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Waikoloa, Hawaii, USA

JPL

Mars Exploration Rover

Operation and Performance of the Mars Exploration Rover Imaging System on the Martian Surface

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Number of Images from the Surface of Mars

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Mars Exploration Rover

Total for all Mars Missions	144,338	100%

Mission	Number of Images	% of total
Viking 1	3,542	2.5%
Viking 2	3,043	2.1%
Mars Pathfinder Lander	16,635	11.5%
Mars Pathfinder Rover	628	0.4%
Total non-MER	***23,848***	***16.5%***
Spirit	65,028	45.1%
Opportunity	55,462	38.4%
Total MER	***120,490***	***83.5%***

MER Camera resolution compared to other Mars surface landed cameras

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increasing resolution

Rank	Camera	Resolution	Spatial Resolution at 3 meters
1.	MER Microscopic Imager	30 microns/pixel	N/A
2.	MER Pancam	0.28 mrad/pixel	0.8 mm/pixel
3.	Viking Lander (high-resolution mode)	0.70 mrad/pixel	2.1 mm/pixel
4.	MER Navcam	0.82 mrad/pixel	2.5 mm/pixel
5.	Mars Pathfinder (IMP)	0.99 mrad/pixel	3.0 mm/pixel
6.	Viking Lander (low-resolution mode)	2.1 mrad/pixel	6.3 mm/pixel
7.	MER Hazcam	2.1 mrad/pixel	6.3 mm/pixel
8.	Mars Pathfinder Rover	3.1 mrad/pixel	9.3 mm/pixel

= Mars Exploration Rover Camera

MER Camera Overview

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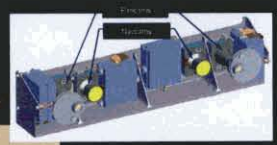
Mars Exploration Rover

- Each Rover has 9 cameras
- Each camera produces 1024 x 1024 pixel images (1 Megapixel)
- All cameras share the same electrical interface and are electrically equivalent.
- All cameras produce the same image format



Navcam

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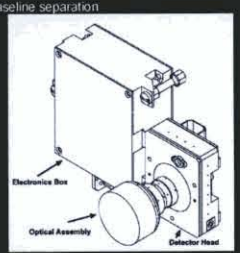
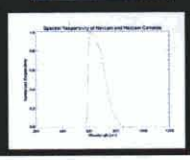
- f/12 optical system, 14.67 mm focal length
- 45x45-degree FOV, 60.7-degree diagonal FOV
- Angular resolution of 0.82 mrad/pixel at the image center.
- Roughly equivalent to a 40 mm lens on a 35 mm camera.
- 20 cm stereo baseline separation

Navcams





Hazcams

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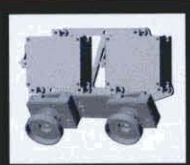
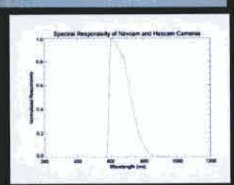


- The Hazard Avoidance Cameras (Hazcams) are an f/15 optical system with a focal length of 5.58 mm.
- The Hazcam optics are fisheye lenses with a 124 x 124 degree horizontal/vertical field of view and a 180-degree diagonal FOV.
- 10 cm stereo separation.



Pancam Description

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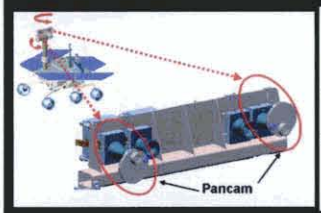
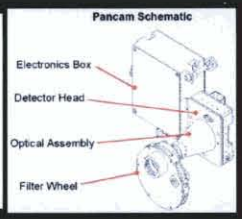


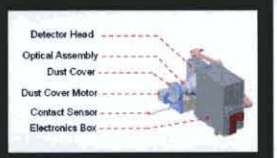


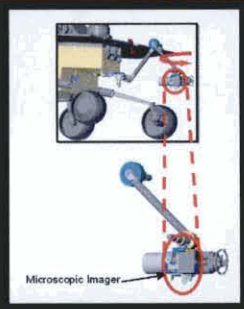
- The Panoramic Cameras (Pancams) are an f/20 optical system with a focal length of 43 mm
- The Pancam optics have a 16 x 16 degree horizontal/vertical field of view and a 22.5-degree diagonal FOV
- 30 cm stereo separation

Microscopic Imager (MI) Description

Mars Exploration Rover

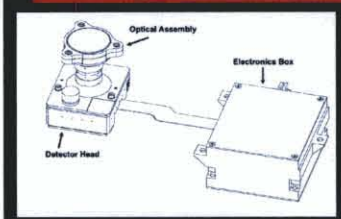
- The Microscopic Imager (MI) is an f/14.4 optical system with a focal length of 20.2 mm.
- The MI optics have a 31.5 x 31.5 mm horizontal/vertical field of view.
- 30 micron/pixel spatial resolution

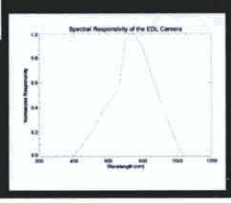




Descent Camera

Mars Exploration Rover





- f/12 optical system, 14.67 mm focal length
- 45x45-degree FOV, 60.7-degree diagonal FOV
- Angular resolution of 0.82 mrad/pixel at the image center.

