HAWKEYE: DECIPHERING LITHOLOGIC CLUES REMOTELY AND RAPIDLY FROM STATIONARY AND MOBILE PLATFORMS.

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Executive Summary: Grain-scale lithology provides diagnostic data allowing interpretation of geologic environments. However, current rover platforms do not provide the appropriate resolution at an actionable distance; or conversely, when current platforms make high resolution observations, they are too late to be actionable (they serve the purpose of examining the target, not guiding the rover to the most ideal target). Hawkeye, a mast-mounted, 2-megapixel RGB color camera with a focusable macro lens, is a simple, heritage-rich, low cost-risk investigation that addresses this challenge. Hawkeye provides fundamental scientific data – hand lens scale lithology – from actionable distances, thus maximizing the efficiency of landed and roving vehicles in assessing the most promising targets for science and engineering goals.

The importance of resolving lithology: Lithologic features involving grains and grain relationships (0.5-10 mm in scale) provide key indicators of rock-forming environments on any planetary surface. For example, particle details in volcaniclastic sediments can reveal important information for distinguishing between primary volcanic processes (including eruptive patterns and mechanisms within a volcanic terrain) and reworking by secondary surface processes. Sedimentary structures and fabric (cross-bedding, lamination, ripples and mudcracks, biogenic forms) may be revealed at the hand lens scale, even in cases where the depositional process was so subtle that macroscale structures are difficult or impossible to discern. Grain size, shape, and sorting are all affected in unique ways by impact processes. Expressions of rock texture at this scale are critical to discerning evidence for crystal habit, grain size, sorting, bedding and fabric, grain morphology, and characterization of the potential for habitability and biosignature preservation. Resolving lithological features at this scale is therefore a key capability for many roving and landed missions. Indeed, such a capability was so important to the Apollo astronaut-geologists that they were willing to trade mass and margin for the inclusion of a long focal length lens on their cameras to provide this level of resolution.

The challenges to interpreting lithology: The transition from lithologic characterization at grain scale to interpretation of rock type and depositional process requires broad spatial coverage at high resolution. Most environments are also spatially variable; thus broad coverage is required to permit identification of, and focus on, only those sub-environments of interest. For example, observations of bedded outcrop at resolutions provided by mast-mounted panoramic cameras currently in use may mistake volcanically emplaced layers settled out from the atmosphere, for fluvial, or even lacustrine layers. Where the geologic details are sufficient for identifying a sedimentary environment, this resolution would provide little data relevant for deciphering depositional mechanism and biosignature preservation [1, 2].

Why the need for this camera: Nothwithstanding the crucial nature of lithologic data in deconvolving geologic history, current mission configurations and operations scenarios are challenged to gather or efficiently use lithologic information. In terms of data collection, current rovers are not equipped to gather sufficient data at the appropriate resolution, because the only camera capable of doing so is arm-mounted, making the acquisition of numerous grain-scale images too resource-costly. For example, diagnostic features such as grain size and sorting are necessary to reconstructing the depositional setting, but because the only camera that has sufficient quality and resolution on MSL is arm-mounted, the rover rarely acquires sufficient grain-scale data to allow definitive characterization of a given sedimentary environment.

As a terrestrial example, **Figure 1** shows textural variation in a clastic, bedded sedimentary rock. Boxes represent notional Hawkeye images. In this figure, images A-C provide critical data in context, for reconstructing depositional environments; only D suggests biosignature preservation potential. None of these images can be acquired by current rover or recent landed configurations.

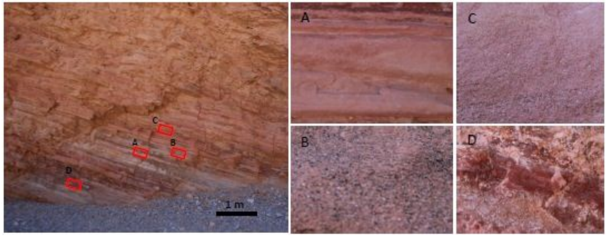

Figure 1. Bedded sedimentary outcrop. Red boxes indicate location of A-D, representing notional Hawkeye images. A. fine-grained laminae with evidence of traction flow and soft-sediment deformation; B. coarse sand, diverse mineralogy;

C. graded coarse to fine sand, indicating deposition under waning flow; D. a single, fine-grained layer with mm-scale laminae, likely deposited under calm water.

