Mars Exploration Rover

Descent Image Motion Estimation System

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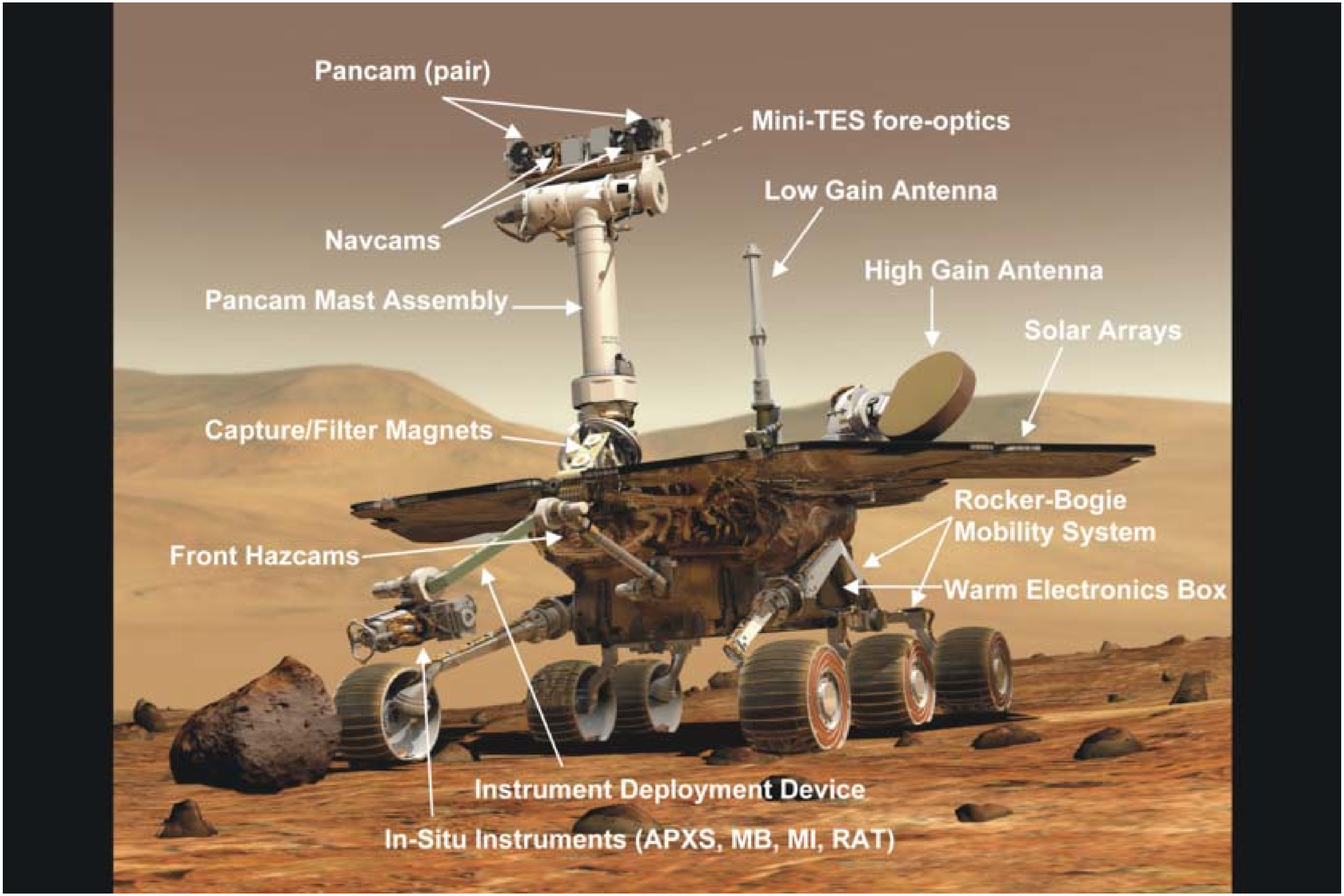
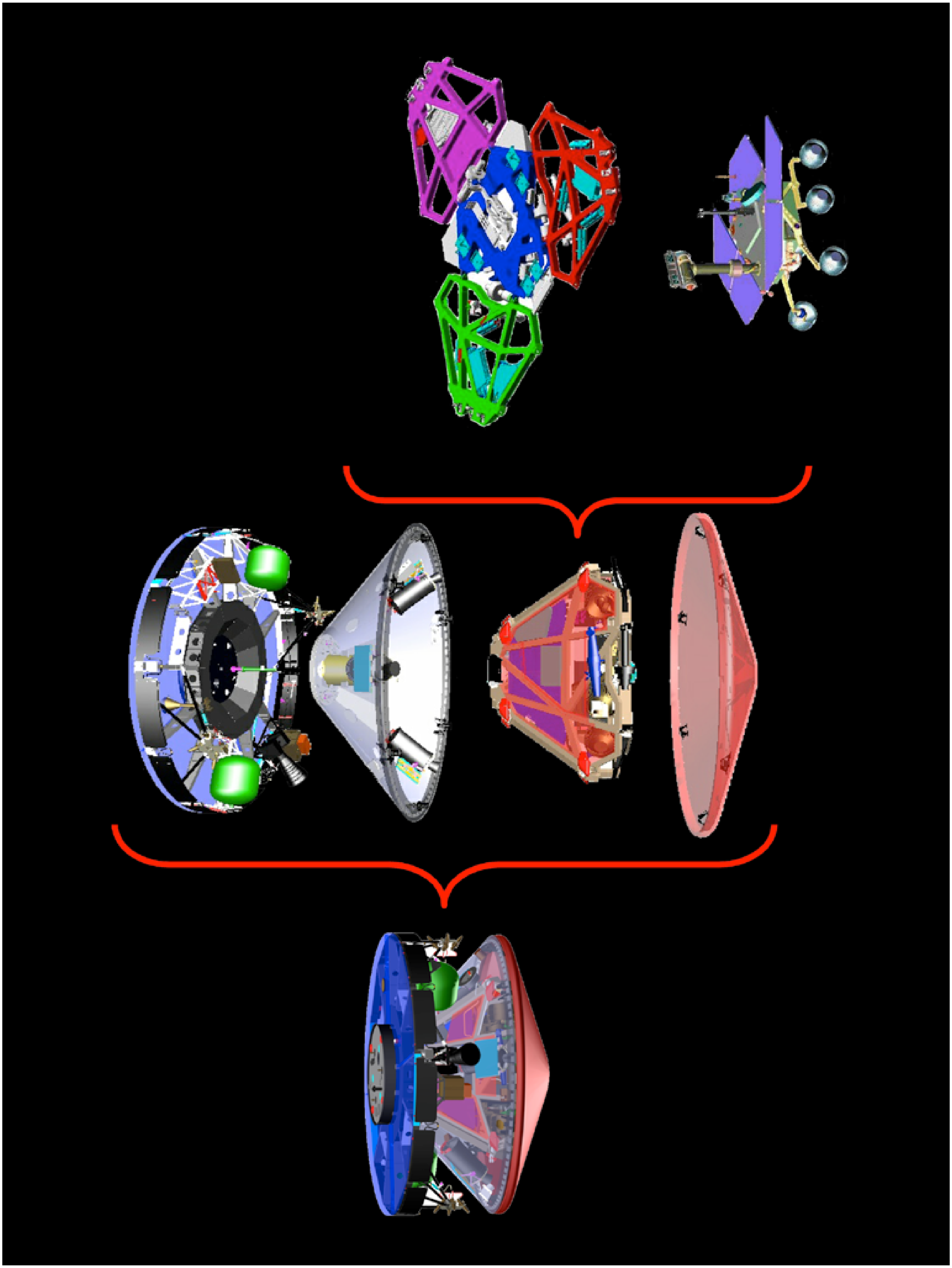
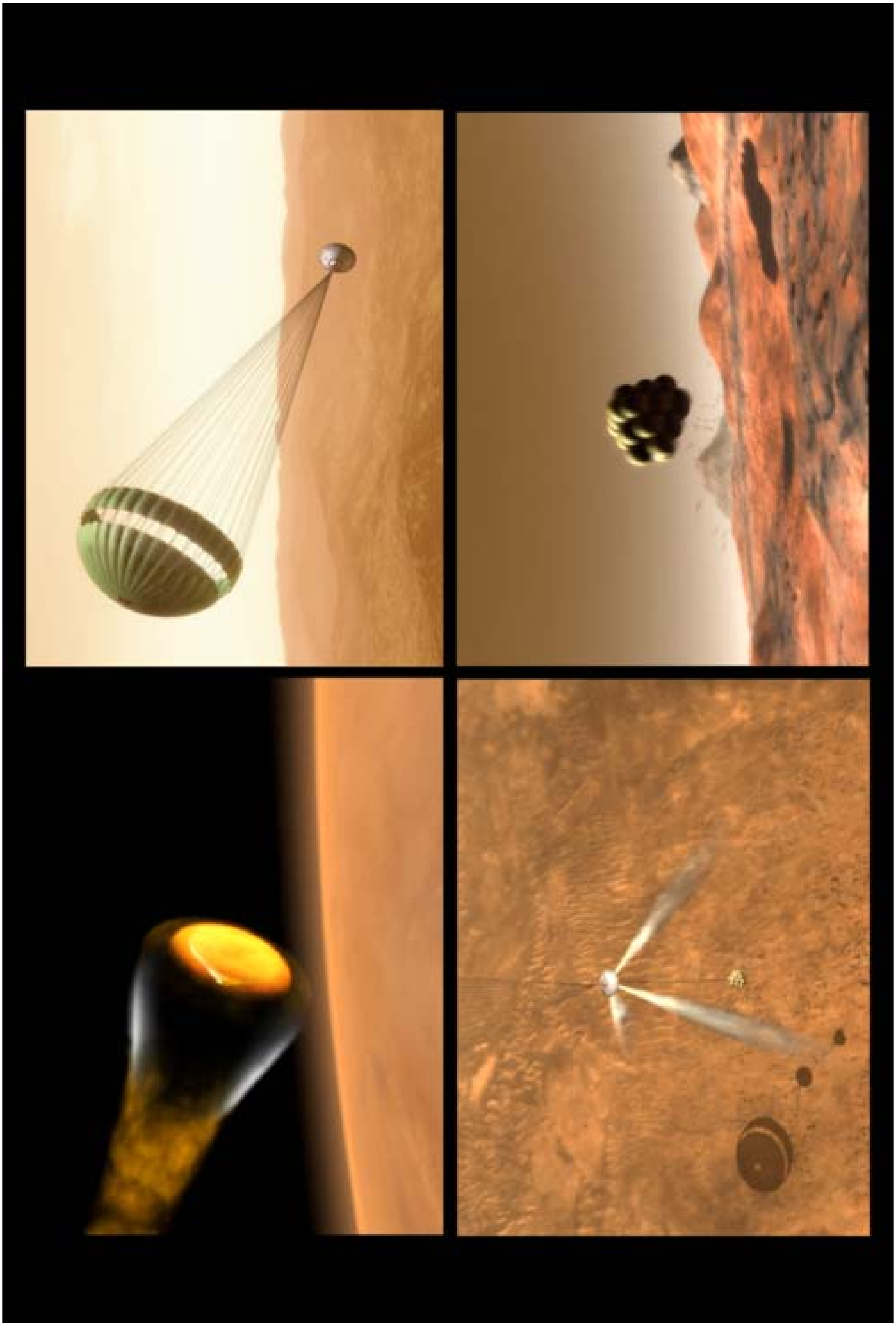
California Institute of Technology


