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The Mars Science Laboratory Engineering Cameras

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Abstract NASA's Mars Science Laboratory (MSL) Rover is equipped with a set of 12 engineering cameras. These cameras are build-to-print copies of the Mars Exploration Rover cameras described in Maki et al. (J. Geophys. Res. 108(E12): 8071, 2003). Images returned from the engineering cameras will be used to navigate the rover on the Martian surface, deploy the rover robotic arm, and ingest samples into the rover sample processing system. The Navigation cameras (Navcams) are mounted to a pan/tilt mast and have a 45-degree square field of view (FOV) with a pixel scale of 0.82 mrad/pixel. The Hazard Avoidance Cameras (Hazcams) are body-mounted to the rover chassis in the front and rear of the vehicle and have a 124-degree square FOV with a pixel scale of 2.1 mrad/pixel. All of the cameras utilize a 1024×1024 pixel detector and red/near IR bandpass filters centered at 650 nm. The MSL engineering cameras are grouped into two sets of six: one set of cameras is connected to rover computer "A" and the other set is connected to rover computer "B". The Navcams and Front Hazcams each provide similar views from either computer. The Rear Hazcams provide different views from the two computers due to the different mounting locations of the "A" and "B" Rear Hazcams. This paper provides a brief description of the engineering camera properties, the locations of the cameras on the vehicle, and camera usage for surface operations.

Keywords Mars · Cameras · Rovers · Mars Science Laboratory · Remote Sensing · Instruments · Imaging systems · Planetary missions

1 Introduction

The National Aeronautics and Space Administration (NASA) Mars Science Laboratory (MSL) mission will land a rover onto the surface of Mars in August 2012. The MSL rover is

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designed to drive up to 20 km across the Martian surface while conducting scientific investigations over the course of a full Mars year (687 Earth days). As it drives across the surface the rover will investigate points of scientific interest, deploy its robotic arm, retrieve samples from the surface and ingest these samples into an onboard sample processing system. In order to conduct these activities the MSL rover is equipped with 8 Hazard-Avoidance Cameras (Hazcams) and 4 Navigation Cameras (Navcams). This set of 12 cameras is collectively referred to as the rover engineering cameras. The MSL engineering cameras were built using the same design as the NASA Mars Exploration Rover (MER) engineering cameras, described in Maki et al. (2003). This paper provides a brief overview of the MSL engineering cameras with a specific focus on aspects of the cameras that are unique to the MSL configuration. Because the MSL engineering cameras are identical copies of the MER cameras, the reader is directed to Maki et al. (2003) for a more detailed description of the engineering camera hardware and software.

1.1 Instrument Objectives and Requirements

The primary objective of the MSL engineering camera system is to support the operation of the MSL rover on the Martian surface. Engineering camera images will provide the first views from the landing site and will be used to assess the traversability of the near-field terrain surrounding the rover. During a rover traverse, onboard engineering camera images will be used to autonomously detect, monitor, and avoid hazards. At the end of a drive, images will be acquired and sent to Earth, where they will be used by ground operators to characterize the rover position and orientation relative to the surrounding terrain. Engineering camera images are also necessary for the operation of the robotic arm and delivery of sample material into the rover's sample processing system. The requirements for the MSL engineering cameras are inherited from MER and adapted for MSL (see Table 1). Although there are no science requirements levied on the MSL engineering cameras, the cameras will return images that will help meet project-level science objectives and contribute to individual instrument science objectives by providing contextual support for many of the MSL science payload observations.

2 Hardware and Software Description

2.1 Instrument Heritage and Overview

The MSL engineering cameras are build-to-print copies of the MER engineering cameras. In addition to the 20 cameras that flew on the MER mission, the NASA Mars Phoenix mission flew two flight spare MER camera detectors and electronics assemblies in the Surface Stereo Imager (SSI) camera (Lemmon et al. 2008). The MSL engineering cameras were built at the Jet Propulsion Laboratory (JPL) by the same group that built the MER cameras. The MSL engineering cameras are equipped with slightly more powerful heaters than the MER cameras, enabling potential usage in colder temperature conditions. Each MSL engineering camera is composed of two mechanical housings—a detector/optics head and an electronics box (Fig. 1). Table 2 lists the MSL flight unit engineering cameras by serial number and Tables 3, 4, 5 provide a summary of the MSL Engineering Camera performance and functional characteristics. A total of 26 cameras were built for MSL (12 flight units, 4 flight spares, and 10 engineering units). These cameras were calibrated (flat field, dark current, responsivity, and geometric properties) at our calibration facility at JPL. The MSL camera flight and ground software was inherited from the MER mission and has been adapted and incrementally improved for MSL.

Table 1 Summary of engineering camera functional requirements

Cameras (number per Rover Compute Element)	Requirements
Navcams (2 per RCE, 4 total)	Provide terrain context for traverse planning and Mastcam, Chemcam targeting.
	360-degree field of regard at <1 mrad/pixel pixel scale.
	Stereo ranging out to 100 meters (42 cm stereo baseline).
	Support Robotic Arm (RA) operations, including the transfer of material to the surface sampling system.
	Broadband, visible filter.
Hazcams (4 per RCE, 8 total)	Provide image data for the onboard detection of navigation hazards during a traverse.
	Provide terrain context immediately forward and aft of the rover (in particular the area not viewable by the Navcams) for traverse planning.
	Support Robotic Arm (RA) operations, including the transfer of material to the surface sampling system.
	Support Rover fine positioning near RA targets.
	Wide field of view (120 degrees), pixel scale of 2 mrad/pixel.
	Stereo ranging immediately in front of the rover (10 cm stereo baseline for Rear Hazcams, 16 cm baseline for Front Hazcams) to an accuracy of ±5 mm.
	Broadband, visible filter.

