CAMERAS ON LANDED PAYLOAD ROBOTIC ARMS — MAHLI ON MARS AND LESSONS LEARNED FROM ONE MARS YEAR OF OPERATIONS.

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Introduction: Operating > 720 sols on the martian surface, the Mars Hand Lens Imager (MAHLI), aboard the Mars Science Laboratory (MSL) Curiosity rover, has interrogated geologic targets at the mm- to sub-mm scale (individual grains and grain relationships) to identify and interpret lithologic and textural clues to processes that formed and modified the geologic record at the rover's Gale crater field site. We present here a brief overview of the MAHLI investigation Primary Mission activities and results, and some of the key lessons learned thus far.

Instrument: MAHLI is a 2-megapixel, color camera with a macro lens that can focus on targets at working distances from 2.1 cm to infinity [1]. The camera head is mounted on a rotatable turret at the end of Curiosity's robotic arm (**Fig 1**). The arm positions the camera for imaging. The investigation centers on stratigraphy, grain-scale texture, structure, mineralogy, and morphology of geologic material. The instrument includes four white light and two ultraviolet (365 nm) LEDs to illuminate targets when warranted. MAHLI onboard data processing includes a focus merge (z-stacking) capability and lossless and lossy data compression options.

Primary Mission Summary: During its Primary Mission (August 2012 – June 2014), Curiosity operated on Aeolis Palus, a lowland in northern Gale between the crater's north wall and a 5-km-high mountain of stratified rock, Aeolis Mons (Mt. Sharp). The area explored consists largely of thinly-mantled to bare outcrops of wind-eroded sedimentary rock. Most of these were mafic fluvial standstones and conglomerates, as well as a mudstone (important in the context of NASA objectives centered on geologic records of past, habitable environments). Eolian bedforms, usually of centimeters to decimeters height, were also encountered. Some example images acquired by MAHLI, over a range of scales, are shown in **Figs 2–5**.

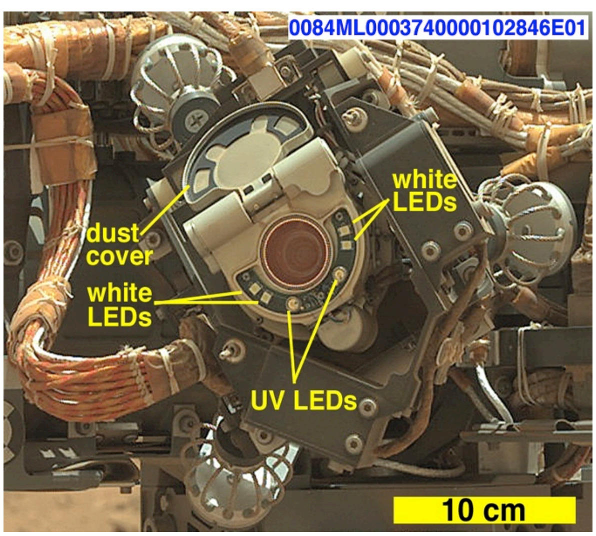

Figure 1. Left: MAHLI camera head with dust cover open, as seen on Mars by MSL Mastcam-34 on 31 Oct. 2012.

Typical MAHLI imaging of rock, regolith, and eolian targets included acquisition of color images, focus stacks, and stereo pairs at 16–22, 31, and 100 µm per pixel. While MAHLI science is conducted in a context provided by other rover and orbiter instruments, the images provided vital science and science-enabling observations, such as:

(1) grain-scale rock textural analysis (e.g., grain size, shape, rounding, voids) which contributed to interpretations regarding rock type, facies, and diagenetic conditions [e.g. 2–4];
(2) examination of eolian sand deposits that permit a global understanding of fundamental properties and processes of eolian transport and bedform stabilization when compared to similar features at other Mars rover sites [e.g., 4-6];
(3) quantitative measurements to support placement of the rover's drill and scoop [4];
(4) imaging of rover wheel damage (**Fig 4**) and images that contributed to identification and avoidance of terrain that might damage the wheels so the rover could proceed to and examine new outcrops;
(5) consistent documentation of APXS analysis spots to support interpretation of geochemical data across three rover sites [e.g., 7-9];
(6) rover self-portraits to provide context for sample extraction sites (**Fig. 2**);
(7) imaging of other instrument hardware to support their science and instrument health [e.g., 10];
(8) imaging in support of robotic arm operation and commissioning (**Fig 5**);
(9) observations of landscape geomorphology (**Fig 4**) and airborne dust; and
(10) observation of the properties and configuration of eolian dust that settled on natural and rover hardware surfaces.