The nominal ability to resolve such features is necessary, but insufficient. This information must be available in the science process in context, at a point early enough to affect target choice, such that the time- and resource-intensive process of conducting contact science is put to best use. This is especially true for roving missions, or for landed missions with a short timeline, in which broad-coverage, diagnostic lithologic data must be acquired rapidly and frequently. Imager configurations on previous rovers that also allowed acquisition of crucial context imaging, achieved such resolution only when the target was directly under the mast, or when the rover was already committed to contact science and arm-mounted imagers could be deployed. Thus, the information could never be used for *selecting* targets of interest, but only for *examining* targets selected based on other, potentially misleading, indicators. Broad coverage was never possible due to lack of time and arm reachability.

For example, when the Mars Exploration Rover (MER) Spirit characterized Home Plate, over 25 sols of repetitive operational sequences were required (deploy the Instrument Deployment Device (IDD), acquire MI images, fold the IDD, move the rover 20 cm, repeat). Similarly, the configuration for Mars Science Laboratory (MSL) requires weeks of strategic planning for contact science, days of strategic planning to determine candidate sites that can accept arm deployment, days of tactical planning approaching the site, assessing slip risk, then doing contact science on whatever targets are reachable. A mast-mounted hand-lens scale imager such as Hawkeye could acquire an equivalent dataset in only 1-2 sols, while consuming fewer mission resources, allowing the science team to choose ideal targets, rather than being limited by time or reachability.

As an example of Hawkeye's rapid triage benefits, **Figure 2** compares potential science return from a single observing sequence using an arm-mounted high-resolution imager (e.g., MER MI or MSL MAHLI), to one using Hawkeye [3, 4]. The outcrop shows clear bedding, with greater erodability and a knobbly texture in its lower half, similar to massive clay deposits on Earth, which may be interpreted as suitable for biosignature preservation and thus a high priority target for contact science. However, multiple images and greater FOV achievable using Hawkeye combine to reveal the true lithology of the outcrop, even though resolution is 15x coarser than current arm-mounted imagers, or the Remote Microscopic Imager (RMI). The richer context facilitates an interpretation of this feature as a tuff deposit (low habitability potential as a volcanic pyroclastic deposit). Notably, instead of 5-30 sols it might take to acquire the single highest-resolution MI- or MAHLI-type image, or the 30-40 images (at ~20 minutes, not including >10 m for ChemCam instrument on-off and 20 minutes for TEC cooling) that might be required to cover similar context with the RMI, this target could be identified as low priority in a single sol (and in minutes of rover time), thereby mitigating potential hazard and resource consumption necessary to conduct contact science.

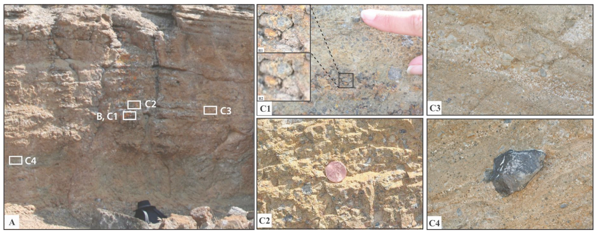

Figure 2. A. Outcrop at 1 cm/pxl (panoramic cameras at ~100 m). B. Inset images at MAHLI scale illustrating differences in MAHLI-type (~10 μm/pxl) and Hawkeye (150 μm/pxl) resolution. C. Hawkeye image simulation at 5 m distance (16x12 mm FOV). C1. Coarse, clast-supported grains that refute interpretation of clay deposition. C2. entrained angular crystals in fine groundmass; C3. Mixture of grain sizes and distinct secondary minerals in interstitial space; C4. Bomb sag. Together, these images, which could be acquired in 6-8 minutes, suggest the outcrop is a volcanic pyroclastic deposit, of low habitability potential.