MER Engineering Camera Description and Objectives

Mars Exploration Rover

Cameras

Descent Camera	Acquire 3 images of the Martian surface between altitudes of 2000 m and 1200 meters during descent. Field of view: 45 degrees, 3-meter pixel spatial resolution. Broadband, visible filter.
Navcams	Provide terrain context for traverse planning and Pancam/Mini-TES pointing. 360-degree field of regard at 1 mrad pixel angular resolution. Stereo ranging out to 100 meters (20 cm stereo baseline). Broadband, visible filter.
Hazcams	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 Instrument Deployment Device (IDD) operations. Support Rover fine positioning near IDD targets. Wide field of view (120 degrees), 2 mrad pixel angular resolution. Stereo ranging immediately in front of the rover (10 cm stereo baseline) to an accuracy of ~ 5 mm. Broadband, visible filter

MER Science Camera Description and Objectives

Mars Exploration Rover

Cameras

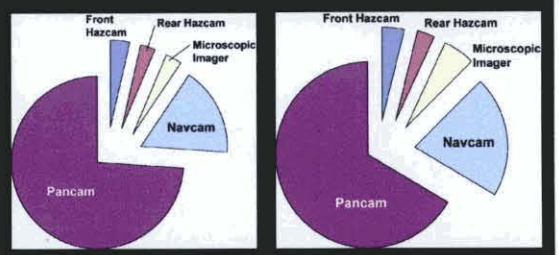
Pancam	Obtain monoscopic and stereoscopic image mosaics. Obtain multispectral visible to short-wave near-IR images over a range of viewing geometries. Obtain images of the Sun and Martian sky. Serve as the primary Sun-finding camera for rover navigation. Resolve objects on the scale of the rover wheels to distances of ~100 m. Support acquisition and release of exciting E/PO products.
Microscopic Imager	Image fine-scale morphology of natural surfaces. Image fine-scale texture and reflectance of abraded surfaces. Aid in the interpretation of data gathered by other instruments by imaging areas examined by them at high resolution.

MER Lens Assemblies

Mars Exploration Rover

Cameras mounted on flight rover

Representative Fraction of Image Data from Different MER Cameras

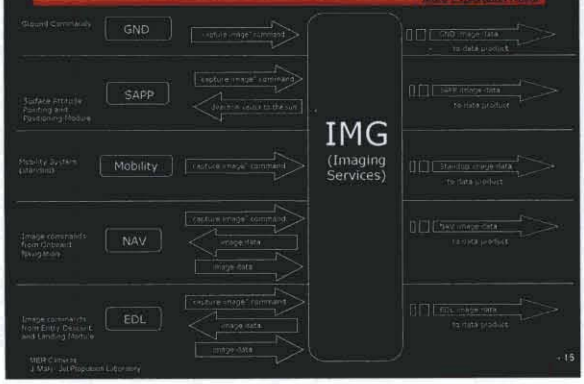


Combined Image Area (number of pixels)

Compressed Data Volume (number of compressed bits)

Excludes thumbnail and reference pixel images

Onboard Users of the Camera



Onboard Image Processing

- All onboard image processing code is implemented in flight software
  - Includes software compression and stereo correlation
- Coded in C
- Running on a CPU rated at 20 MIPS
- 256 Mbytes of FLASH memory
- For more details see
  - Litwin T. E., and Maki, J. N., "Imaging Services Flight Software on the Mars Exploration Rovers", (this conference).

Onboard Image Processing

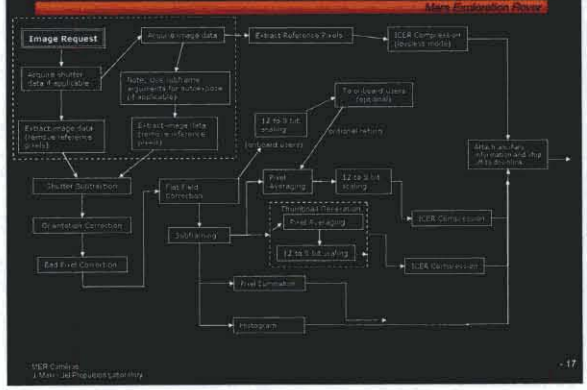


Image Processing Capabilities

The Mars Exploration Rover onboard image processing capabilities include the following:

- Autoexposure, multiple exposure types
- Shutter Subtraction, Bad Pixel Correction, Flat Field Correction
- Exposure tables
- Histogram generation
- Image Orientation
- Thumbnail Generation
- Row/Column Summation
- 12 to 8 bit downsampling (radiometric)
- Spatial downsampling
- Subframing (windowing)
- Image File Storage
- Sun Identification
- Camera Models (geometric)
- Image Compression

MER Uses Two Image Compressors

Mars Exploration Rover

- **ICER** (not an acronym)
  - Progressive wavelet image compressor
  - Developed at JPL by A. Kiely and M. Klimesh (JPL) [1]
  - Can be used for lossy and lossless compression
  - Achieves rate-distortion tradeoff comparable to that of JPEG-2000
    - Lower complexity for onboard compression in space
  - Error containment to limit effects of data losses on the deep space channel
- **LOCO** (LOw COmplexity)
  - Very fast, non-progressive, lossless compressor
  - Developed at Hewlett-Packard Laboratories by Weinberger et al. [2]
    - LOCO-I (Low Complexity Lossless Compression for Images) later standardized to JPEG-LS
  - MER uses a modified version of LOCO (fast lossless compression)