Pancam (pair)
Mini-TES fore-optics
Navcams
Low Gain Antenna
High Gain Antenna
Pancam Mast Assembly
Solar Arrays
Capture/Filter Magnets
Rocker-Bogie
Mobility System
Front Hazcams
Warm Electronics Box
Instrument Deployment Device
In-Situ Instruments (APXS, MB, MI, RAT)





MER Entry, Descent & Landing Scenario

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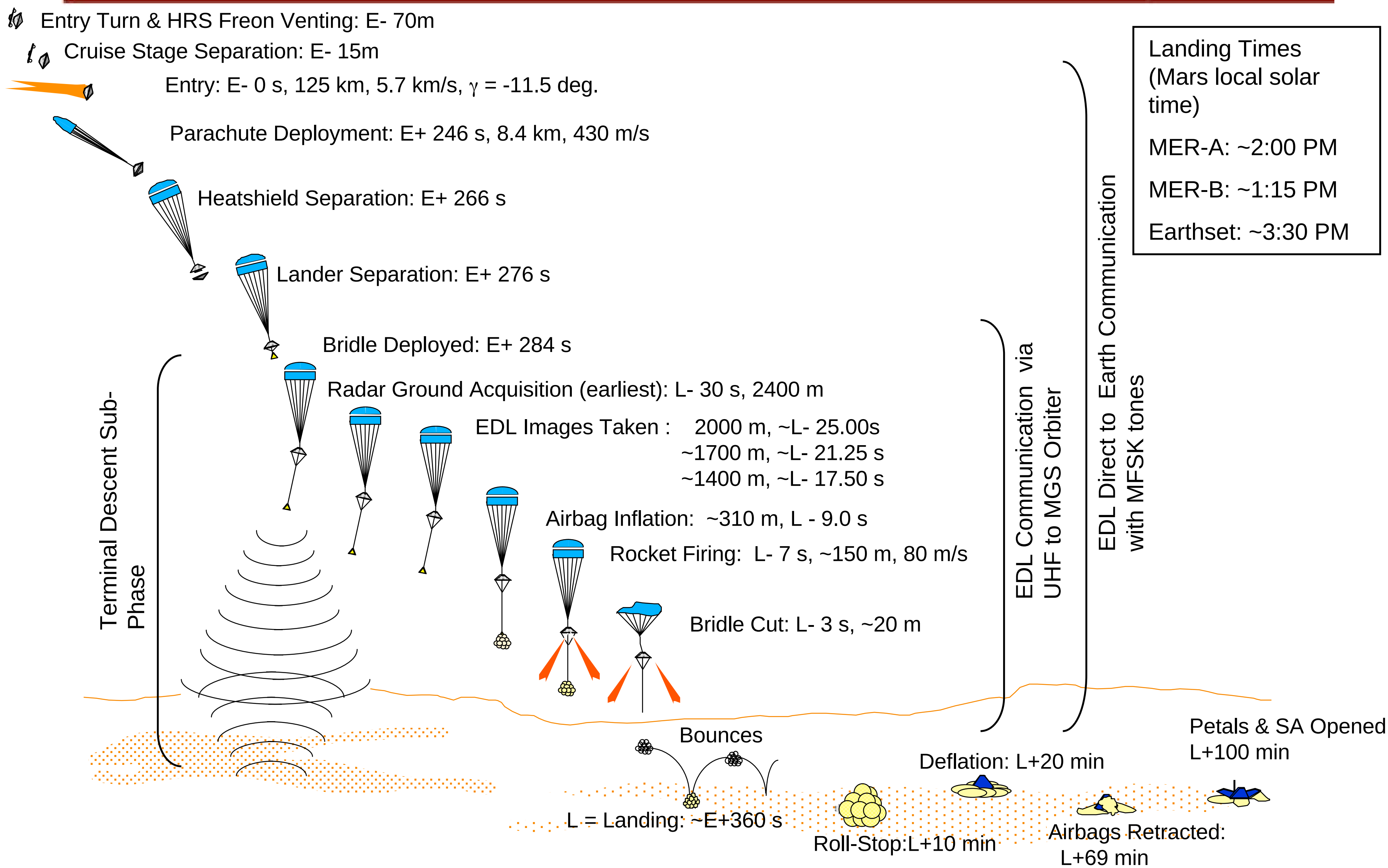
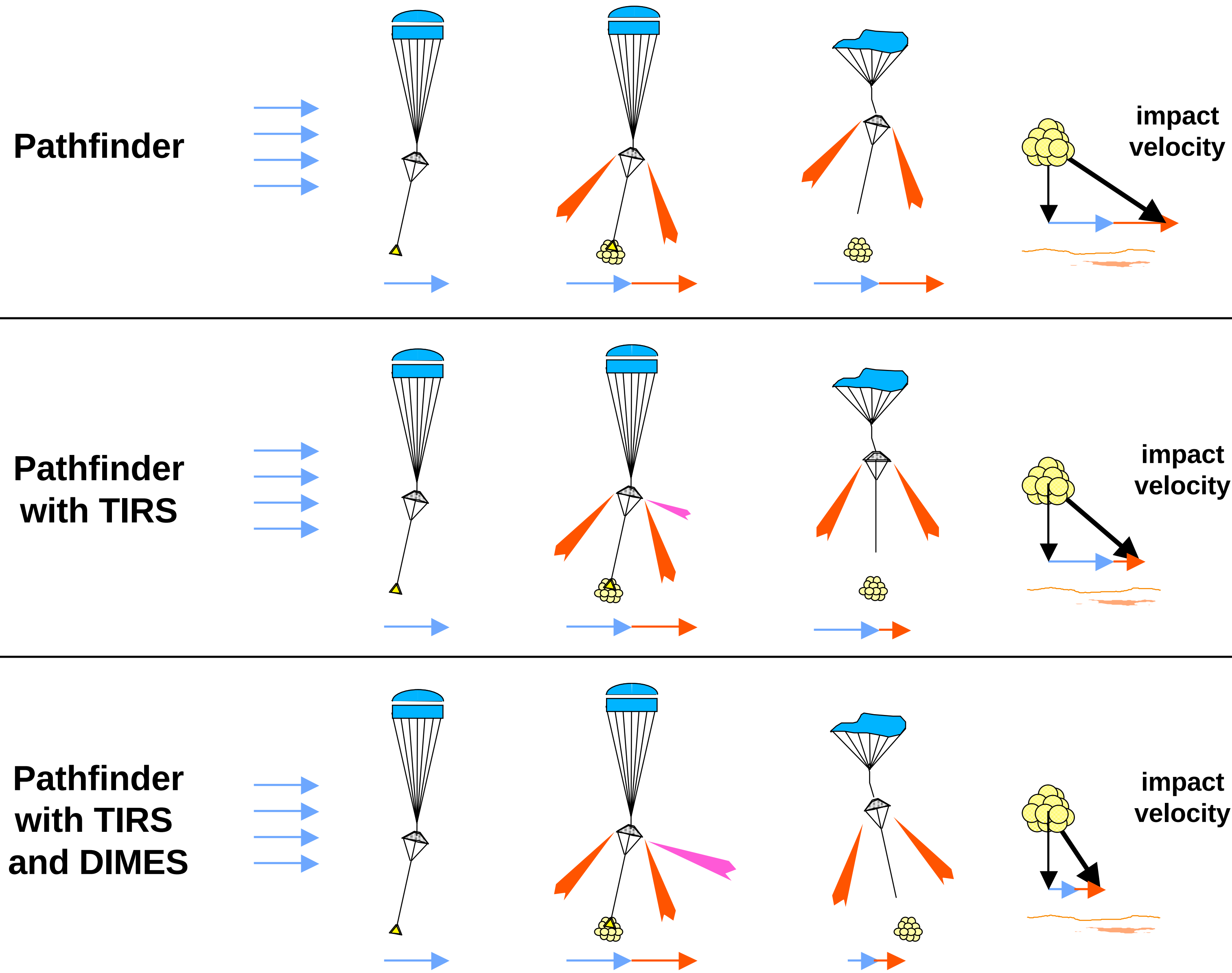


Effect and Mitigation of Winds



No TIRS Probability of Success with various wind distributions

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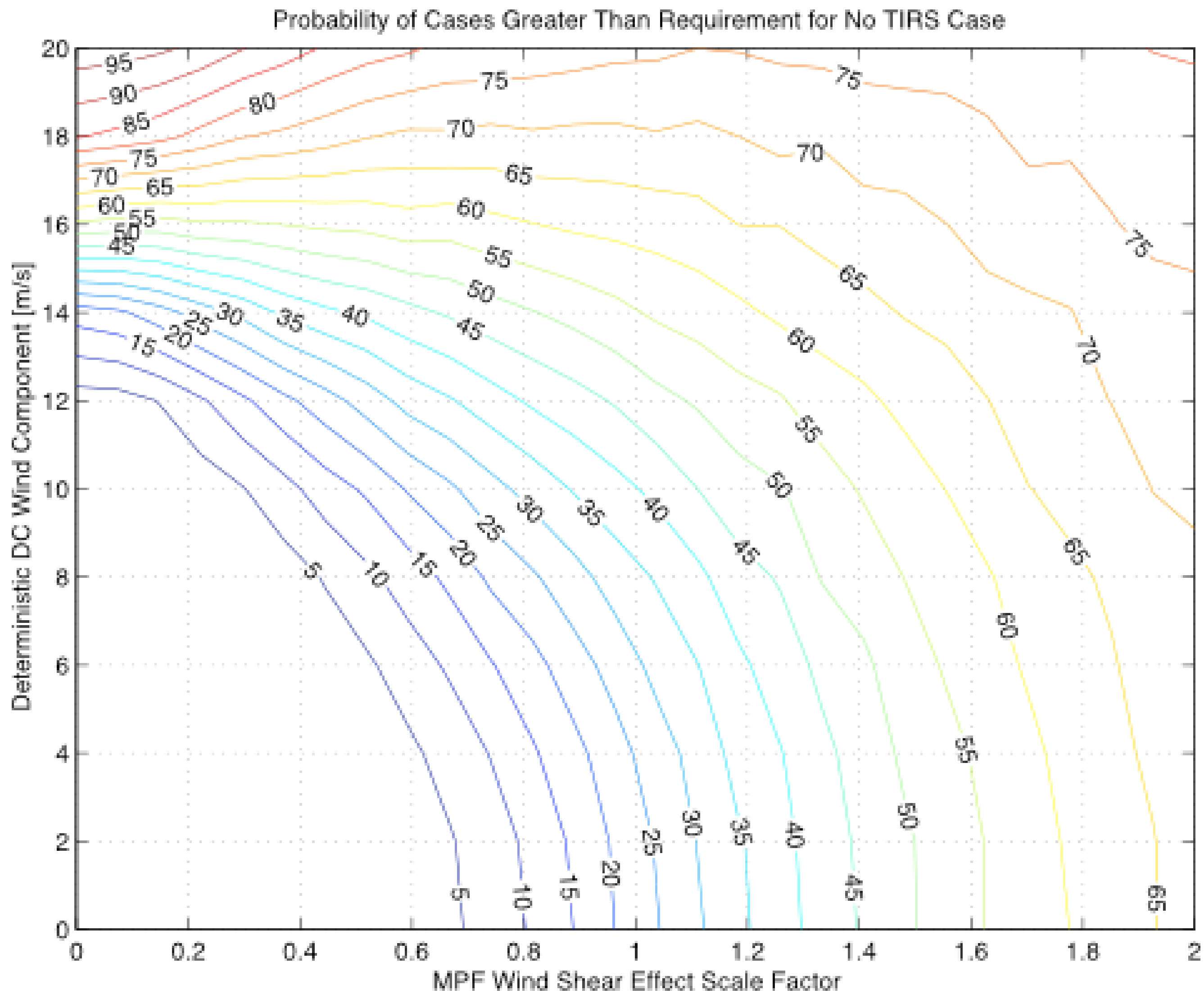