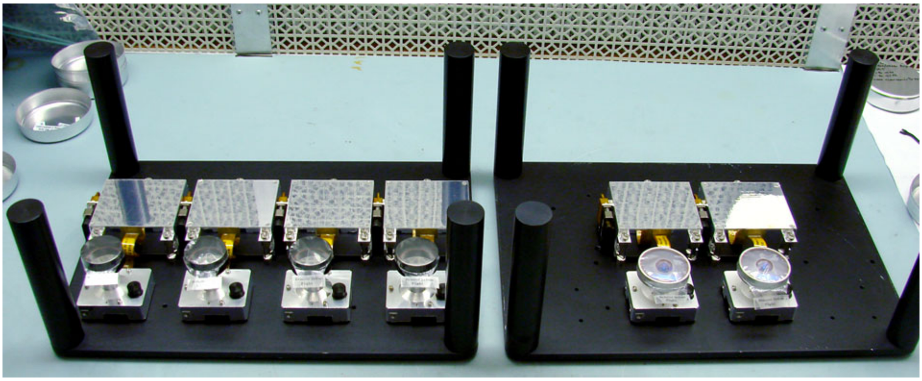


Fig. 1 Four MSL Flight Navcams (*left*) and two MSL Flight Hazcams (*right*). The cameras consist of a detector/optics head connected to an electronics box via a flex cable. In the above picture the camera lenses are covered with a protective remove-before-flight lens cover. The electronics boxes in the picture are each approximately 67 × 69 × 34 mm in size

2.2 Optics Summary

The optical properties of the Engineering Cameras are described in detail in Smith et al. (2001) and are briefly summarized here. The Navcam cameras use f/12, 14.67-mm fixed-focal length lenses that provide a 45 × 45-degree field of view (60.7-degree diagonal) and a pixel scale at the center of the field of view of 0.82 mrad/pixel. The depth of field of the

Table 2 Serial numbers of the Flight Unit MSL Engineering Cameras. These serial numbers are attached to the image at the acquisition time and are used to for tracking calibration parameters and data archiving

Camera	RCE A	RCE B
Left Navcam	216	215
Right Navcam	206	218
Front Left Hazcam	205	208
Front Right Hazcam	213	209
Rear Left Hazcam	211	212
Rear Right Hazcam	217	207

Table 3 MSL Engineering Camera detector properties

Average Detector Full Well	170,000 electrons
Average Readout Noise (at −55 °C)	25 electrons
Average Detector Gain (at −55 °C)	50 electrons/DN
ADC Digitization	12 bits/pixel
Frame Transfer Time	5.1 m sec
Detector Readout Time (full-frame mode)	5.4 seconds
Detector Readout Time (4 × 1 binned mode)	1.4 seconds
Pixel Size	12 × 12 microns
Fill Factor	100 %
SNR	>200:1
Exposure time	0–335.5 seconds, in steps of 5.12 m sec

Table 4 MSL Engineering Camera optical properties

	Navcam	Hazcam
Pixel scale at the center of the FOV	0.82 mrad/pixel	2.1 mrad/pixel
Focal Length	14.67 mm	5.58 mm
f/number	12	15
Entrance Pupil Diameter	1.25 mm	0.37 mm
Field of View (horizontal × vertical)	45 × 45 degrees	124 × 124 degrees
Diagonal FOV	67 degrees	180 degrees
Depth of Field	0.5 meters–infinity	0.10 meters–infinity
Hyperfocal Distance	1.0 meters	0.5 meters
Spectral Range	600–800 nm	600–800 nm

Navcam camera ranges from 0.5 meters to infinity, with a hyperfocal distance of 1.0 meters. The Hazcam cameras use f/15, 5.58 mm fixed-focal length f-theta fisheye lenses with a 124 × 124 degree field of view and a 180-degree diagonal FOV. The f-theta terminology refers to the mapping of equal angles in object space to correspondingly equal distances on the image plane. The pixel scale at the center of a Hazcam image is 2.1 mrad/pixel and the Hazcam depth of field ranges from 0.10 meters to infinity, with a hyperfocal distance of 0.5 meters. Both the Navcam and Hazcam cameras have bandpass filters that cover 580 nm to approximately 800 nm (Fig. 2).

Table 5 MSL Engineering Camera configuration summary

Property	Navcam	Front Hazcam	Rear Hazcam
Stereo baseline	42.4 cm	16.7 cm	10 cm
Stereo co-alignment difference	<1 degree	<2 degrees	<2 degrees
Boresight Pointing Direction	0–360 degrees, azimuth −87 through +91 degrees, elevation	45 degrees below nominal horizon	45 degrees below nominal horizon
Height above Martian Surface	1.9 meters (exact value depends on elevation of RSM head)	0.68 meters	0.78 meters
Mass (per camera)	220 grams	245 grams	
Dimensions (per camera)	67 × 69 × 34 mm (electronics) 41 × 51 × 15 mm (detector head)		
Power (per camera)	2.15 Watts		

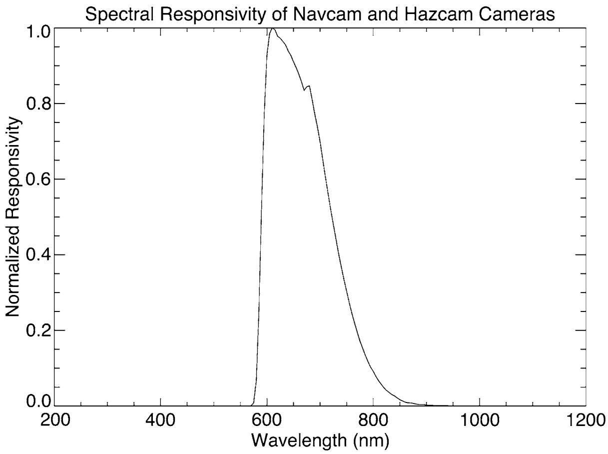


Fig. 2 Normalized, representative spectral responsivity for the Navcam and Hazcam cameras. This curve incorporates the spectral transmission properties of the optics, filters, and CCD QE

2.3 Detector Summary

The MSL engineering camera detectors were assembled and packaged using spare MER Charged Coupled Device (CCD) wafers. The detector is a frame-transfer device with a 12.3 mm × 12.3 mm imaging region containing 1024 × 1024 pixels. Each pixel is 12 microns square. The detector has 3 readout modes: full-frame, 4 × 1 binned, and windowed. The detector readout time is 5.4 seconds for full-frame mode, 1.4 seconds for binned mode, and a variable readout time (proportional to the window size) of less than 5.4 seconds for windowed mode. The full-well capacity of a single pixel is approximately 170,000 e-, the detector gain is 50 e-/DN, and the read noise of the signal transfer chain is approximately 0.5 DN. A more detailed description of the engineering camera detectors can be found in Maki et al. (2003) and Bell et al. (2003).