[1] A. Kiely, M. Klimesh, The ICER Progressive Wavelet Image Compressor, *IPN Progress Report 42-155*, pp. 1-46, November 15, 2003, http://ipnpr.jpl.nasa.gov/progress_report/42-155/155.pdf
[2] Marcelo J. Weinberger, Gilbert Seroussi and Guillermo Sapiro, LOCO-I: A Low Complexity, Context-Based Lossless Image Compression Algorithm, *Proc. 1996 IEEE Data Compression Conference*, pp. 140-149, 1995

MER Cameras
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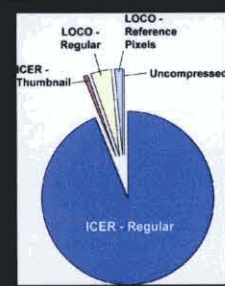
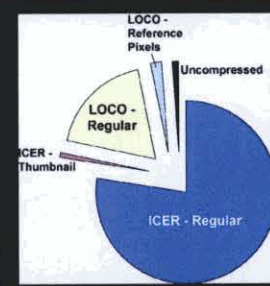
Fraction of Image Data from Different MER Compressors and Image Types

Mars Exploration Rover



Combined Image Area (number of pixels)



Compressed Data Volume (number of compressed bits)

MER Cameras
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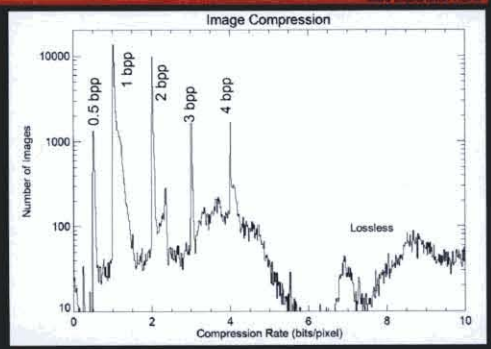
Compression Rates

Mars Exploration Rover



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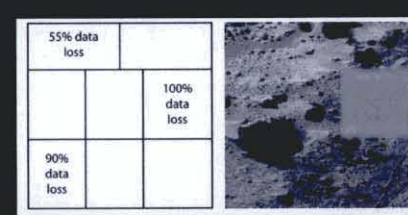
Error Containment

Mars Exploration Rover



Example of the ICER error containment capability in an image compressed to 1 bit/pixel, and suffering packet losses affecting three of eight image segments.

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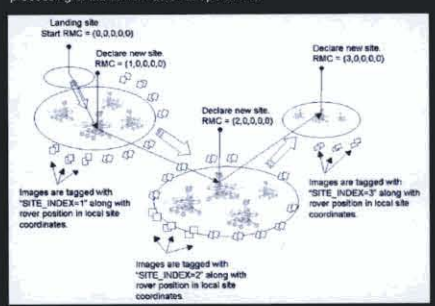
Multiple Site Frames

Mars Exploration Rover

Use of telemetry tags for Rover site allows easy downlink, identification, and processing of instrument data for operations.



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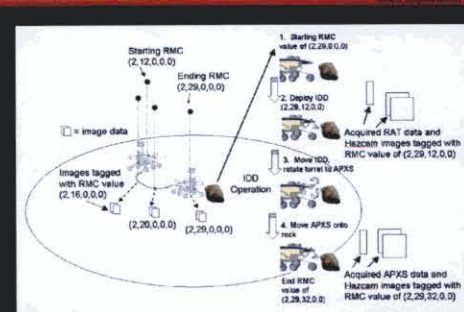
MER Data Product Organization Tags: Rover Motion Counter

Mars Exploration Rover



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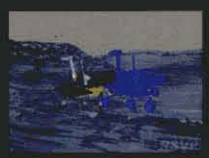
Penultimate Front Hazcams

Mars Exploration Rover

Prior to arriving in the final position at the end of a traverse, a penultimate Front Hazcam stereo pair is often acquired. This image set provides a view of the area that the rover drives into (and parks on) as part of the final drive step (see figure 3). Because the deploy space of the IDD is not fully visible from any of the cameras at the ultimate position, the penultimate set is required to determine if there are any obstructions in the IDD workspace that would prevent the IDD from safely deploying.



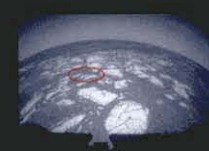
Ultimate Front Hazcams

Mars Exploration Rover

Figure 4. A Penultimate Front Hazcam image from Sol 399-B, compressed at 0.5 bits pixel

more heavily compressed than the typical image. compression rates of 0.5 bits pixel to 1 bit pixel are typically used for this image data.

Upon arrival at the final rover position for a given sol, an Ultimate (final) Front Hazcam stereo pair is almost always acquired. These images are used for near-field hazard determination as well as IDD target designation on the following sol (if applicable).