TIRS Probability of Success with various wind distributions

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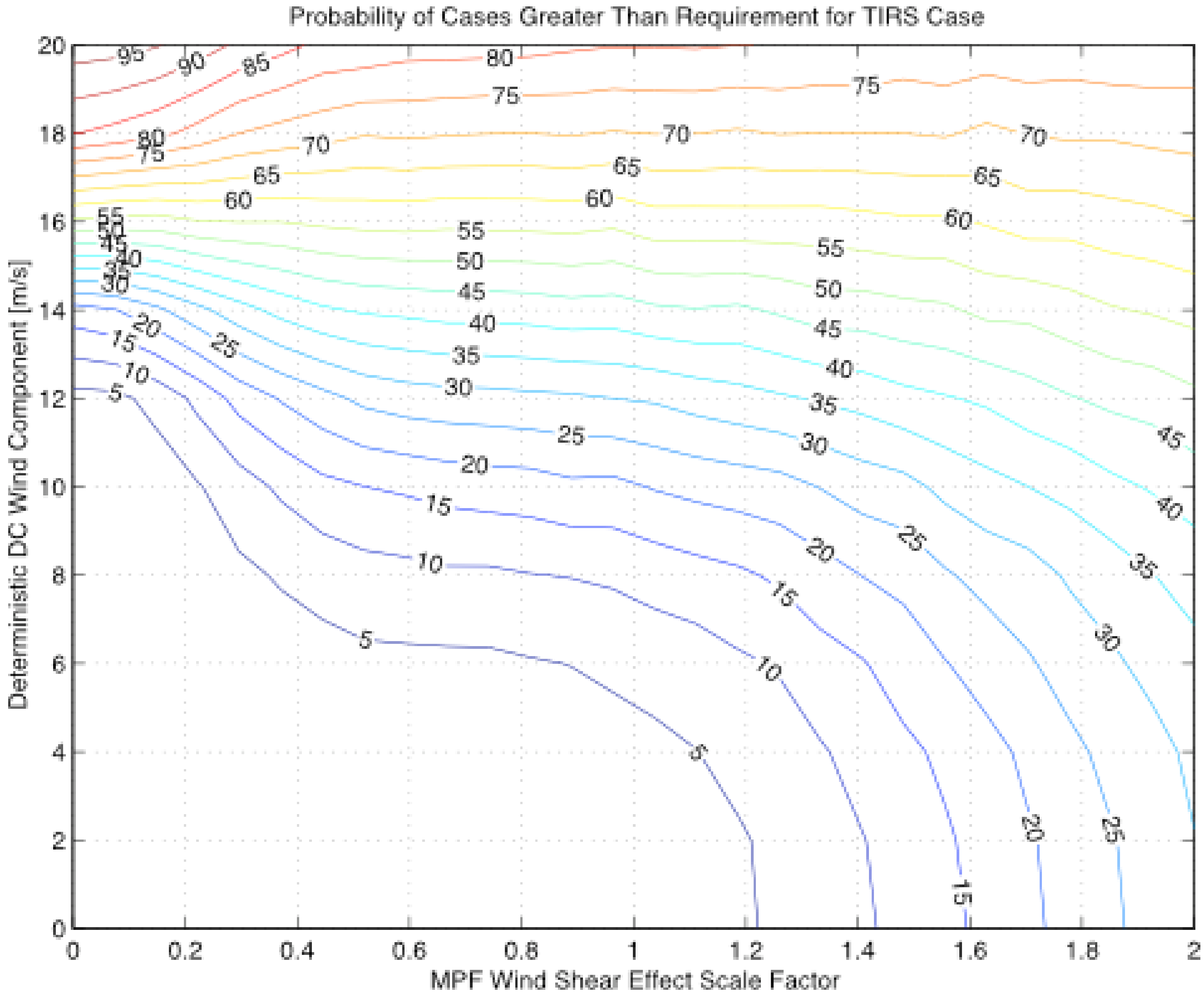
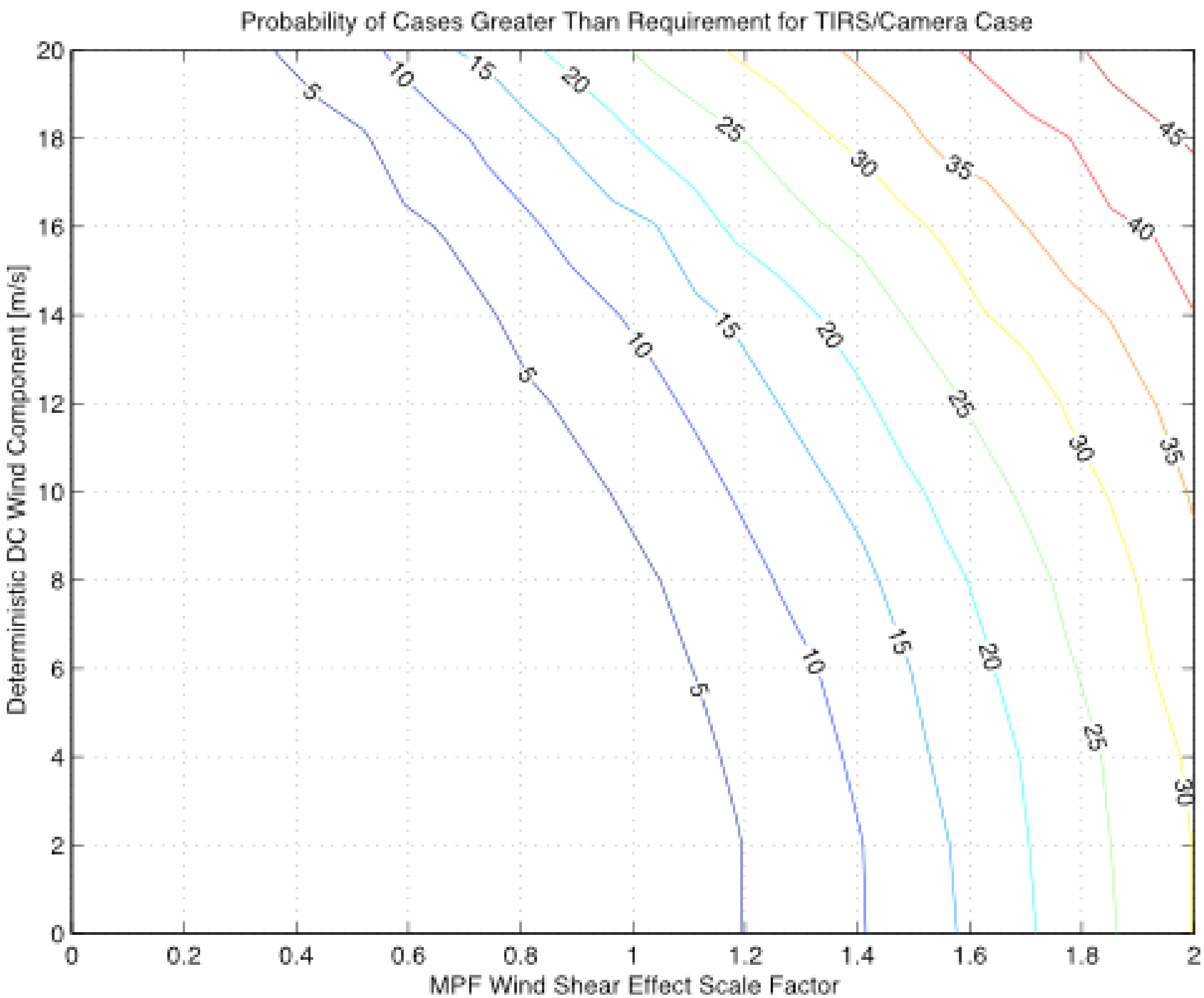


TIRS+DIMES Probability of Success with various wind distributions



Meanwhile, back in the Machine Vision Lab...