2.4 Remote Sensing Mast (RSM) and Navcam Pointing

The MSL rover utilizes a Remote Sensing Mast (RSM), a pan/tilt assembly capable of 360 degrees of commanded motion in the azimuth (pan) direction and 178 degrees of

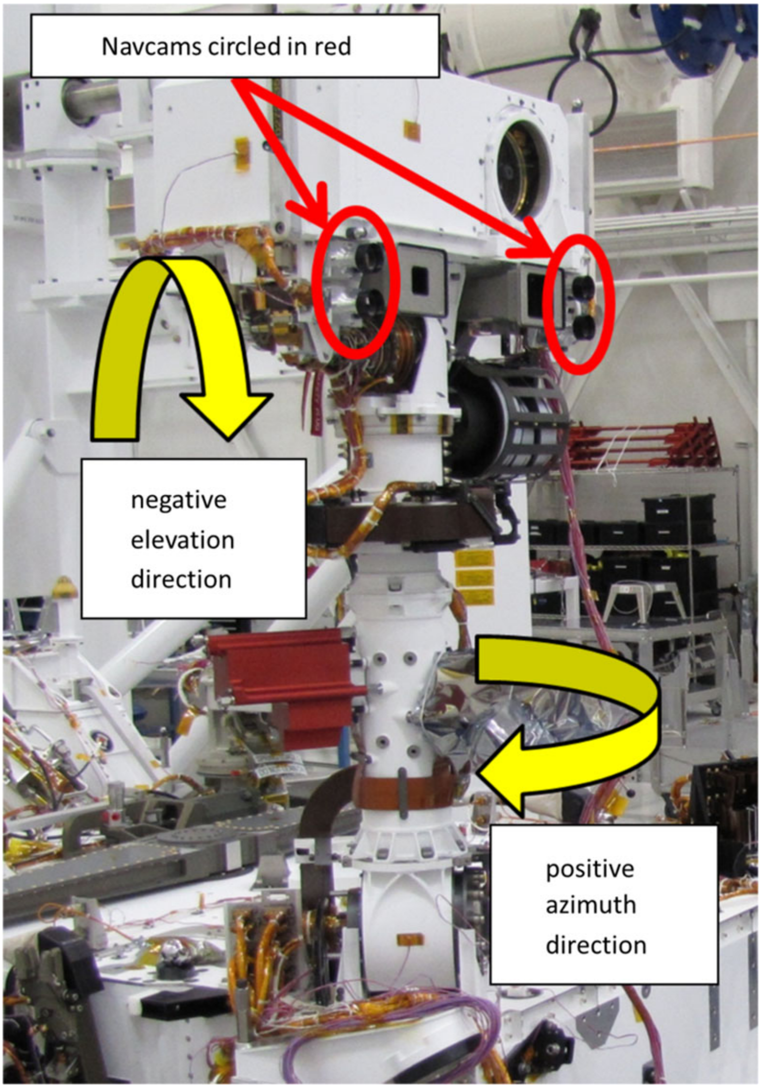


Fig. 3 The MSL Remote Sensing Mast (RSM). The mast height is 1 meter, as measured from the rover deck to the top of the box (Remote Warm Electronics Box) on the RSM head

commanded motion in the elevation (tilt) direction (see Figs. 3 and 4). The RSM is physically capable of pointing over a slightly larger range (362 degrees between the upper and lower azimuth hardstops and 182 degrees between the upper and lower elevation hardstops), but the commanded motion is restricted slightly (via rover software parameters) to provide margin against hitting the actuator hardstops. Additionally, 4 degrees of margin is added to the lower elevation hardstop to avoid adding tension to the RSM cable bundle. The resulting pointing capability enables the acquisition of azimuthal 360-degree Navcam panoramas of the Martian surface, images of the rover top deck, mobility system, robotic arm workspace, and the Martian sky. The absolute pointing accuracy of the

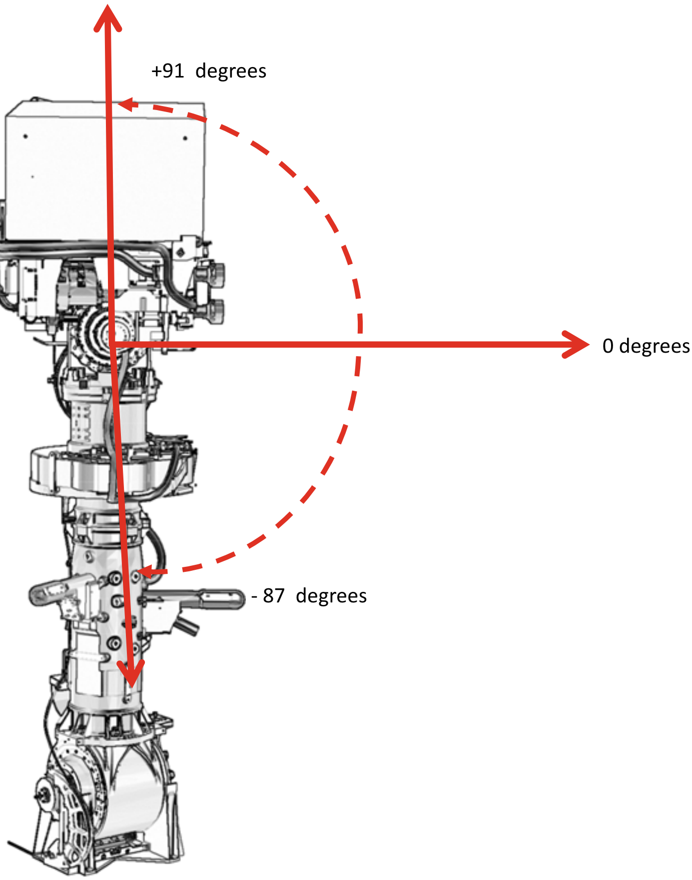


Fig. 4 Allowable elevation range of travel for the RSM head. The Navcams can be pointed past zenith (+91 degrees) and nearly straight down (−87 degrees). In this figure the Navcams are pointed straight out towards the horizon (0 degrees). The elevation pivot axis is located at the intersection of the 3 arrows