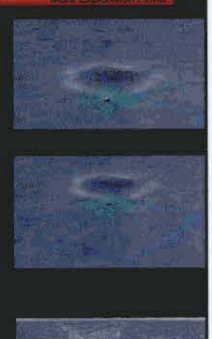


Navcam Imaging

Mars Exploration Rover

Navcam images are used extensively for traverse planning, localization, and as targeting maps for the science instruments (i.e., Pancam and Mini-TES). A typical end of drive Navcam image set includes a 360 x 45-degree panorama (i.e., 10 images wide by 1 image high). The "drive direction" portion of the panorama is typically compressed at higher bit rates (i.e., less compression) than the rearward-looking portion of the panorama.

Not all Navcam panoramas are 360-degrees in extent. Constrained downlink volumes will often limit the size of a Navcam panorama. If a traverse is particularly short, the panorama is sometimes only 3 images wide by 1 image high, or in some cases even smaller.



IDD Operations Imaging

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Operation of the IDD is done primarily through the use of Front Hazcam imagery. The Ultimate Front Hazcam images (see figure 5) are used as the source data for 3-D terrain mesh generation and provide the data necessary for IDD command visualization. The Front Hazcams are also used to document the actual placement of the IDD onto the selected targets. Because these images are predominantly for documentation purposes only, they are generally compressed at a rate of 1 bit/pixel and are often spatially downsampled at half-resolution. Figure 11 shows an example documentation image.

Dust Contamination

Mars Exploration Rover

Dust Contamination

On Sol 331, during the Opportunity Heat-shield observation campaign, Rear Hazcam (both left and right) images started exhibiting a mottled pattern (i.e., a spotted, following pattern) in the sky portion of the image. The previous image (from Sol 330) does not show this effect. Subsequent Rear Hazcam images show that the mottled pattern is virtually identical from Sol to Sol, suggesting that the pattern is an instrument effect and not an atmospheric feature. The pattern does not appear in any of the Front Hazcam, Navcam, Pancam or MI camera images.

On Sol 417, Spirit's Front Hazcam images also showed a contamination pattern consistent with dust adhesion onto the surface of the lenses. The patterns appeared suddenly on Sol 417 and did not exist on Sol 416 or earlier. The contamination pattern is similar to the patterns that appeared on the Opportunity Rear Hazcams, but the Spirit contamination is more pronounced. Peak to peak DN differences for the Spirit spots (i.e., the DN value of a dark spot subtracted from the neighboring sky background) are around 120 DN vs. around 100 DN for Opportunity. The Spirit spots are also slightly bigger than Opportunity (17-18 pixels in diameter on Spirit vs 15-16 on Opportunity). The Spirit dust contamination appears to be related to an increase in local wind activity.

Mars Exploration Rover

Ground Image Processing

(on Earth)

Ground Image Processing

Mars Exploration Rover

- Done at the Jet Propulsion Laboratory's Multimission Image Processing Laboratory (MIPL)
  - Section 386
- VICAR (Video Image Communication and Retrieval)
  - Heritage dating back to the 1960s
  - C++
  - Runs mainly on Linux systems (also Solaris)
    - 6 dual-CPU Linux machines do the bulk of the processing work
- Development Team: 8 people, Operations Team: 16 people
- Two main types of processing: stereo processing and mosaicking
- See Alexander paper, this conference.

Stereo Processing

Mars Exploration Rover

- Stereo Processing (left/right pairs)
  - Raw Images
  - Radiometric correction (flat field, responsivity)
  - Geometric processing (epipolar alignment)
  - Stereo correlation (1 or 2 dimensional)
  - Triangulation (Cartesian 3-space)
  - Range (distance)
  - Surface Normals (perpendicular to surface plane)
  - Slope Maps
  - Solar Energy Maps
- All processing must be done within 30 minutes of data receipt !
- See Deen/Lorre paper, this conference.