Range Finding and Image Scale: MAHLI image scale, for targets at working distances (w, in cm) of 2.1 to 210 cm, is related directly to the instrument's step-

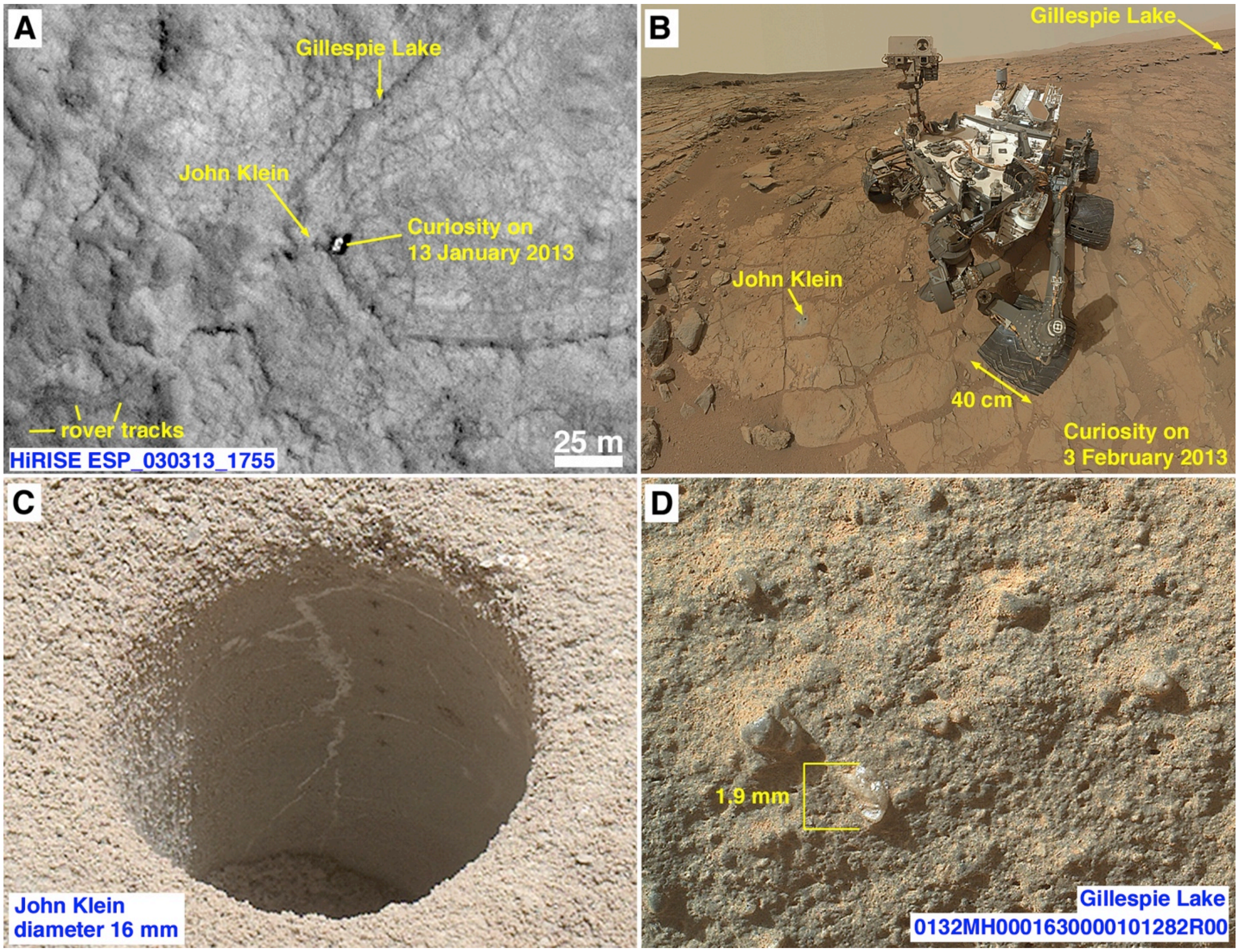

Figure 2. MSL MAHLI is used mainly for micro-scale imaging of targets in the rover's robotic arm work volume. The camera can also image the landscape and provide its own context, connectable to orbiter views. Except for the HiRISE image **A**, the other pictures, here, are from MAHLI. **B** is a mosaic of MAHLI images; **C** is a focus merge composite of the John Klein drill hole, with white mineralized veins and a vertical column of ChemCam LIBS spots, in the Sheepbed mudstone; and **D** is a focus merge product showing the gray, mafic Gillespie Lake sandstone and a single, 1.9 mm opalescent sand grain.

per motor count (m). This relationship was empirically determined by measuring features of known scale, at known distance, on both Earth and Mars. When the dust cover is open (which is the nominal operation mode on Mars because the dust cover was coated with a film of dust during the rover's terminal descent), that relationship is expressed as follows:

$$w = (\mathrm{a}m^{-1} + \mathrm{b} + \mathrm{c}m + \mathrm{d}m^2 + \mathrm{e}m^3)^{-1} \quad (1)$$

in which a = 0.576786, b = –11.8479, c = 2.80153×10^{-3}, d = -2.266488×10^{-7}, e = 6.26666×10^{-12}

The relation between working distance (w, in cm) and the width of the area covered by each MAHLI square pixel (p, in µm), assuming the target is in focus and is a plane parallel to the camera's CCD, is:

$$p = 6.9001 + 3.5201w \quad (2)$$

Depth of field (DOF) contributes to uncertainty in the relation between working distance, motor count, and pixel scale. Depth of field increases with increasing working distance (e.g., **Table 1**). Note that, at the minimum working distance of 2.1 cm (MAHLI tool-frame +x of 0.2 cm), each pixel covers an area ~14 µm wide; at 6.9 cm (MAHLI tool-frame +x of 5 cm), each pixel covers an area about 31 µm wide, comparable to the fixed-focus Microscopic Imagers (MI) aboard the Spirit and Opportunity rovers.