RSM is approximately 4.6 milliradians (approximately 6 Navcam pixels), and pointing is repeatable to less than a Navcam pixel. Movement of the RSM is controlled directly via image command arguments as azimuth/elevation angles or 3-dimensional Cartesian target points in a specified coordinate frame. When the Navcams are pointed out towards the horizon, they sit 1.9 meters above the nominal surface, providing an unobstructed view out to 3.6 km for a featureless sphere of Martian radius. Pointing of the Navcams to the sun is achieved via the onboard Inertial Vector Propagation (IVP) system, a software ephemeris system inherited from MER and the Mars Pathfinder missions. Although the Navcams are not designed to image the sun directly (Navcam images of the sun at Mars are generally overexposed, even at the minimum commandable exposure time of 5.12 milliseconds), the cameras can be safely pointed at the sun without damage. MSL will use the RSM to point the Navcams at the sun and autonomously identify the location of the sun in the sky from the overexposed sun image. The resulting location will be used to update the rover heading relative to the local Martian surface coordinate frame.

2.5 Rover Compute Element

The MSL imaging flight software runs on the rover main computer, referred to as the Rover Compute Element (RCE). The MSL rover contains two functionally identical RCEs: RCE "A" and RCE "B". Each RCE is connected to a dedicated set of 6 engineering cameras (2 Navcams and 4 Hazcams), for a total of 12 cameras. The engineering cameras are not cross-strapped between RCEs, meaning that a single RCE can communicate only with the six cameras that are connected to it. In order to acquire images from the other set of 6 cameras, the rover must switch over to the other RCE. During surface operations, one RCE will be designated as the prime computer while the other RCE will be unpowered and designated as a backup unit. Switching from one RCE to the other will likely be performed only if necessary and is expected to occur infrequently during the surface mission. Because the camera commands are identical for either RCE, the same commands and command sequences can be loaded and executed on either RCE. Onboard parameters specific to a particular camera (e.g., geometric parameters describing each of the camera optics) must be loaded onto the specific RCE of interest and saved to the RCE non-volatile memory.

2.6 Imaging Flight Software

The MSL engineering camera imaging flight software is inherited directly from the MER mission (Maki et al. 2003) and has been adapted for use on MSL. The onboard software capabilities of the MSL system include: manual and autoexposure, exposure time table storage, exposure time scaling, histogram generation, row/column summation, thumbnail generation, 12-to-8 bit companding, spatial downsampling, spatial subframing, shutter subtraction, bad pixel correction, flat field vignette correction, geometric camera model management, stereo processing, and image metadata collection. The flight software also uses the ICER wavelet image compressor for lossy image compression (Kiely and Klimesh 2003) and the LOCO image compressor for lossless image compression (Weinberger et al. 1996; Klimesh et al. 2001). Hazcam and Navcam images are acquired using a fully-specified, self-contained image command for image acquisition and processing. Navcam panoramas (see example in Fig. 7) are acquired by executing a series of individual image commands in sequential fashion. The flight software automatically powers on the camera(s) of interest based on incoming image commands and automatically powers the camera(s) off after a timeout idle period. Up to two cameras can be powered simultaneously. Images are read out from the cameras and buffered in a non-volatile memory/camera interface (NVMCAM) card before they are transferred to the RCE for further processing, storage, and subsequent downlink.

2.7 Imaging Ground Software

The MSL engineering camera imaging ground software is also inherited directly from the MER mission. JPL's Multimission Image Processing Laboratory (MIPL) will perform the ground processing of the Engineering Camera image data during MSL surface operations. The ground software imaging processing capabilities include the writing of all downlinked image data to Experiment Data Record (EDR) files, followed by further processing into Reduced Data Record (RDR) files for use by the operations team. Examples of RDRs include: flat-field corrected images, geometrically-linearized images, stereo disparity maps, XYZ images, range images, surface normal maps, robotic arm reachability maps, and surface slope maps. Also generated are multi-image mosaics, projected in cylindrical, perspective, polar, and vertical projections. For a detailed description of the engineering camera imaging processing system, see LaVoie et al. (1999) and Alexander et al. (2006).

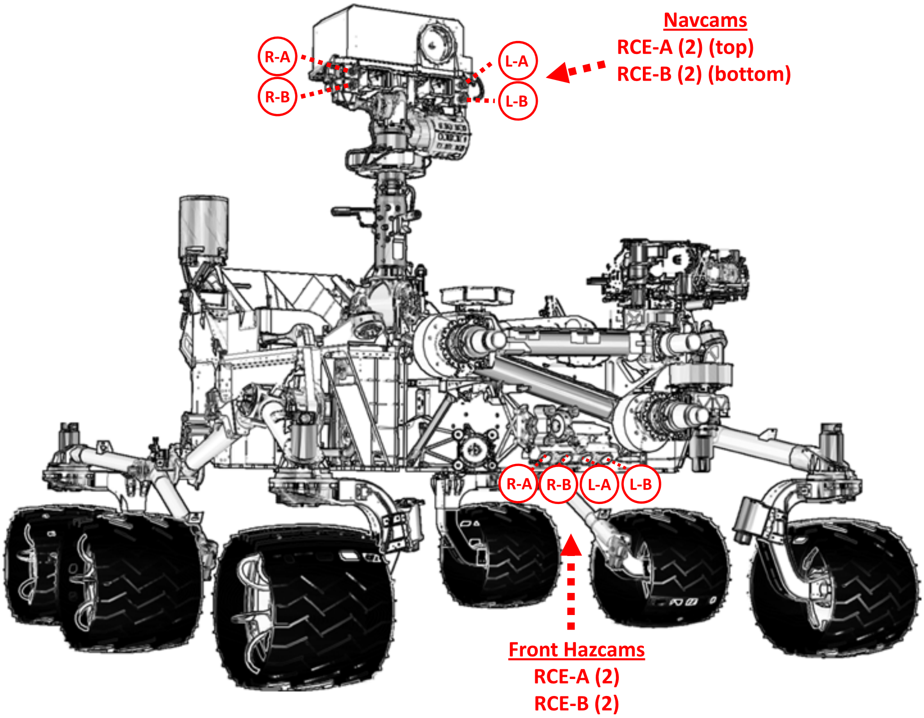


Fig. 5 Locations of the Navcam and Front Hazcam cameras. The left/right camera designations are denoted by the letters *L*/*R*, and the Rover Compute Element (*RCE*) assignments are designated by the letters *A*/*B*