Autonomous Helicopter Development

Dense Structure From Motion

Target Tracking

The email (edited)

Mars Exploration Rover

Subject: I need your advice/help
From: Robert.Manning @ jpl
Date: 11/1/01 1:14 PM
To: Stewart.Collins @ jpl, Andrew.Johnson @ jpl

I'm Rob Manning. I'm the systems engineering manager and EDL Phase manager for MER.

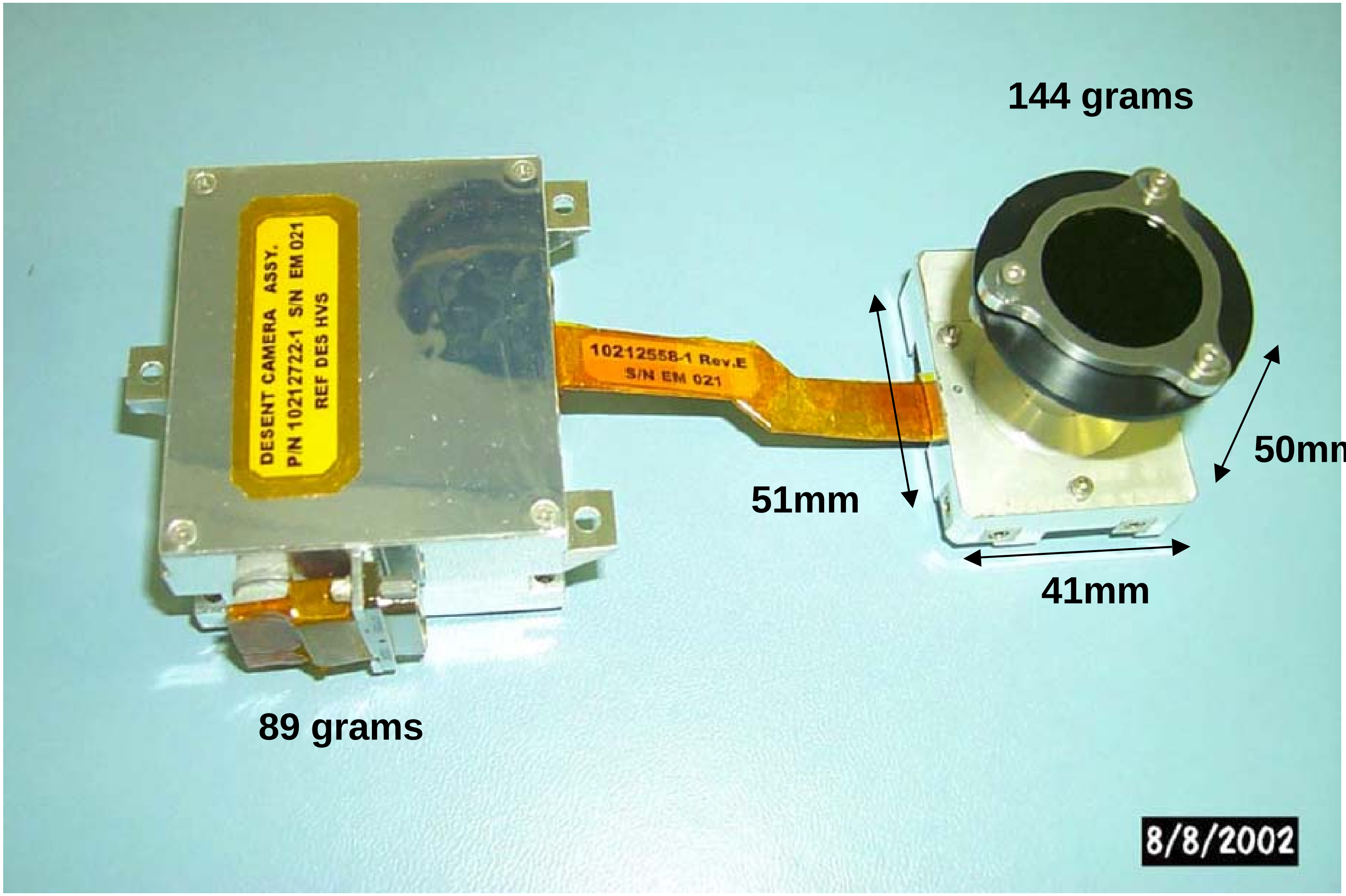
MER has a problem that I think might be solvable with a little help from you.

It re-occurred to me that a measure of our absolute (ground relative) velocity would go a long way to mitigating the steady-state contribution of winds....

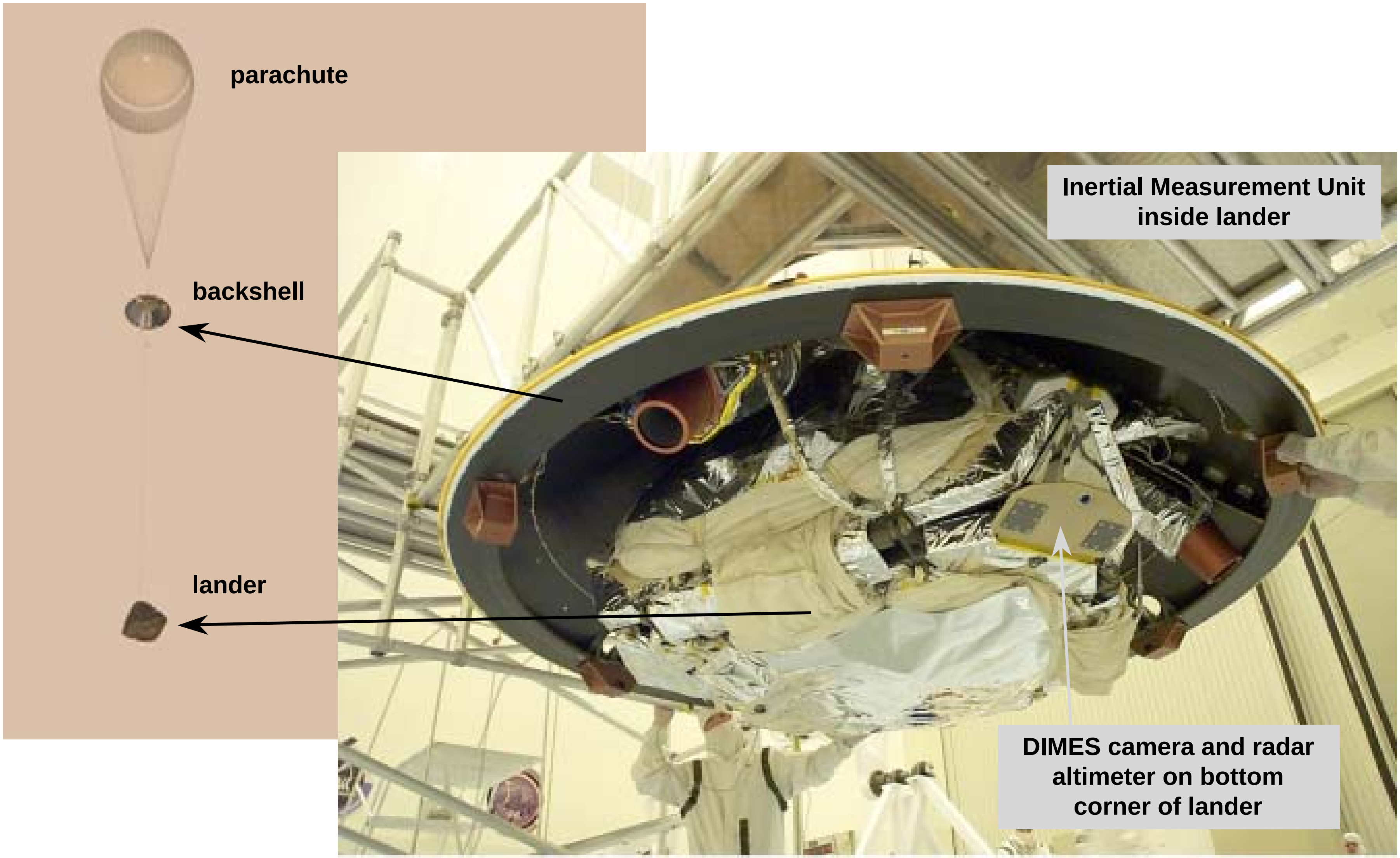
... two images taken during terminal descent might "easily" provide the data necessary.