Data Distribution: MAHLI data and data products are archived with the NASA Planetary Data System (PDS) according to a release schedule determined by the MSL Project and NASA PDS. As of 1 August 2014, all data *received* as of Sol 583 (28 March 2014) have been validated and archived; this includes all MAHLI images acquired during interplanetary cruise and pre-launch testing. In addition to the NASA PDS archives, all MAHLI images are placed online, typically < 1 hour after receipt on Earth, on a public web site maintained by the MSL Project at JPL-Caltech. For MAHLI images that arrive on Earth as JPEG-compressed products, the actual as-received JPEG is placed online; for data received with lossless or no compression, the data are color-interpolated, saved as a JPEG with compression quality 95/100, and then placed online; these practices ensure the public immediately receives the highest quality JPEGs. It differs, in detail, from data immediately released by most other planetary instruments.

Table 1: Example Depth of Field as Function of Target Distance for Typical MAHLI Images

Working distance (cm)	MAHLI tool-frame +x distance (cm)	Depth of Field (cm)
2.9	1	0.12
6.9	5	0.30
15.2	13.3	1.3
26.9	25	4.4
51.9	50	17
101.9	100	62

Lessons Learned During Operations: MAHLI has performed nominally on Mars. We discuss the lessons learned through one Mars year of operation.

– Imaging Best Practices –

(1) Dust-Free Surfaces. Dust-free surfaces yield best results in determining lithology when imaging on Mars; areas where wind, the rover's dust removal tool (DRT; [11]) or ChemCam Laser Induced Breakdown Spectrometer (LIBS; [12]) removed the surface dust provided better science return than dust-covered areas. A tool specifically designed to remove dust and provide contact instrument access to fresh rock surfaces, such as the descoped surface removal tool (SRT [1]) or a notional robotic rock hammer, would have been more ideal. *In lieu* of such a tool, targets that have been disturbed by the rover or other hardware (e.g., broken rocks, disturbed dirt) can provide cleaner surfaces.