In short, acquisition of numerous grain-scale images from tactically relevant distances increases potential for detecting materials most relevant to a particular mission, and maximizes the impact of time invested in contact science by finding the most promising materials before sampling.

Hawkeye design and specifications: The Hawkeye flight hardware consists of a camera head with high MSL heritage (**Figure 2**), and a copy of the MSL Mastcam digital electronics assembly (DEA), which can be located inside the rover chassis. The Hawkeye camera head consists of an optomechanical lens assembly and focal plane assembly and electronics. The Hawkeye focal plane assembly (FPA) and electronics is a build-to-print copy of the flight MSL Mastcam camera head electronics. It is designed around a ON Semiconductor (formerly Truesense Imaging) KAI-2020 CCD with 1600 by 1200 pixels (7.4 μm by 7.4 μm). The CCD uses interline transfer to implement electronic shuttering. RGB filters arranged in a Bayer pattern provide three color channels. Camera head electronics are laid out as a single rigid-flex printed circuit board (PCB) with three rigid sections, sandwiched between housings that provide mechanical support and radiation shielding. Camera head functions are supervised by a single Actel RTSX field- programmable gate array (FPGA). In response to DEA commands, 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 also operates the focus mechanism motor. The camera head has an integral heater controlled by the rover to warm the mechanism for operation if needed. The camera head can operate between -40°C to +60°C and was qualified on MSL to survive > two Earth years of diurnal temperature cycles (down to -135°C) without heating.

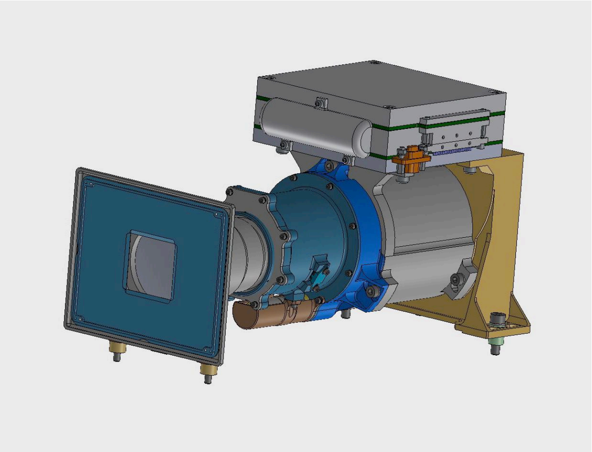

Figure 2. Hawkeye camera head.

The Hawkeye optomechanical assembly is a modification of the focus assembly flown for the MSL Mastcams. The Hawkeye lens was designed to the form-factor of the MSL Mastcam, to minimize development cost and risk. Hawkeye uses a build-to-print copy of the MSL Mastcam focus mechanism, although the mechanism is moved ~2 in. farther away from the focal plane. Optics are an all-refractive design consisting of one moving focus group and a single front stationary group. With a focal length of 370 mm and focal ratio of f/10, it can focus closer than 2 m. The design has an on-axis MTF of > 0.4 at the Nyquist frequency of the detector (68 l.p./mm). The optics and all moving parts are sealed within the lens housing to prevent dust contamination. A MER/MSL heritage Aeroflex 10 mm stepper motor drives the focus mechanism. The motor drives the integral gear of a cam tube, driving the focus group along linear bearings under the control of the cam follower pin. End-of-travel sensing is provided by a Hall-effect sensor and magnet pairs on the cam. This mechanism was qualified for MSL, and three copies of it (MSL Mastcams and MAHLI) have been operating on Mars for more than 700 sols. The Hawkeye DEA is copy of MSL Mastcam DEA with minimal changes to the FPGA logic and flight software.