2.8 Camera Configurations on the Rover

The individual cameras within an engineering camera stereo pair are referred to anthropomorphically as "left" and "right" cameras (see Figs. 5 and 6). The Navcams are mounted on the RSM (described earlier). Each RCE Navcam stereo pair has a 42.4 cm stereo baseline. The RCE A Navcams are mounted 4.8 cm above the RCE-B Navcams. The Navcams are able to view all 3 of the wheels on the right (starboard) side of the rover. However the Navcams are not able to view the middle and rear wheels on the left (port) side of the rover and have only a partial view of the front left wheel, depending on the robotic arm configuration. The Navcams do not have lens covers but are stowed in a protective nook during descent and landing. After the one-time deployment of the RSM on the surface, the Navcams will be pointed downward to prevent dust from settling onto the camera lenses when not in use.

The Front Hazcams are hard-mounted to the front of the rover chassis with a 16.6 cm stereo baseline and sit 0.68 meters above the ground. The Front Hazcam stereo pairs for the A and B RCEs are interleaved horizontally with an 8.2 cm offset (see Fig. 5). All 4 of the Front Hazcams are able to view the left and right front wheels in a single image (Fig. 8). The Rear Hazcams are hard-mounted to the rear of the rover chassis with a 10 cm stereo baseline and sit 0.78 meters above the ground. The RCE A Rear Hazcams and RCE B Rear Hazcams are mounted on opposite sides of the RTG (Radioisotope Thermoelectric Generator), 1.0 meters apart (see Fig. 6). The different mounting locations between the RCE-A and RCE-B Rear Hazcams offer different views out the rear of the rover, with the

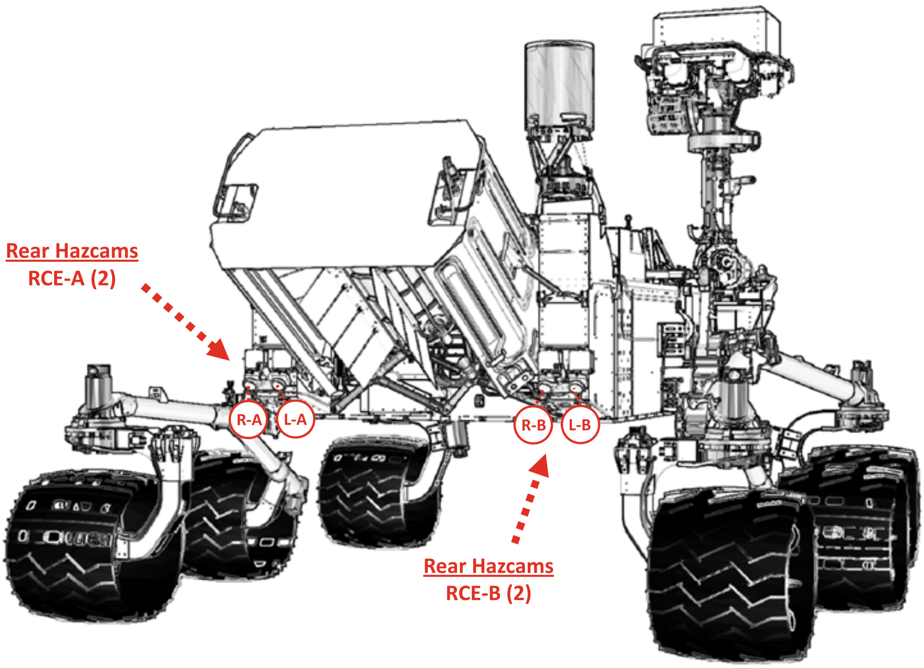


Fig. 6 Locations of the Rear Hazcam cameras. The left/right camera designations are denoted by the letters *L*/*R*, and the Rover Compute Element (*RCE*) assignments are designated by the letters *A*/*B*

RCE-A Rear Hazcam cameras able to view the left rear wheel of the rover but not the right rear wheel, and the RCE-B Rear Hazcam cameras able to view the right rear wheel but not the left rear wheel (see Fig. 9). As mentioned earlier, if necessary it is possible to switch RCEs during the surface mission to obtain views of both rear wheels with the Rear Hazcams. All of the MSL Hazcam lenses are protected during descent using optically transparent covers that are opened after touchdown using a one-time deployable hinged cover mechanism.

2.9 Camera Models and Stereo Ranging

All 12 of the Engineering Cameras have been geometrically calibrated using the CAHV(ORE) camera model system (described in Yakimovsky and Cunningham 1978; Gennery 2001, and Gennery 2006). These models allow image linearization, epipolar alignment, stereo triangulation, and stereo ranging. One notable difference between MER and MSL is that the stereo baselines of the MSL Navcam and Front Hazcam camera pairs are larger on MSL. This increase in stereo baseline improves the absolute stereo ranging accuracy according to the following approximation:

$$\Delta z \approx \frac{Z^2 \cdot \theta \cdot \phi}{b} \tag{1}$$

where Δz is the estimated range error in units of meters, Z is the range from the camera to the object in units of meters, θ is the pixel field of view in radians/pixel, ϕ is the sub-pixel stereo correlation accuracy in units of pixels, and b is the stereo baseline between the camera pairs in units of meters (Chang et al. 1994). Because of the increase

