can be relayed to Earth, and/or a focus merge can be performed in the instrument onboard the rover. The latter serves as a form of data compression which can reduce as many as eight 1600 by 1200 pixel raw images to a single best-focus 1600 by 1200 color JPEG plus a grayscale JPEG range image.

Figure 1 shows an example of a best-focus and range map product from a testbed (non-flight unit) MAHLI. The DN values in a range map indicate the position of the best focus portions of each of the parent images merged to compile the best focus product, with an interpolation of the positions between them. Table 4.4-6 of the MSL Mast Camera (Mastcam), Mars Hand Lens Imager (MAHLI), and Mars Descent Imager (MARDI) Experiment Data Record (EDR) and Reduced Data Record (RDR) PDS Data Product Software Interface Specification (SIS) [Ref 4] describes how the DN values are assigned to each image in the stack. The scaling between these is linear such that intermediate DN values represent interpolated focus positions between the ranges represented by each of the parent images. For MAHLI, after the data are received on Earth—and, as was performed to produce Fig. 1—the motor count positions for each focus stack parent image can be related to these DNs to determine range.

1.2 Focus Stack Commanding

Commanding a MAHLI or Mastcam focus stack can be a 1-step or 2-step process. If the focus merge will be performed on Earth, the camera is commanded to acquire the images and they are later sent to Earth individually. If the focus merge will be performed onboard the instrument, the camera is commanded to acquire the stack and then a separate command performs the merge.

The parent images for an onboard focus merge are acquired in raw form and stored in the DEA. Owing to data volume and processing limitations, only 2 to 8 images can be focus merged onboard. Instrument users can elect, however, to obtain >8 images (up to at least 32), return thumbnail versions of these, and select, from these, 2–8 consecutively-stored images for an onboard merge that will be performed some number of sols after the data were acquired.

To acquire a focus stack, the imaging command specifies a starting position (i.e., motor count) for the lens focus group, the number of images to be acquired, and the number of motor counts for the camera focus mechanism actuator to step through between each image. The choices of starting motor count and number of motor count steps are based on knowledge of the relationship between motor count and working distance and knowledge or estimates (e.g., based on engineering camera observations of the rover workspace) of the range of distances that will be in view in the image. It is also possible to command the camera to determine autofocus and build the focus stack such that the found-focus position from the autofocus algorithm is captured as one of the focus stack images.

1.3 Onboard Focus Merge

When onboard focus merge processing begins, a Bayer color interpolation is performed on each of the images to be stacked. Then each is split into $Y:C_R:C_B$ components. The focus merge and range map are generated on the $Y:C_R:C_B$ data using a technique described by Nayar and Nakagawa (1994) [Ref 6]; a windowed Sum-Modified-Laplacian focus measure determines the areas of best focus and a Gaussian interpolation is used to produce the range map.

MAHLI and Mastcam instrument users have four options to produce a focus merge product: merge-only, merge + registration, merge + blending, or merge + registration + blending. The merge-only case is the least computationally intensive and is accomplished most quickly. For an eight-image (1600 by 1200 pixels) stack, the merge-only option takes ~5 minutes to run onboard MAHLI, merge + registration and merge + blending each take ~10 minutes, and merge + registration + blending requires ~15 minutes.

Nominally, most onboard focus merges are performed using the “merge-only” option. The registration and blending options are available to mitigate the effects of small camera head movements that could occur during acquisition of a focus stack. If they are needed, the focus merge registration option is accomplished using multi-resolution Kanade-Lucas-Tomasi (KLT) feature tracking based on the work of Lucas and Kanade (1981) [Ref 5] and Shi and Tomasi (1994) [Ref 7] with Harris corner detection (based on Harris and Stephens (1988) [Ref 3]) to identify feature points and track them between image pairs in the stack. The blending option combines the images using multi-resolution spline-based image blending (based on Burt and Adelson (1983) [Ref 1]). The few focus merge products produced during testing on Earth (in the absence of rover vibrations or Mars wind) using all of these options (merge-only, merge + registration, merge + blending, or merge + registration + blending) showed no difference in the quality or resolution of the products (mainly because the camera did not move during focus stack acquisition).