Hawkeye performance and use: The combined position on the mast, range of resolutions possible, and optimal FOV, enable synergy with, and support of, other instruments and investigations on any lander or rover:

(1) With resolution better than 60 μm/pxl at 3 m distance, and a 1.4° x 1.8° FOV, Hawkeye provides a unique combination of high resolution and context coverage required to support lithologic assessment of targets for remote assessment and triage prior to contact science on roving or landed missions with a robotic arm. Hawkeye can acquire high-resolution, in-focus color images of an arm's work volume at resolutions comparable to that of MER's MI (31 μm/pxl [5]), but with a much larger FOV, so that each grain-scale image may be placed into geologic context. For comparison, we note that a camera similar to the current mast-mounted Remote Microscopic Imager (RMI) on MSL would require 4-9 images from 5 m away, to resolve and characterize common cm-scale sedimentary structures such as cross-bedding, ripples, mudcracks and associated evaporite structures. Acquisition of such images comes at the resource cost of time (>30 m to accommodate instrument preparation and shut down). By contrast, at the same stand-off distance, Hawkeye would require only one image, at an estimated cost of less than a minute, and that single image would provide the context required for confident interpretation.

As another example, on MSL, the contact science imager must provide its own context images (typically ~100 μm/pxl [6]), requiring both camera and arm/turret resources. Acquisition of context images by Hawkeye would leave contact science instruments free to conduct the fine-scale investigations for which they are ideally suited.

(2) Hawkeye can provide data across a continuum of scales, from context to fine-scale resolution, thereby improving scientific return and mission productivity. High-resolution Hawkeye images can be nested within coarser-resolution context images from mast-mounted panoramic cameras, providing lithologic observations to support outcrop-scale interpretation. Additionally, at 1 km distance, Hawkeye could resolve features down to ~2 cm — sufficient to resolve features of this size from 5-10 drive sols away in the case of a roving mission. Thus, Hawkeye may be used to reconnoiter potential regions of interest, or obstacles to a drive, from an actionable distance, similarly to the Apollo astronauts' long focal length lens or the proposed Farcam imager [7].

(3) Hawkeye can provide sufficient resolution for context imaging for high-resolution mineralogic data from a point or imaging spectrometer. Assuming a point spectrometer with a similar resolution as the MER MiniTES [8], Hawkeye would show physical characteristics at a pixel size 100x smaller than spectrographic measurements, permitting correlation of individual crystals or grains to minerals or mineral classes identified by the spectrometer. Additionally, Hawkeye images would resolve dust or coatings on a rock surface that would require the use of brushing/grinding to remove, or to identify an alternate, less obscured rock for geochemical analysis.

(4) For a roving mission, the ability of Hawkeye to provide an in-focus image with a line-of-sight range of > 8 cm at 3 m working distance permits determination of mm-scale surface roughness and slope required to assess safety of instrument placement prior to committing to a target. For example, during MER Opportunity's campaign to characterize a potentially habitable paleoenvironment at Whitewater Lake, the rover expended valuable time and resources attempting to overcome the placement issues resulting from an uneven surface expression of the target veins; ultimately, the analysis had to be descoped due to time constraints. The ability to identify safety issues for instrument placement prior to the rover's first move onto the target would have saved essential time, and Hawkeye can provide a rover with this ability.

Conclusions: Hawkeye can (1) provide rapid, remote (i.e., tactically relevant) data at the cm to sub mm-scale, a required scale for building confident interpretations of a number of types of environments; (2) provide long-range reconnaissance similar to other long focal length systems [7]; (3) decrease risk to any arm-mounted deployable mission-critical hardware on landed or roving spacecraft, by reducing the need for use of the arm; and (4) decrease operational complexity and cost. Hawkeye is a dual role instrument: a high value standalone science instrument and an operational instrument that streamlines identification and characterization for contact science and further investigation.

References: [1] Gehling, J. G. (1999), *Palaios* **14**, 49-57. [2] Schieber, J. (1999), *Palaios* **14**, 3-12. [3] Yingst, R. A., et al. (2009), *Jour. Geophys. Res*., **114**, CiteID E06004. [4] Yingst, R. A., *et al*. (2011), *Mars*, **6**, 13-31. [5] Herkenhoff, K.E., *et al*. (2004), *Jour. Geophys. Res*., **305**, 824-826. [6] Minitti, M. E. *et al*. (2013), *Jour. Geophys. Res*., **118**, 2338-2360. [7] Robinson, M. S. and M. A. Ravine (2012), Int'l Workshop on Instrumentation for Planetary Missions, Abstract #1064. [8] Christensen, P., *et al*. (2004), *Science*, **306**, 1733-1739.