Raw Image

Mars Exploration Rover

Geometrically Corrected Image

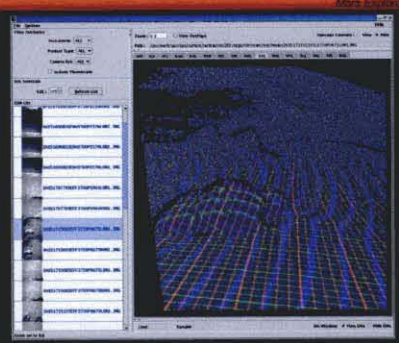
Mars Exploration Rover

Stereo Disparity Map

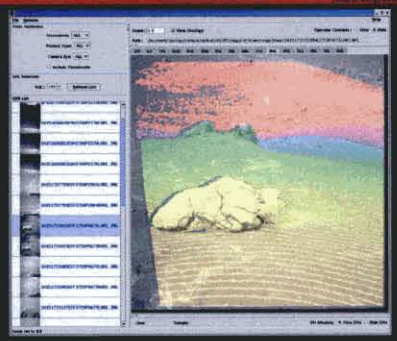
Mars Exploration Rover

XYZ Position Map

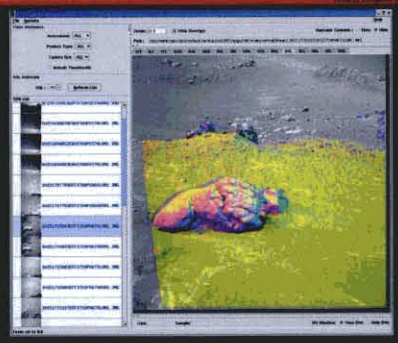
Mars Exploration Rover



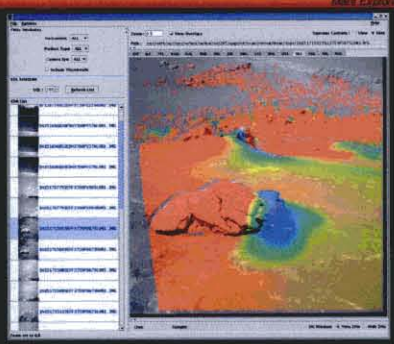
Range Map



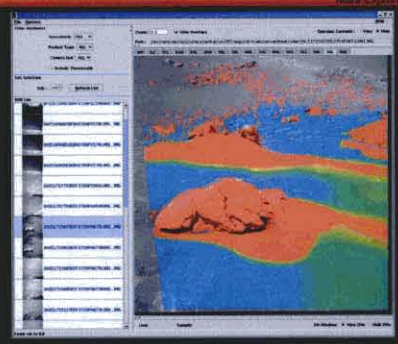
Surface Normal Map



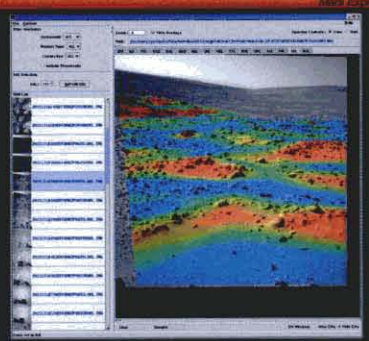
Slope Map



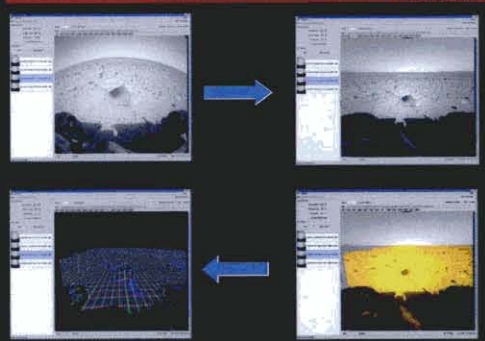
Solar Energy Map



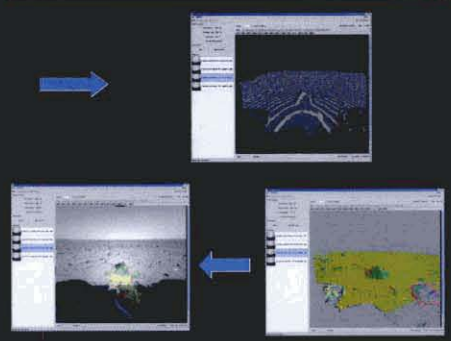
Solar Energy Map



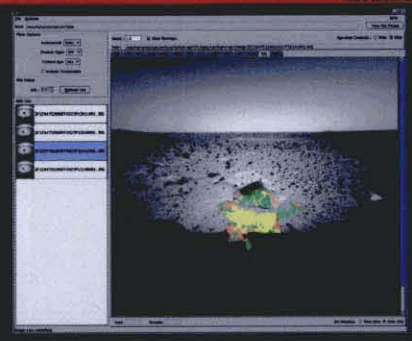
Stereo Processing Pipeline



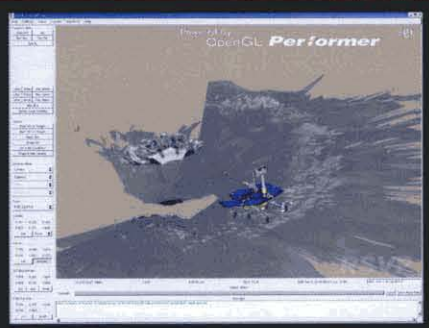
Stereo Processing (cont.)



Arm (IDD) Reachability Map



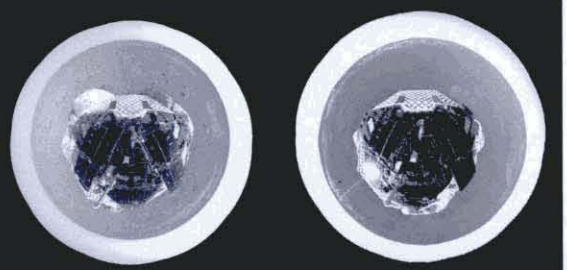
Terrain mesh



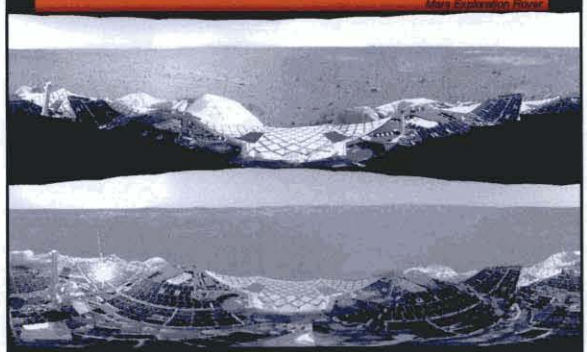
Mosaicking

- Mosaicking
  - Multiple-image inputs (typically 2 through 200 images)
  - Five different projection types
    - Cylindrical
    - Perspective
    - Cylindrical-perspective
    - Polar
    - Vertical
  - Performs radiometric correction
- All processing must be done within 30 minutes of data receipt