Andy J. would you care to comment here?

DIMES Camera



DIMES Hardware



DIMES Functional Block Diagram

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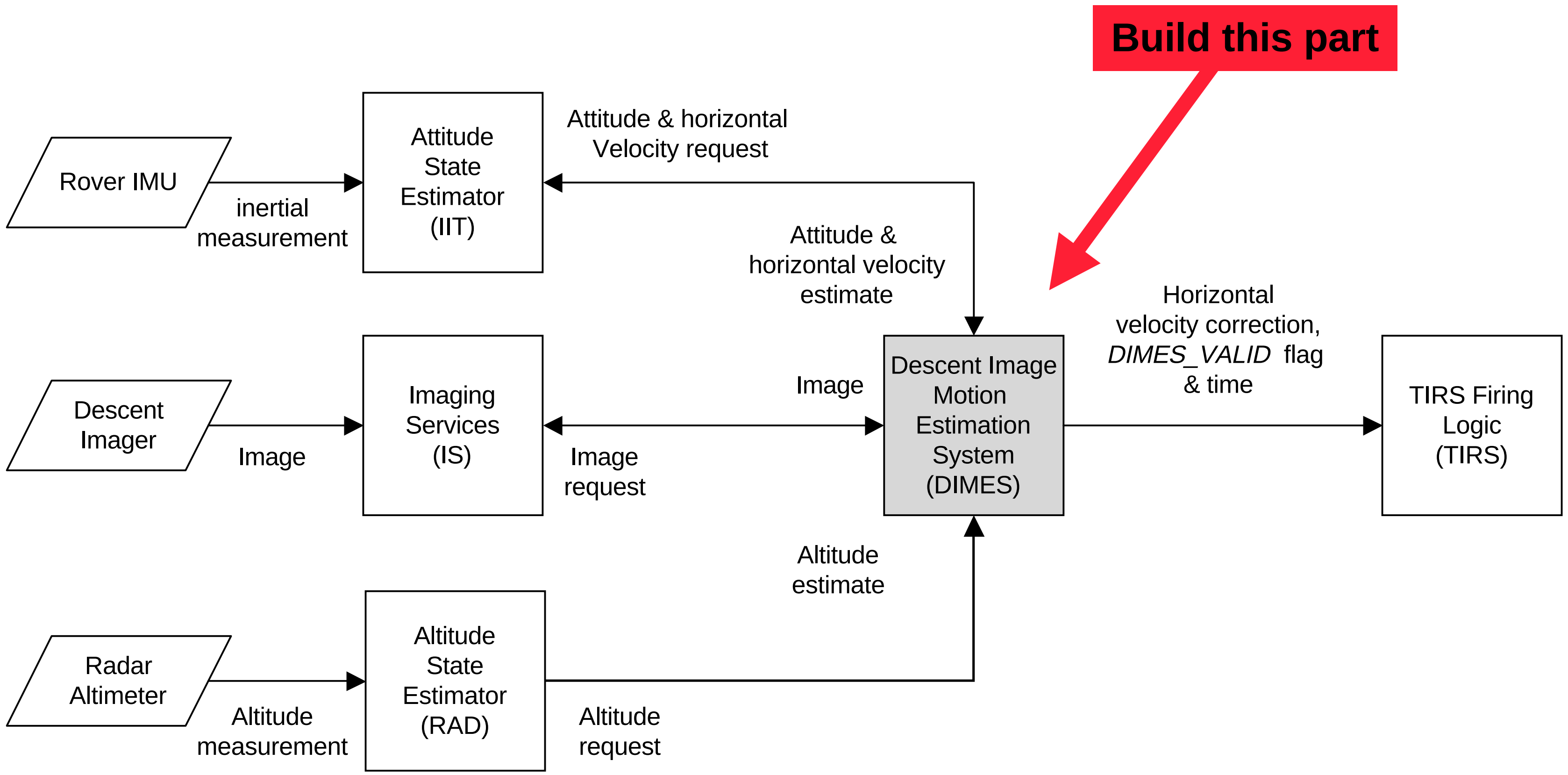

Challenges to Development of DIMES

- Development from concept to flight qualified system in 26 months before landing
  - accommodate camera and software into mature EDL system with minimal impact
- Numerous non-ideal imaging effects possible during EDL
  - bland landing sites, dust, cosmic rays, heatshield
- Algorithm must never generate an incorrect velocity
  - algorithm must be self checking
- Algorithm must run with minimal processing resources
  - 20% of 20 MHz RAD6000 for 20 seconds
- MER cameras not designed for descent imaging
  - motion blur, frame transfer smear, long readout time
- Imaging in the loop never used during EDL
  - skeptics wanted to kill the development
- Development must be low cost

DIMES Motion Estimation Concept
(not the actual optimized order of operations)

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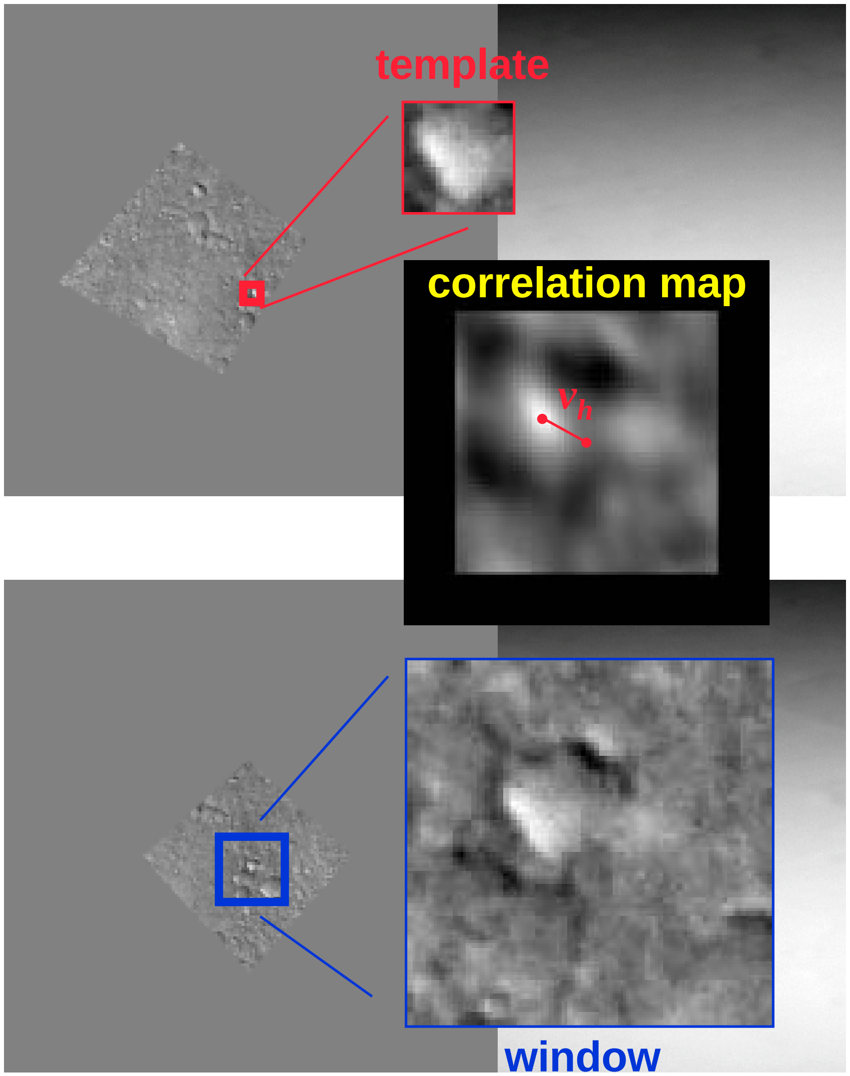


Correct Images

- Bin each image
- Radiometric correction of each image.
- Rectify each image to ground plane using IMU attitude and radar altitude.