(2) Solar Illumination and Shadow: Daytime MAHLI images of geologic materials are best acquired when the target is illuminated by sunlight, particularly with phase angles approaching 90°; targets (on Mars) in full-shadow tend to appear to be more orange-brown than they actually are, and the shadowing de-emphasizes vital color and textural detail. That being said, an ideal image site includes both sun-lit and shadowed views of the same target at the same scale, because both provide information the other does not provide, alone.

(3) Artifical Illumination Source: When using an artificial light source, phase angle can reduce apparent texture and challenge autofocus; MAHLI's white light LEDs are at different positions that can operate independently [1], which provides shadowing, lessening this problem. We note that, under Mars conditions, the LEDs provided good illumination under nighttime conditions [13], but did not improve image quality when used to illuminate shadows during daytime.

4) Focus Range and Field of View: The relatively large field of view (FOV) of MAHLI (38.5° diagonal at infinity focus), and its ability to focus over a large range of working distances, were key capabilities that permitted crucial science-enabling rover and instrument hardware engineering needs, including imaging

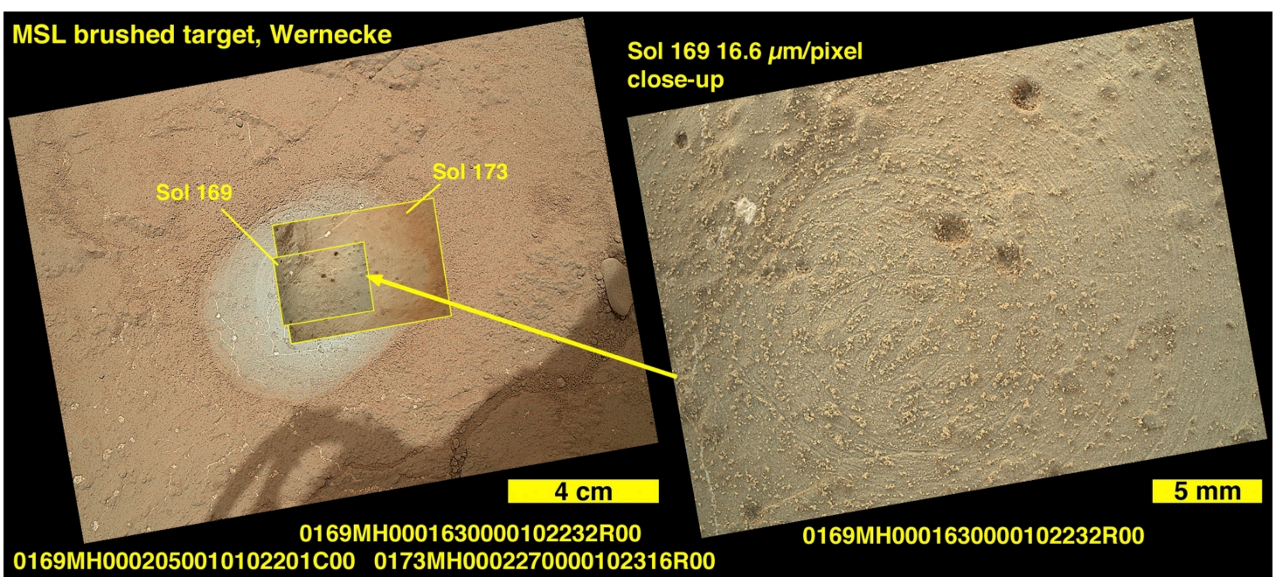

Figure 3. Sheepbed mudstone and example of nested MAHLI images of increasing spatial resolution. Left: Three MAHLI images. Right: High resolution image from the nested suite.

the rover wheels to identify and monitor damage; monitoring of other instruments for dust accumulation; imaging inside the CheMin inlet for contamination; and contributing to diagnosis or better understanding of other hardware problems (e.g., damage on REMS boom 1). Future landed missions (e.g., Moon, Mars, small bodies) should consider the benefits of utilizing a high-fidelity arm-mounted camera with a large FOV and focus range to support engineering diagnostic concerns, both seen and unforeseen.