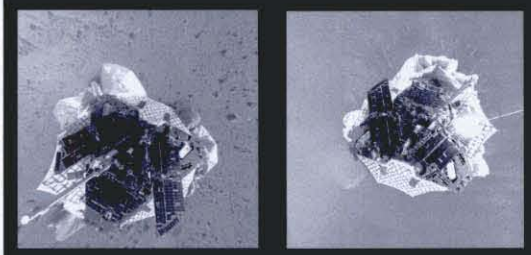
Spirit Sol 1 Navcam Panorama, Polar projection



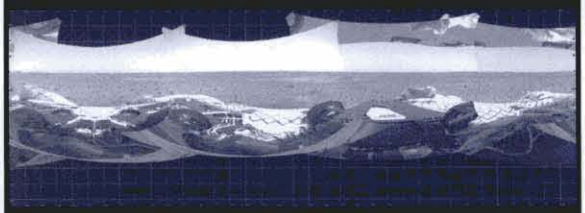
Spirit Sol 1 Navcam Panorama, Cylindrical projection



Spirit Sol 1 Navcam Panorama, Vertical

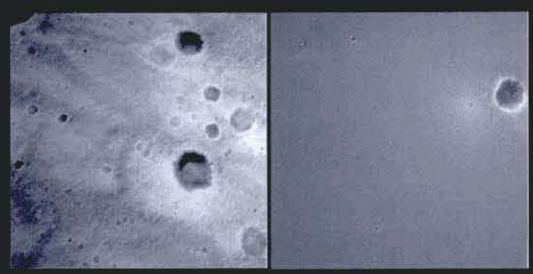


Hazcam panorama

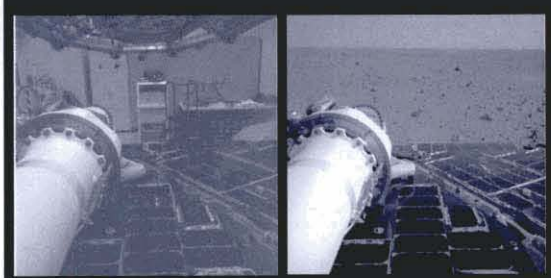


BACKUP

Descent Camera Images



Navcam Images, before and after



Pasadena, Earth

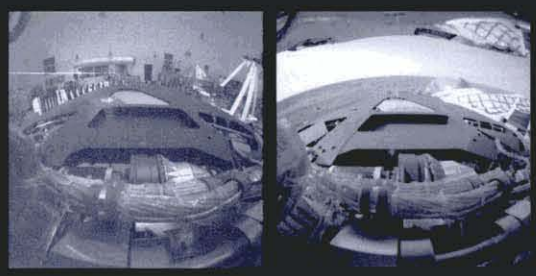
Gusev Crater, Mars

First Images, Spirit/Opportunity

Spirit (Gusev Crater)

Opportunity (Meridiani Planum)

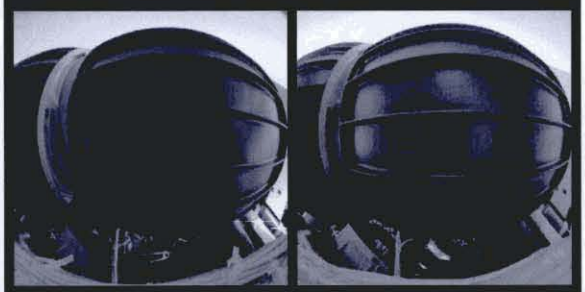
Rear Hazcam Images



KSC (PHSF), Florida, Earth

Gusev Crater, Mars

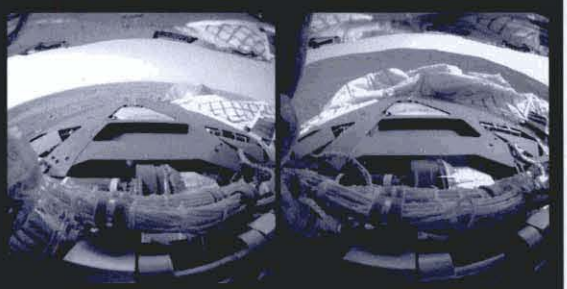
Landing Day - Right Front Hazcam images



Spirit (Gusev Crater)

Opportunity (Meridiani Planum)

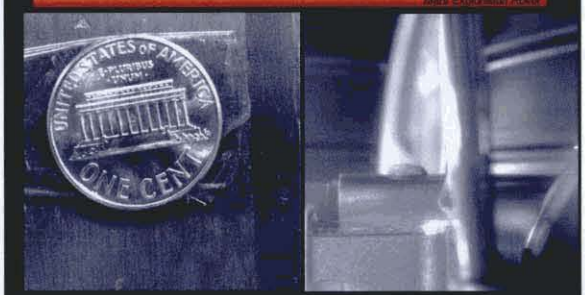
Landing Day – Left Rear Hazcam images



Spirit (Gusev Crater)

Opportunity (Meridiani Planum)