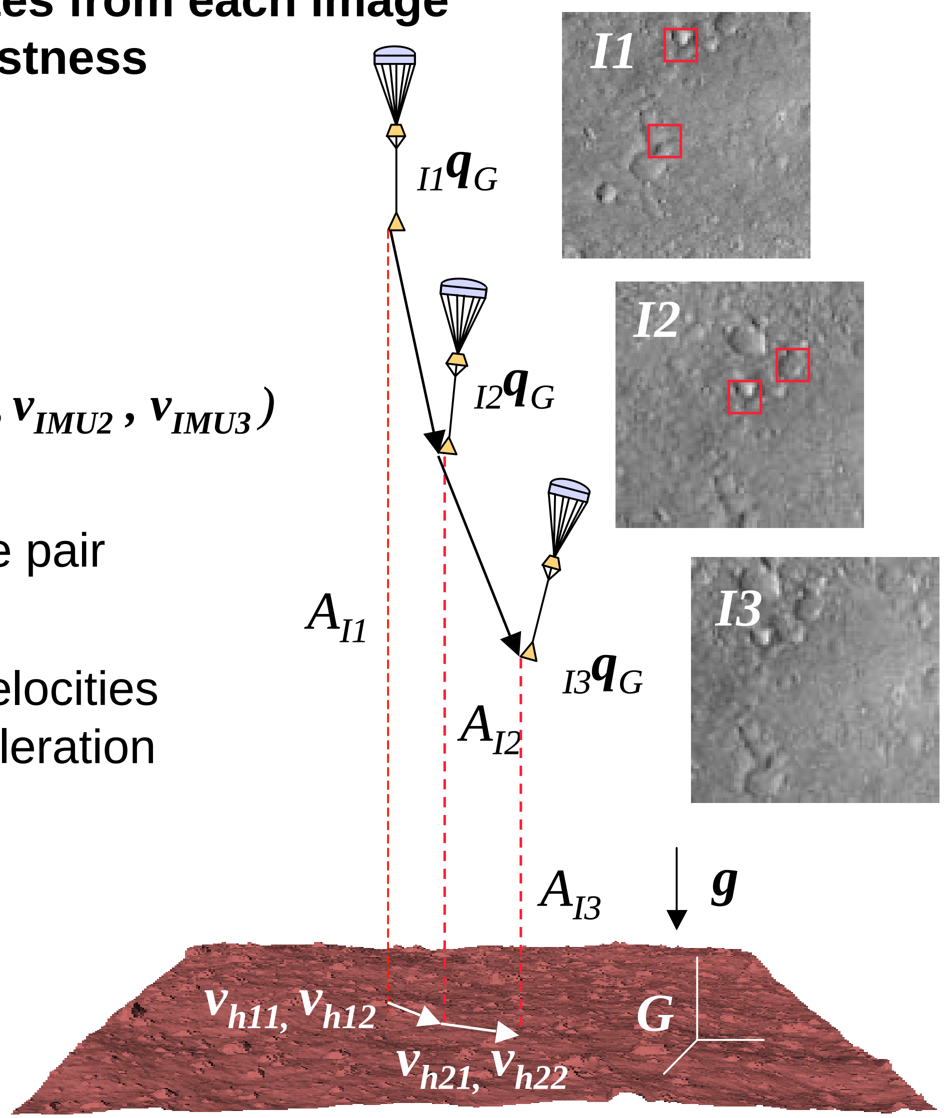
Correlate Images

- Apply Interest Operator to first image.
- Select high contrast template in image overlap that avoids zero phase spot.
- Slide template over window in second image and at each pixel compute linear correlation coefficient between template and window DN.
- Find maximum correlation and compute correlation performance metrics.
- Compute horizontal velocity from template shift and VALID measurement.

DIMES Algorithm

Using three images and two templates from each image pair improves overall DIMES robustness

- **Input**
  - 3 images $(I1, I2, I3)$
  - 3 IMU attitudes $({}_{I1}q_G, {}_{I2}q_G, {}_{I3}q_G)$
  - 3 radar altitudes (A_{I1}, A_{I2}, A_{I3})
  - 3 IMU horizontal velocities $(v_{IMU1}, v_{IMU2}, v_{IMU3})$
- **Algorithm**
  - track two templates in each image pair
  - verify correlation of templates
  - compare difference of template velocities between image pairs to IMU acceleration



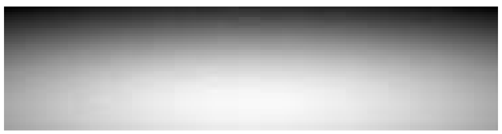
DIMES Algorithm Details

Image Binning

- Purpose: Reduce Computation
- Descent Camera bins image rows in hardware
  - 1024x1024 to 256x1024
  - Adds charge
- DIMES algorithm bins image columns
  - 256x1024 to 256x256
  - Add DN instead of averaging

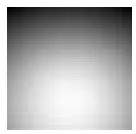
1024x1024

Hardware Binning



256x1024

Software Binning



256x256

Radiometric Correction

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- Purpose: <u>Reduce Differences Between Images</u>
- Remove known radiometric distortions
  - Dark current (subtract a constant look up table)
  - Frame transfer ramp (subtract ramp that is computed based on signal)
  - CCD pixel to pixel variations (multiply by scale factor lookup table)
  - Optical transfer/radiometric fall off (multiply by scale factor lookup table)
- Cannot remove unknown photometric differences
- Memory Efficient Implementation
  - Offset and scale images are computed by fitting a line to multiple images taken inside an integrating sphere at different exposure times
  - Bi-quartic polynomials are fit to scale and offset images (15 coefficients) and stored
  - During EDL, but before image acquisition, scale and offset images are pre-computed from the bi-quartic polynomials