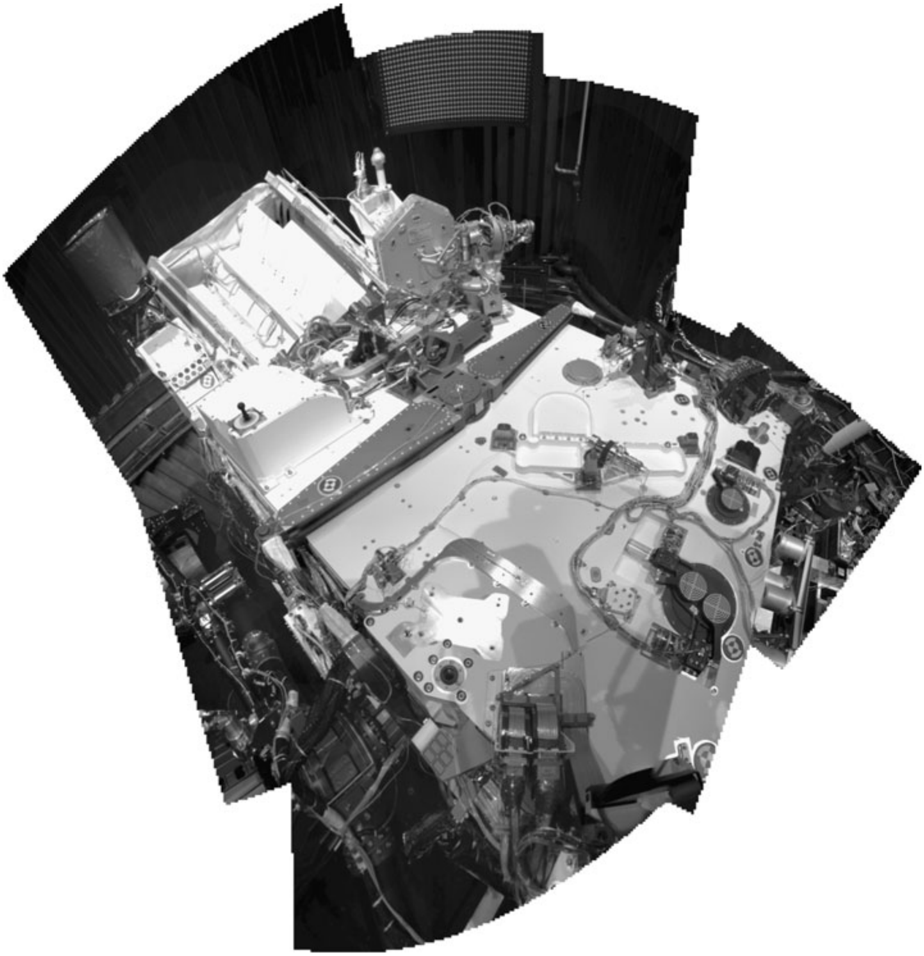
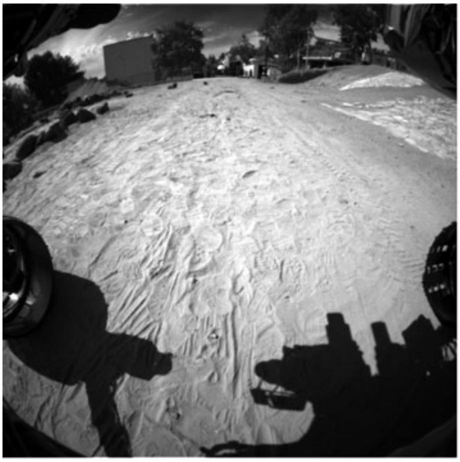


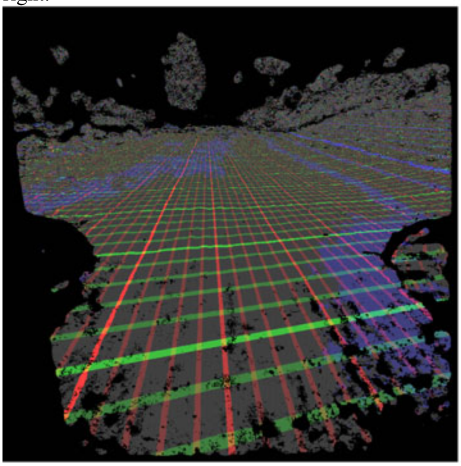
Fig. 7 MSL Navcam panorama of the rover deck, acquired during system thermal vacuum testing. The rover deck measures approximately 1 meter wide by 2 meters long

in stereo baseline relative to MER, the MSL Navcams and Front Hazcams produce stereo range errors that are, in theory, a factor of 2.1 and 1.7 times smaller than the MER Navcam and Hazcams, respectively. In practice this improvement is attenuated somewhat due to the increased parallax, particularly in the near field. The MSL Rear Hazcam stereo baselines are unchanged from MER. The stereo range performance is also affected by stereo correlation accuracy (ϕ), which depends on the scene content in an image (including parallax effects), image compression artifacts in downlinked image data, and the quality of the stereo correlation algorithms. We typically assume a sub-pixel accuracy of 0.25 pixels for flight Mars rover cameras. Figure 10 shows a plot of the MSL Engineering Camera range error as a function of distance, and Table 6 lists the calculated errors for a set of representative distances, all calculated from (1). The stereo ranging capabilities of the MSL engineering cameras have been tested and validated on all of the flight cameras.

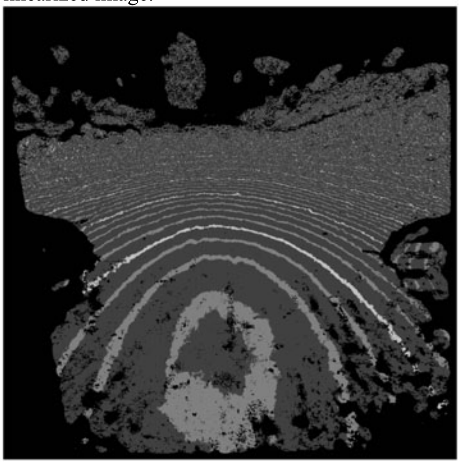


(a) Raw Left Front Hazcam image showing the JPL "Mars yard", with a sloped hill on the right.

(b) Linearized Left Front Hazcam image. Note how the horizon (center) becomes straight in the linearized image.



(c) XYZ Cartesian location of each pixel of the Left Front Hazcam image shown in (b), with 10 cm spacing between X (red), Y (green) gridlines and Z (blue) contours.