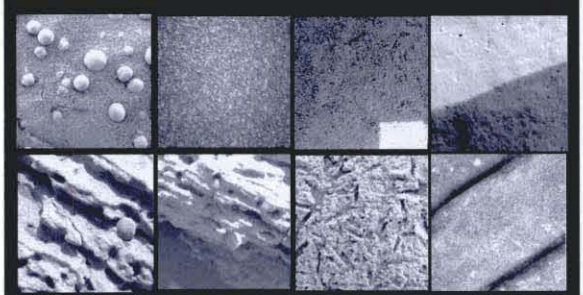
First MI Image



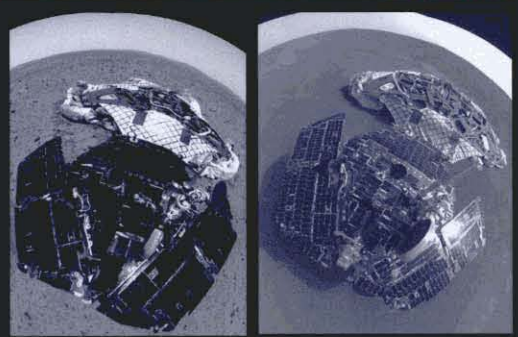
Pasadena, Earth

First Image from Mars

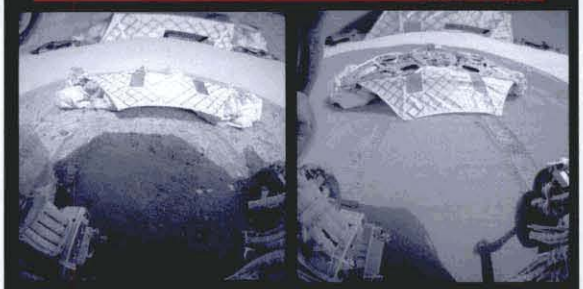
More MI Images



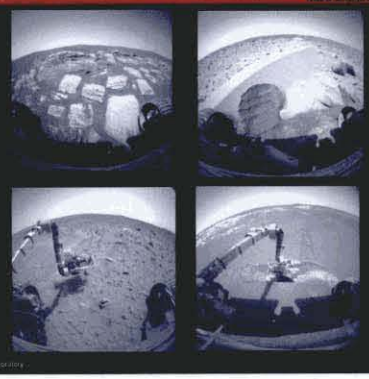
Post-egress Navcam Panorama



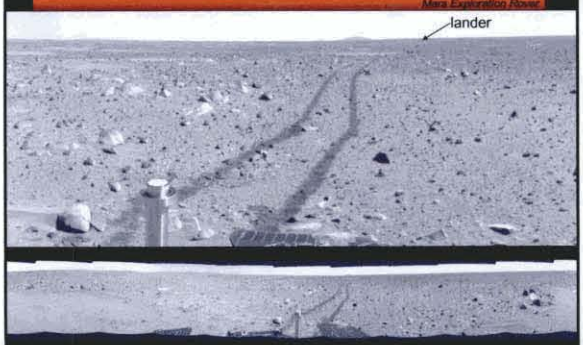
Post-egress Rear Hazcam - Spirit



Instrument Deployment Device (IDD) Operations

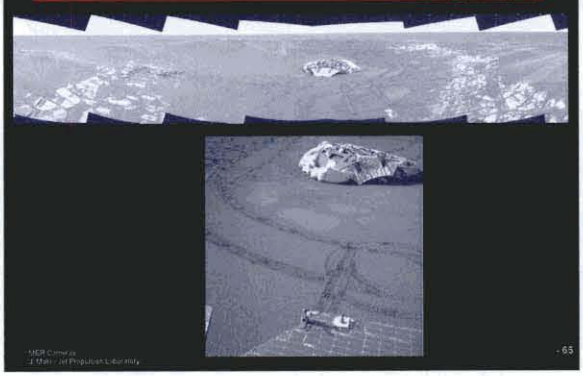


Long-distance drives

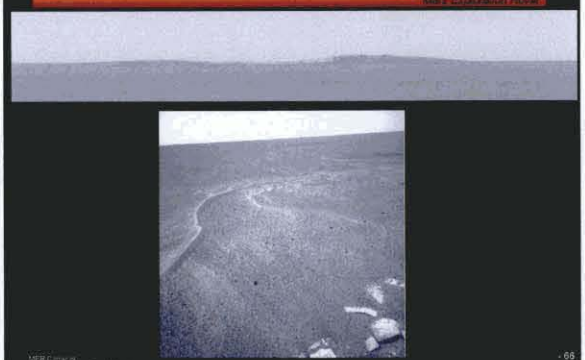


Bonneville Crater

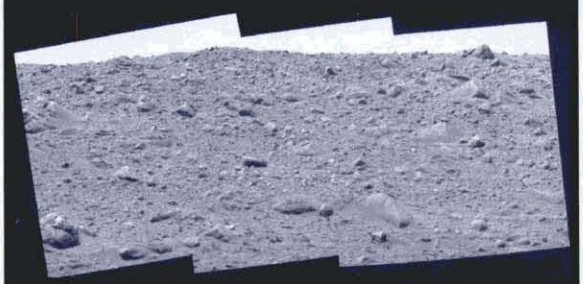
Eagle Crater (looking inward)