– Operations Lessons Learned –

(1) Use Limitations: MAHLI's science investigation was somewhat limited during the rover's Primary Mission by two basic circumstances: (a) arm deployment and (b) long drives necessary to reach waypoints and the ultimate geological targets on Aeolis Mons (Mt. Sharp). The robotic arm on Curiosity is not used every martian day (sol), as it requires significant time and power resources to utilize. As a consequence, the camera is commonly only used when another science investigation or engineering need requires it; MAHLI use is almost never driven entirely by the needs of the MAHLI science investigation. We recommend (and are working toward) a solution in this rover configuration to design and execute a robust set of science-driven criteria for MAHLI targets and a plan for reaching them (via arm motion and rover drive positioning) that is on par with, as well as in accord with, the needs of the other onboard science instrument investigations.

(2) Imaging Targets of Opportunity: In the current MSL operations paradigm, MAHLI images are often taken of targets that are available, rather than targets that are scientifically optimal. Limitations on the choice of targets available in the robotic arm workspace include (a) the need to spend many sols driving to the highest-priority science targets, (b) the number of extra sols that might be expended to perfect rover positioning for arm placement of the MAHLI at a given target, and (c) operational time of day constraints, which are a convolution of thermal state of rover hardware at a given time of day, power for mechanism operation and heating, rover position as a function of daytime sun position, and communications relay periods that can interrupt science data acquisition. For future, similar missions, one candidate solution would be for the mission to include an additional camera (e.g., mast-mounted) that acquires similar very high resolution images without the need for arm motion; such images would be used to prioritize candidate contact science targets, including those for higher-resolution, arm mounted camera viewing (e.g, MAHLI) [14].

(3) Terminal Descent Plume: While the MAHLI dust cover and camera head survived Curiosity's terminal descent to the martian surface, the capability of the camera to image through its transparent dust cover [1] was lost. Future missions with similar instruments should consider avoiding an instrument accomodation in which an instrument is pointed directly into the plume of dust and debris lofted by descent engines.

(4) Stowed Camera Position: Since July 2013, MAHLI has regularly acquired images when the robotic arm is stowed (**Fig 4**), after each drive sol. These images document a portion of the landscape, in color, although the pointing is fixed (view is to the left of the

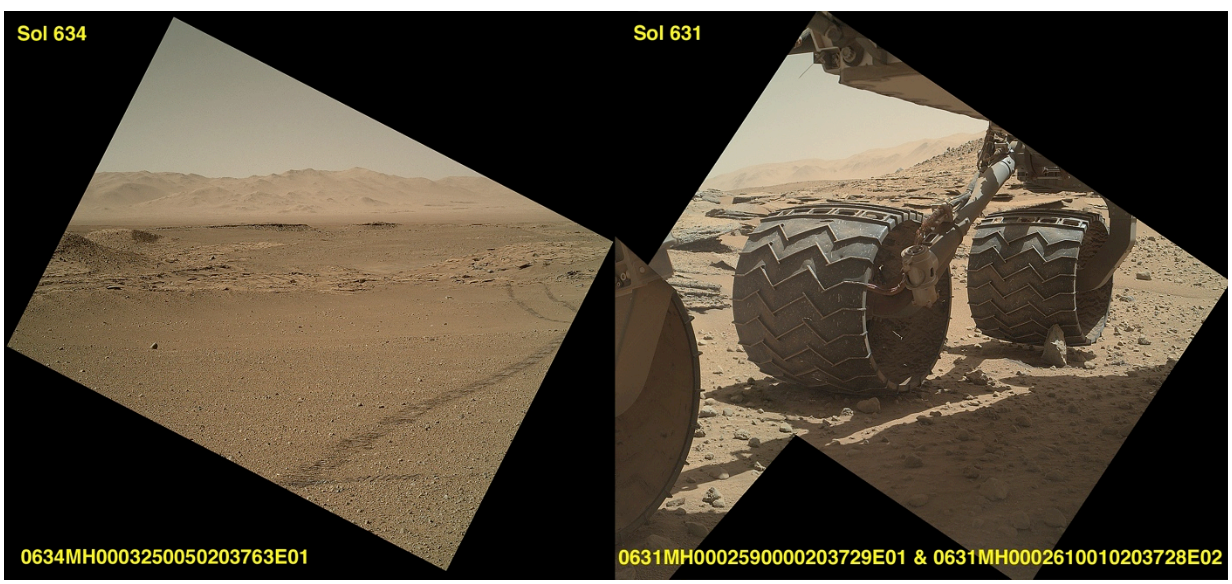

Figure 4. Left: Example of MAHLI view of landscape acquired when robotic arm was in a stowed position; this image shows the Kimberley field site and the north wall of Gale crater. Distance between right and left side wheel tracks is about 2.8 m. Right: Example of rover wheel inspection imaging, acquired near the Kimberley site in May 2014. Wheels are 40 cm wide.