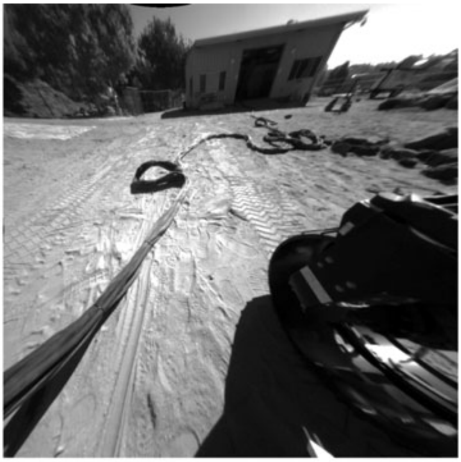
(d) Distance (range) of each pixel to the camera in meters, with 0.10 meter spacing between contours. The first contour (the light grey outline of a circle) is at a distance of 0.7 meters from the camera.

Fig. 8 Example of MSL Front Hazcam stereo products from RCE-A. The views from RCE-A and RCE-B are very similar. Panels (**c**) and (**d**) are not images in the traditional sense, but are instead a form of stereo data that map to the image pixels in panel (**b**). In areas where no stereo correlation solution was found, the data are shown as *black*

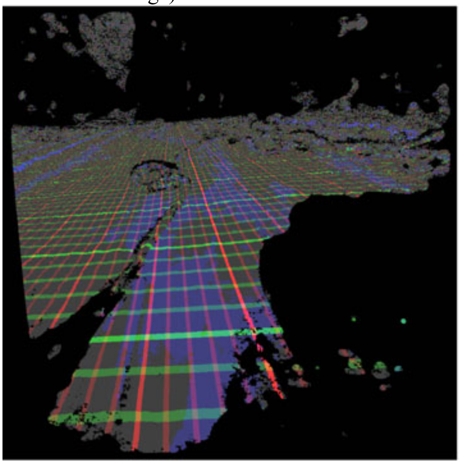
2.10 Operations

A typical 360-degree MSL Navcam stereo panorama consists of a sequence of 12 stereo pairs spaced apart by 30 degrees in azimuth. The 30-degree spacing, which is less than the 45-degree Navcam FOV, ensures that sufficient stereo overlap occurs between image pairs within the panorama. Unlike the MER Navcam panoramas, which utilized a larger 36-degree image-to-image spacing, the larger stereo baseline on MSL (42.4 cm on MSL compared to

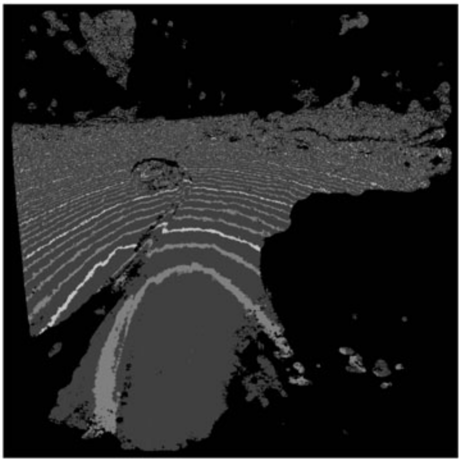
(a) Raw Left Rear Hazcam image. Note the Left Rear Wheel can be seen on the right side of the image (heavily shadowed in this image)



(b) Linearized Left Rear Hazcam image. Note how the horizon becomes straight in the linearized version.



(c) XYZ Cartesian location of each pixel of the Left Rear Hazcam image shown in (b), with 10 cm spacing between X (red), Y (green) gridlines and Z (blue) contours.



(d) Distance (range) of each pixel to the camera in meters, with 0.10 meter spacing between contours. The first contour (the light grey outline of a circle) is at a distance of 0.8 meters from the camera.

Fig. 9 Example of MSL Rear Hazcam stereo products from RCE-A. The views from RCE-B show the Right Rear Wheel on the left side of the image (RCE-B images are not shown here). Note how stereo ranging is precluded on the wheel and the wheel shadow

20 cm on MER) requires a closer inter-image spacing within a Navcam panorama to ensure sufficient stereo overlap between adjacent positions. This inter-image spacing may be adjusted during surface operations (e.g., decreased to allow 11 stereo pairs per 360-degree panorama), depending on the performance of the stereo correlation algorithms on the images of the landing site (see Fig. 11 for an example of Navcam stereo data). During surface operations, individual images within a panorama are often compressed at different compression rates and assigned different downlink priorities, depending on the purpose of the

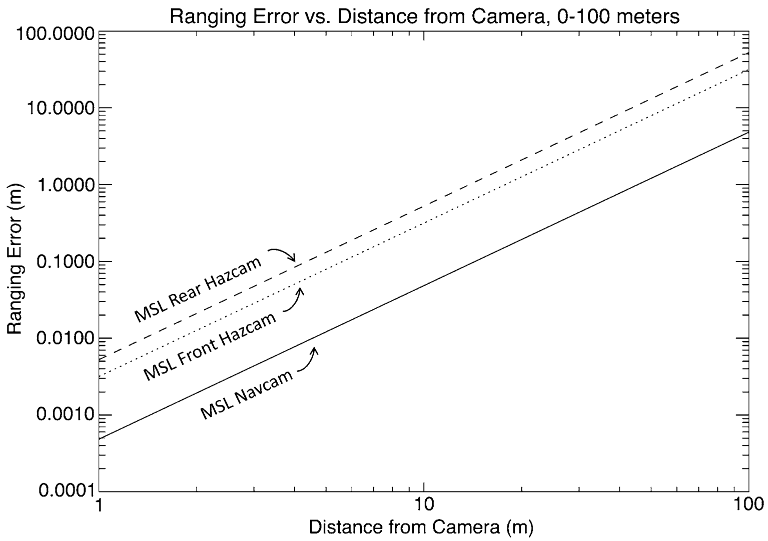


Fig. 10 Calculated stereo range error as a function of distance from the MSL Engineering Cameras, for full-frame, full-resolution images. See Table 6 for a tabular list of values