Eagle Crater (looking outward)



Traverse to Bonneville Crater Rim



Ground-based Astronomy (from the Martian surface)

Earth Imaging

Recent Status (needs updating)

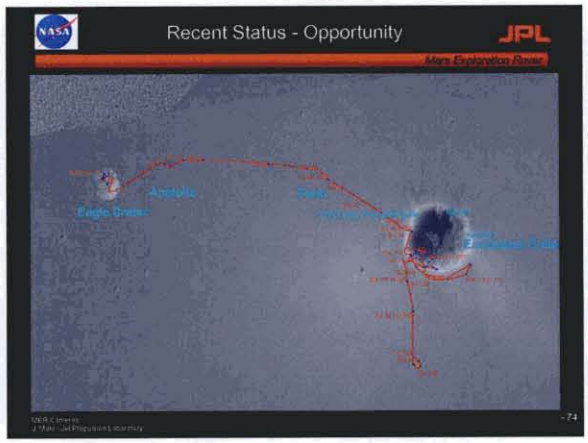
- Distance driven: 3,625+ meters (Spirit)
  1,600+ meters (Opportunity)
- Cameras continue to function nominally

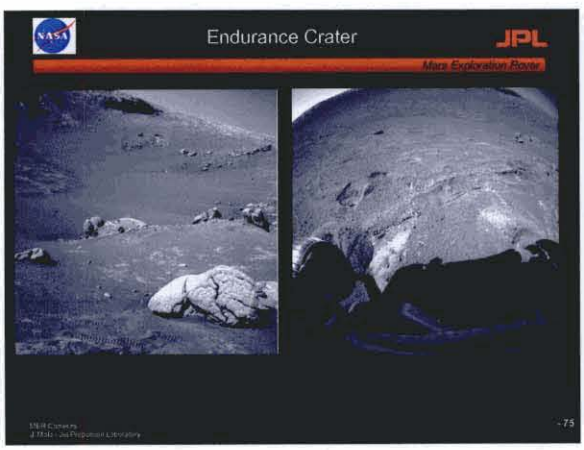
Image Totals, MER A:	Image Totals, MER B:
EDL: 3	EDL: 3
Rear Hazcam: 1254	Rear Hazcam: 388
Front Hazcam: 5589	Front Hazcam: 1748
Navcam: 4682	Navcam: 5173
MI: 1655	MI: 2049
Pancam: 23425	Pancam: 21997
Total for MER A: 36608	Total for MER B: 31658

Total number of images for both Rovers: 68266

Recent Status - Spirit

Columbia Hills
JPL
Mars Exploration Rover
MER Cameras
J Mars - Jet Propulsion Laboratory
- 73


Recent Status - Opportunity
JPL
Mars Exploration Rover
Eagle Crater
Apollo
Erebus
MER Cameras
J Mars - Jet Propulsion Laboratory
- 74

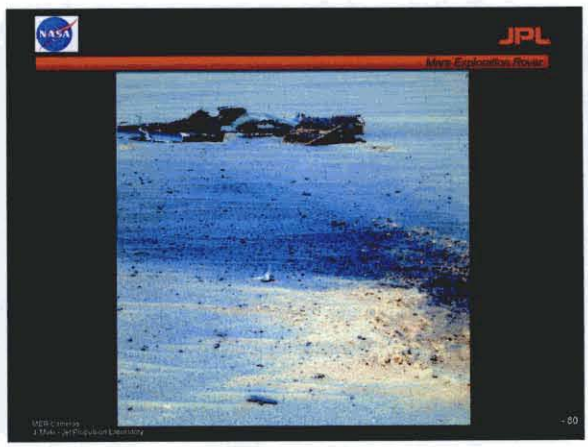

Endurance Crater
JPL
Mars Exploration Rover
MER Cameras
J Mars - Jet Propulsion Laboratory
- 75

JPL
Mars Exploration Rover
MER Cameras
J Mars - Jet Propulsion Laboratory
- 76

JPL
MER Cameras
J Mars - Jet Propulsion Laboratory
- 77

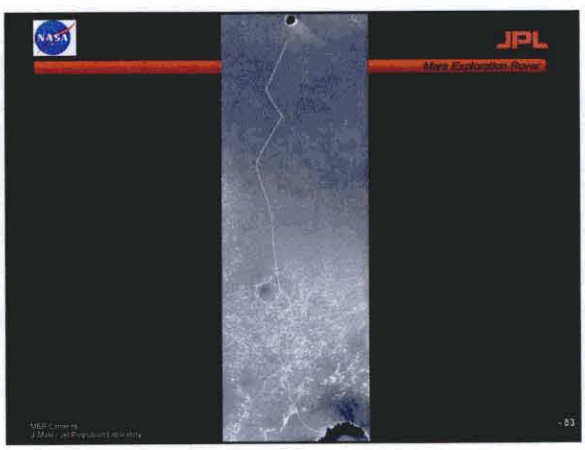
JPL
Mars Exploration Rover
MER Cameras
J Mars - Jet Propulsion Laboratory
- 78

JPL
Mars Exploration Rover
79


JPL
Mars Exploration Rover
80

JPL
Mars Exploration Rover
81

Heat Shield Investigation
JPL
Mars Exploration Rover
82


JPL
Mars Exploration Rover
83