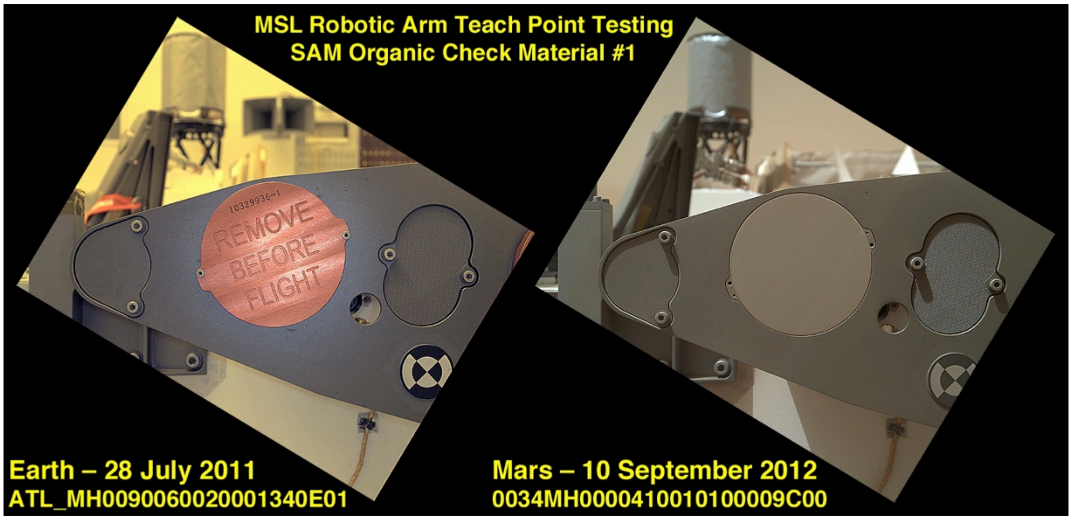

Figure 5. Example of MSL MAHLI imaging support for robotic arm teach point establishment. Engineers compared the results from Earth and Mars to help adjust robotic arm positioning for Martian environmental conditions. The Organic Check Material (circular feature) diameter is 6.25 cm [15].

rover). Because the camera detector (CCD) mounting position inside the instrument is rotated 210° relative to the stowed position of the camera, these images are not acquired in typical "portrait" or "landscape" orientations. Surprisingly, this orientation has been found to be perfect for balancing the information content visible in the vertical and horizontal directions; sky color as a function of height can be observed, as can near-field geologic features and mid- and far-field landmarks visible in the highest resolution orbiter images.

Unique MAHLI Capabilities: MAHLI has proven to be robust, efficient in operation, and flexible in the images and derivative products it yields. The combination of fine-scale resolution, RGB color, ability to focus over a large range of distances, and relatively large FOV, have provided maximum science and science-enabling return given the MSL mission architecture and constraints. Resolution down to coarse silt allows discrimination among potential habitable environments (mudstone versus sandstone, for example) without greatly increasing focal length, and thus mass and volume. Color is a crucial discriminator among sedimentary grains of a similar morphology, fabric or sorting, but different lithologies.

Finally, the MAHLI optical configuration strikes a favorable balance between resolution and FOV. In practical terms, this means that MAHLI has been able to provide full wheel imaging with a minimum number of images acquired (4 images for 6 wheels), and it has been able to produce mosaics that show the entire rover in field context (**Fig 2**), using 2–3x fewer images than would a similar camera with a resolution of 7–8 µm/pxl (because of its narrower FOV). Owing to the balance MAHLI strikes between high resolution imaging objectives and other, science-enabling capabilities, our experience suggests that an increase in spatial resolution on a future MAHLI-like instrument would yield only a marginal improvement in overall science return.

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