Table 6 Calculated Stereo Range Error as a function of distance from camera, for full-frame, full-resolution images

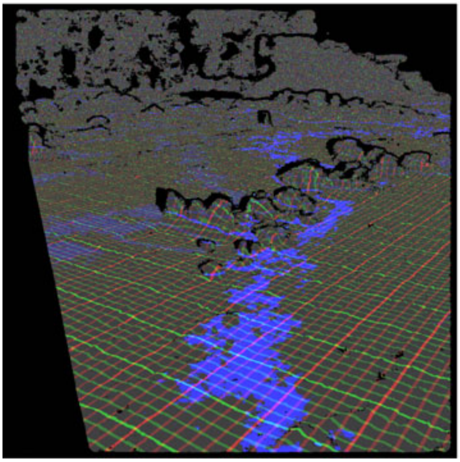
Distance from camera (meters)	Navcam ranging error (meters)	Front Hazcam ranging error (meters)	Rear Hazcam ranging error (meters)
1	0.0005	0.0032	0.0053
2	0.002	0.013	0.021
5	0.01	0.08	0.13
10	0.05	0.3	0.5
15	0.1	0.7	1.2
20	0.2	1.3	2.1
30	0.4	2.8	4.7
40	0.8	5.1	8.4
50	1.2	7.9	13.1
60	1.7	11.4	18.9
100	4.8	31.6	52.5

image acquisition. Table 7 shows a set of representative image data typically used for rover operations. Images that are used for traverse planning and robotic arm placement require high-quality stereo mesh data and are typically compressed at a rate of 3 to 4 bits/pixel. Basic stereo range information can be reliably derived from stereo images compressed at rates as low as 1 to 2 bits/pixel. Compression rates below 1 bit/pixel are generally not usable for stereo ranging because the compression artifacts begin to dominate the image content and reduce the stereo correlation quality of the images.

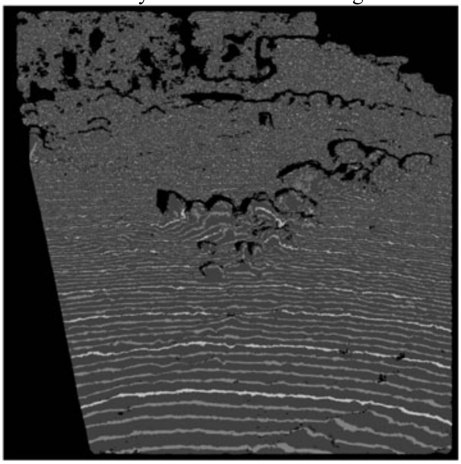
To assist in the imaging of the rover hardware, the RCE flight software maintains an updated list of hardware locations of interest and saves these locations as named coordinate frames. Examples of these locations include calibration targets, fiducial marks, sample inlet

(a) Raw Left Navcam image

(b) Linearized Left Navcam image. Because the Navcam optics have very little distortion, the linearized Navcam images are very similar to the raw images.



(c) XYZ Cartesian location of each pixel of the Left Navcam image shown in (b), with 10 cm spacing between X (red), Y (green) gridlines and Z (blue) contours.



(d) Distance (range) of each pixel to the camera in meters, with 0.10 meter spacing between contours. The first contour (light grey line at the bottom of the image) is at a distance of 3.1 meters from the camera.

Fig. 11 Examples of Navcam stereo products. Note that lack of stereo data (shown as *black*), on the left side of panels (**c**) and (**d**), particularly in the near field at the bottom left. This region corresponds to an area where the left and right images do not overlap due to parallax

covers, locations on the robotic arm, turret, rover wheels, etc. For the case of actuated targets, the RCE flight software dynamically updates the target locations based on actuator and kinematic state information. The resulting system allows the imaging of rover hardware without a priori knowledge of the target location by referencing the named target (e.g., “drill”, “left front wheel”) directly in the image command. In addition, the system allows Navcam pointing to Cartesian offsets from the origin of a named frame (e.g., “30 cm in

Table 7 Representative operational imaging activities. Tactical data are returned to Earth as soon as possible and are immediately used for data assessment and planning. Non-tactical data are returned on less-immediate timescales and are used mainly for non-tactical analysis. All images are acquired as stereo pairs unless otherwise indicated

Type of Imaging	Notes	Downlink priority	Compression rate (bits/pixel)	Size (Mbits)
Navcam drive direction panorama	5 × 1 (5 images wide by 1 image high)	Tactical	3.0	30
Navcam rearward panorama	7 × 1 (7 images wide by 1 image high)	Non-tactical	2.0	28
Front Hazcam end of drive	Typically used for Robotic Arm operations planning and terrain assessment.	Tactical	4.0	8
Rear Hazcam end of drive	Terrain assessment in the rear of the rover	Tactical	3.0	6
Front Hazcam robotic arm placement verification	Used for multiple instruments	Typically non-tactical, for documentation purposes.	1.0	2
Front Hazcam turret/instrument inspection	Used for inspection of turret/mechanism state	Depends on context	2.0	4
Navcam arm state verification	Used to document arm pose, 3 stereo pairs	Depends on context	2.0	12
Navcam Inlet cover imaging	Used to verify inlet cover state	Typically tactical	1.0	2
Autonomously-commanded terrain analysis imaging (Hazcam and Navcam)	Used to find hazards, track features, measure vehicle slip	Non-tactical	Varies, typically spatially downsampled	Varies, depending on length of drives. Not always downlinked

front of the right front wheel”). The MSL rover maintains the onboard state of over 60 named frames for use by the imaging system.

3 Summary

NASA’s MSL mission will land a rover equipped with 4 Navcam cameras and 8 Hazcam cameras onto the surface of Mars in August 2012. The MSL engineering cameras are build-to-print copies of the cameras flown on the MER rovers. Images from the MSL engineering cameras will be used to operate the vehicle, conduct scientific investigations, and document the local terrain around the rover. All of the Navcam and Hazcam image data will be submitted to the Planetary Data System (PDS) within six months of receipt on Earth. The data set will include the entire set of Experiment Data Records (EDRs) from all engineering cameras, along with a set of Reduced Data Records (RDRs), including the derived stereo products and image mosaics.

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