References:

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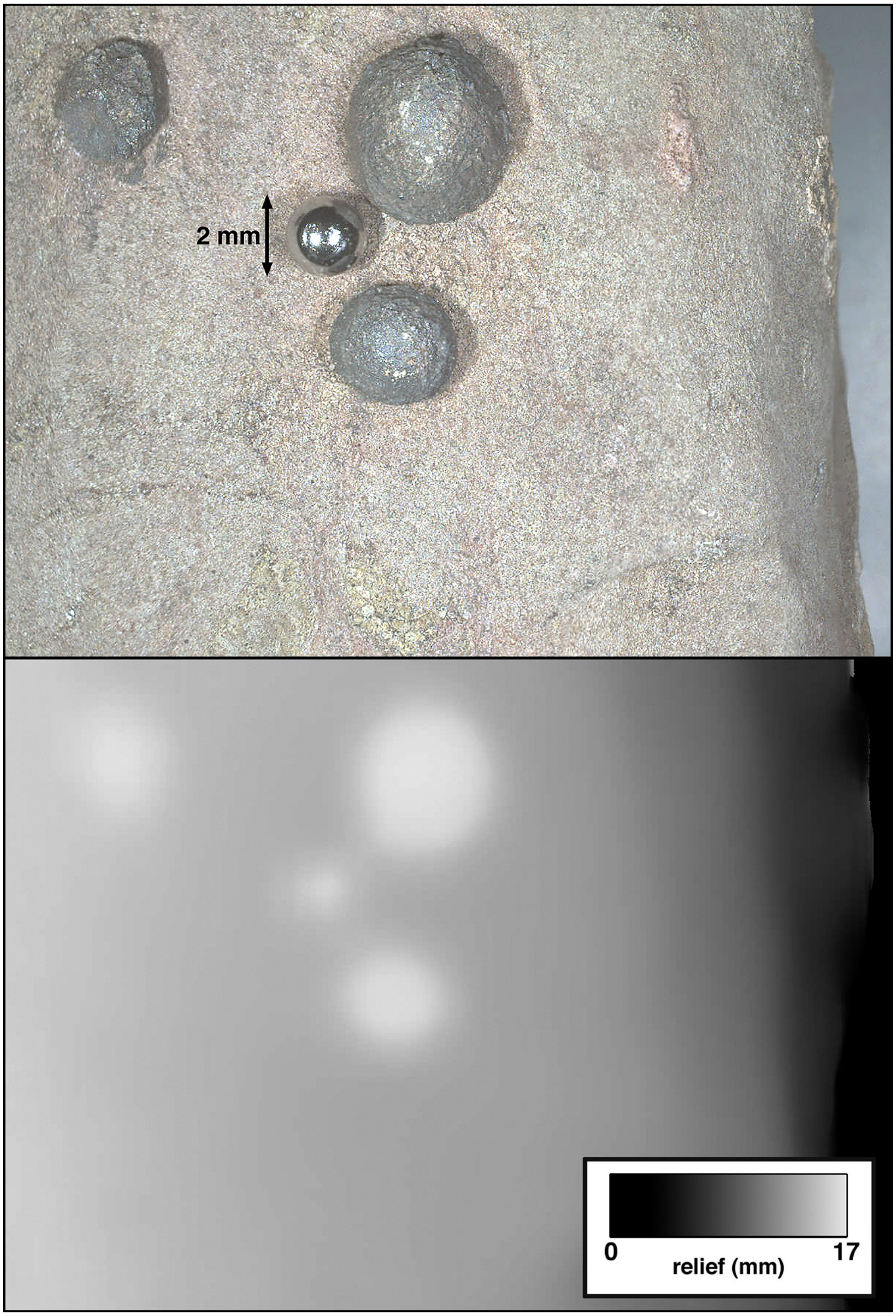

Figure 1: Example of MAHLI onboard focus merge products. Top: Best focus image. Bottom: Range map. These products were made from an 8-image focus stack acquired by a testbed-MAHLI in July 2010. The rock is an iron-rich carbonate from the ~2.5 billion year old Gamohaan Formation in South Africa. The three large, semi-spherical protrusions are hematite concretions formed from oxidation of pyrite nodules. The sphere is a 2 mm diameter steel ball bearing placed on the rock to indicate scale. From Edgett et al. (2012) [Ref 2].