
Introduction: The Heimdall camera system was recently selected for development and flight as part of NASA’s Lunar Surface Instruments and Technology Program (LSITP). LSITP instruments are currently being considered for flight aboard the next round of Commercial Lunar Payload Services (CLPS), envisioned for flight as early as 2022. Heimdall is a high flight-heritage (MSL, OSIRIS-REx, GOSAT-2) instrument consisting of four 5-megapixel color CMOS cameras and DVR (Figure 1). Heimdall science objectives are: (1) map a lunar landing site at multiple scales and perspectives for contextual understanding of the geology; (2) characterize in-situ regolith morphology and other properties at the sub-mm scale; (3) characterize regolith/plume interaction during descent; and (4) provide ground-truth for and support development of autonomous navigation capabilities for future lunar surface missions.

Instrument: Heimdall’s four cameras work together to achieve Heimdall’s science objectives. One wide-angle descent imager captures near-video-speed images of the interactions of the lander plume with the lunar regolith. Once landed, this camera will also acquire images of the surface under the spacecraft at 500 μm/pixel, documenting the final state of the regolith after landing. A narrow-angle regolith imager documents disturbed regolith at ~74 μm/pixel (when mounted 1 m from the surface), to determine regolith particle size and shape, and track particle interaction, for particles ≥ 150-200 μm in diameter. Two wide-angle panoramic imagers image the local terrain in stereo for context and mapping (5 mm/pixel at 10 m distance). The camera system is designed and built by Malin Space Science Systems (MSSS).

Landing site mapping: Descent imaging provided by Heimdall bridges the gap between surface and orbital images [1] that provide the data to define geomorphic units and landforms on the basis of color, albedo, topography, surface texture, and crater densities. In some cases, supplementary data on mineralogy [2], elemental abundance [3], or radar and thermal properties (e.g., [4,5]) are also used to discriminate among surface units (e.g., [6-8]). A mosaic of low-altitude descent images will give local geologic context of the landing site prior to disturbance by the lander plume. Observations of Heimdall’s ground-based images will reveal details beyond the resolution of orbital data, including topographic relationships of geologic structures and rock bodies, and diagnostic rock characteris-

ics that contribute to identifying the lithologies present and their emplacement history. Panoramic cameras provide resolution both near (e.g., 500 μm/pixel at 1 m from the lander) and far field (e.g., 50 cm/pixel at 1 km from the lander), to constrain stratigraphic relationships among units, and identify site-specific features such as pyroclastic deposits, mare deposits, impact structures or ISRU-rich deposits. Imaging at different times of day informs the photometric properties of surface materials and provides insight into factors that affect these properties. Stereo imaging contributes to three-dimensional mapping efforts through measuring

Figure 1. Heimdall wide-angle camera (top) and DVR (bottom).
local slopes, topography, and size-frequency distributions of clasts around the lander.

Regolith characterization: At any location on the Moon, the regolith is the product of a complex set of mechanisms that act heterogeneously over a wide range of scales. Fragments of the basalt and anorthosite bedrock, plus exogenic materials and melt, are mixed both laterally and vertically by impact and micrometeorite bombardment. In addition, particles disturbed by a landing plume will still retain many key physical and visible properties, including grain size distribution, particle shape, cohesion, and slope stability and trafficability. The resolution of Heimdall’s narrow-angle camera is sufficient to characterize the particle size distribution larger than ~100 μm, and to determine particle size, shape, cohesion, and slope stability for particles ≥150–200 μm diameter.

Characterization of landing plume: Analysis of Apollo descent videos has demonstrated that impingement of rocket exhaust was significant enough to cause regolith particles as large as 10 cm or larger to move [9,10]. Clasts of such size could cause severe damage to hardware and instruments, as likely occurred to the wind sensor on the Mars Science Laboratory Rover Environmental Monitoring Station Boom 1 [11]. As a positively charged plasma, rocket exhaust also has electrostatic effects on regolith during descent, causing dust levitation up to a half minute after lunar landings [12]. Impingement of rocket exhaust can also cause morphologic changes on the surface. For example, the soil erodes in clods and discrete layers [9], and the effect of this layered erosion is visible in Apollo surface images of the areas beneath the lunar modules.

Prior efforts to quantify plume interaction with the regolith have used Apollo-era descent videos to estimate dust ejection angles and lofted particle densities through photogrammetry [10], calculate the optical density of the dust plume through optical extinction measurements [13], and determine lunar soil erosion rates using computational fluid dynamics simulations [13]. However, incomplete, inconsistent, and/or missing information with regards to camera settings and descent trajectories [e.g., 10,13] challenge the use of Apollo data.

Several studies have used photometric characterization of orbital images of the areas disturbed by rocket exhaust to better understand the physical effects of rocket exhaust on the regolith [14–16]. These blast zones consist of an area of lower reflectance compared to surroundings, that extends up to a few meters out from the landers, as well as a broader halo of higher reflectance that extends tens to hundreds of meters from the landers [15]. The blast zones likely formed as a result of the removal of fine particles, destruction of the very porous sub-mm-scale layering and structure of the regolith (e.g., fairy-castle forms [17]), and/or surface smoothing [14–16]. But all returned samples from within the blast zones consisted of surface scoops too jumbled to be useful for such studies.

Heimdall’s descent imager acquires images and “video” sequences at 2.8 frames/second that, combined with quantitative camera information (model, spacing, angle, etc.), will yield a more quantifiable, digital record of changing conditions during descent. Submillimeter-scale resolution will allow for validation of photometric models and provide insight into physical mechanisms responsible for the increased brightening at the landing sites.

Autonomous navigation ground truth: Development of autonomous surface navigation is identified as an enabling or enhancing technology for operating on the lunar surface [18]. Heimdall will acquire in situ lunar stereo data, which will yield DTMs that provide ground truth for orbital hazard characterization at lander-scale resolution. Additionally, Heimdall stereo images acquired at different times of the lunar day will characterize the terrain (e.g., clast sizes, clast spacing, and slopes at the local scale) and generate topographic data. These will serve as a reference dataset with which to train software and develop hardware for robust autonomous navigation.

Acknowledgements: This work was funded by NASA’s LSITP program.