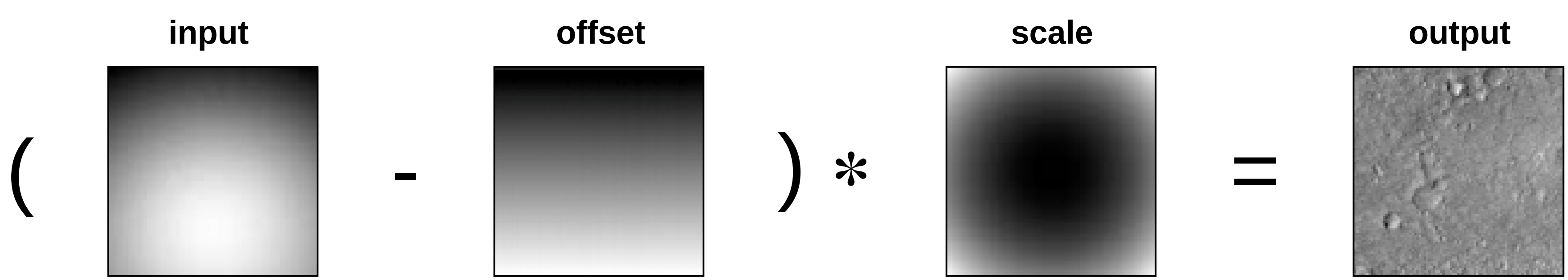

Image Rectification Concept

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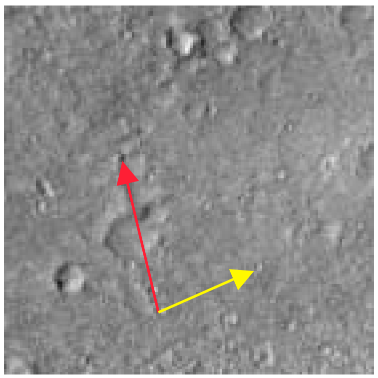
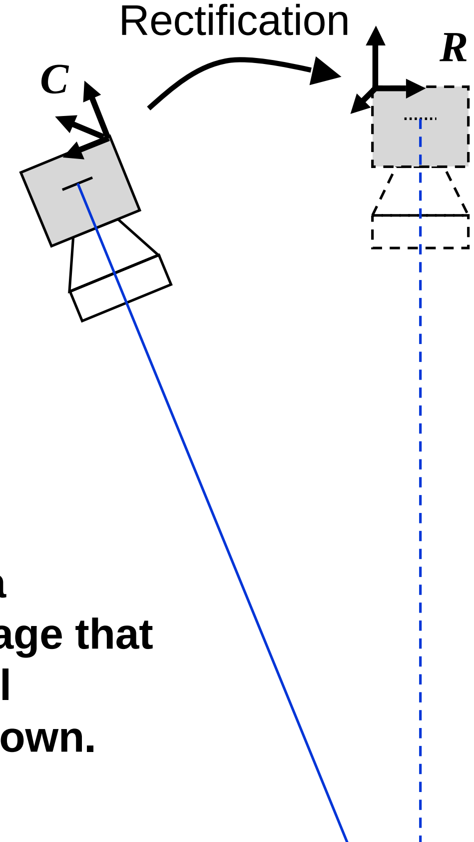
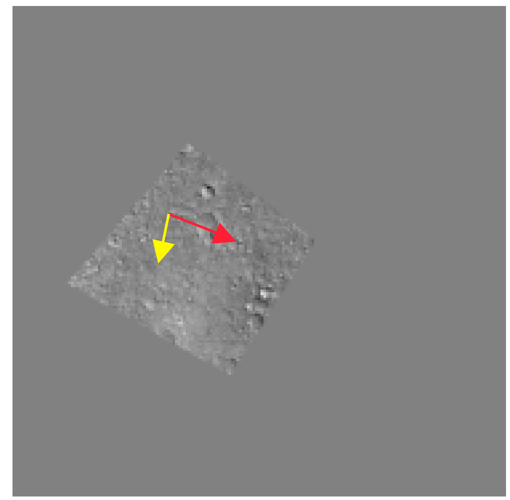
Descent Image





Rectified Image



Rectification transforms a descent image into an image that would be seen by a virtual camera looking straight down.

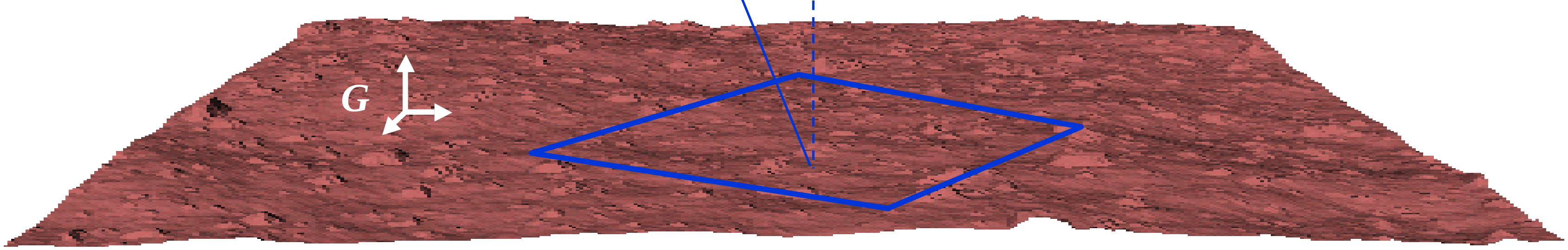


Image Rectification

- **Rectification removes orientation and scale differences between images**
  - **Both images rectified to a virtual camera at altitude of first image**
- **Requires position and attitude of camera in ground frame**
  - **Ground relative attitude comes from IMU**
  - **Use altitude from radar altimeter for vertical position**
  - **Assume lander is dropping straight down (i.e., horizontal position is zero)**
- **Based on flat surface approximation**
  - **Surface slope and terrain relief introduce minor errors in rectification**
    - **high altitude**
    - **landing site safety requires small slopes and terrain relief**

Image Rectification With Radial Distortion

- **Objective**
  - To remove radial distortion and rectify image data to the ground plane.
- **Approach**
  - The templates and windows are small.
  - Radial distortion is approximately linearly in a small area.
  - Use a homography transformation (linear) to rectify templates and windows

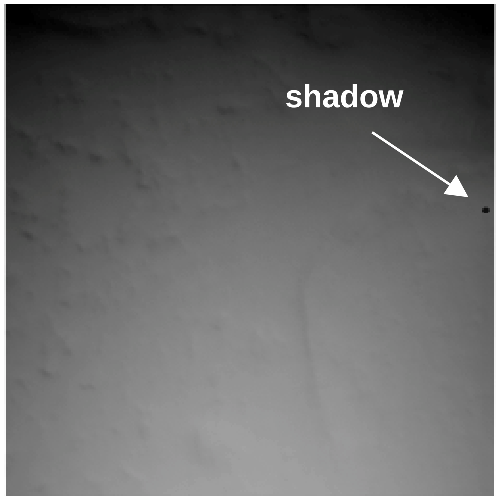
$$X = \frac{a_1 x + a_2 y + a_3}{a_7 x + a_8 y + 1} \qquad Y = \frac{a_4 x + a_5 y + a_6}{a_7 x + a_8 y + 1}$$

- **Algorithm**
  - The rectified positions of the four corners of the template are determined directly using the camera model that includes radial distortion.
  - These four points are used to estimate the parameters of the homography transform.
  - The template is rectified using this transform.
- **Approach is much faster than using camera model directly**
  - Avoids the slow and iterative between image 2d and 3d computations.
  - Current pixel rectification can use the result from the previous pixel.
  - Suitable to any camera model.

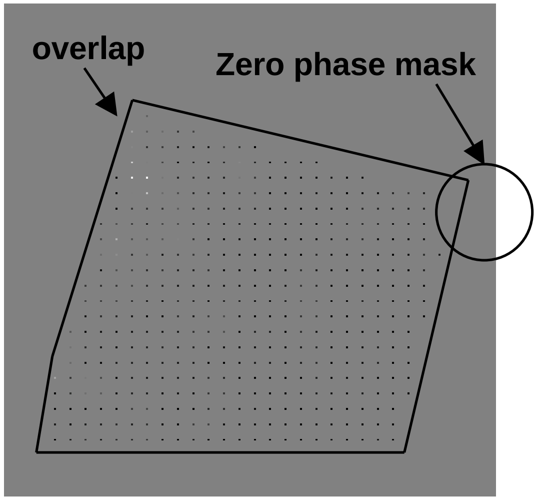
Template Selection

- **Standard Interest operator**
  - smallest eigenvalue of template autocorrelation
- **Efficient Implementation**
  - Interest operator computed before rectification and image flattening
    - Only template and window need to be rectified and flattened
  - Computed on a coarse grid
    - Width of template broadens interest operator peaks, so skip pixels
- **Application Region**
  - Only computed in overlap region of images
  - Sun direction parameter is used to mask out region around zero phase
    - Zero phase brightening
    - Parachute shadow

Binned image



Interest Operator Image



Two Stage Correlation

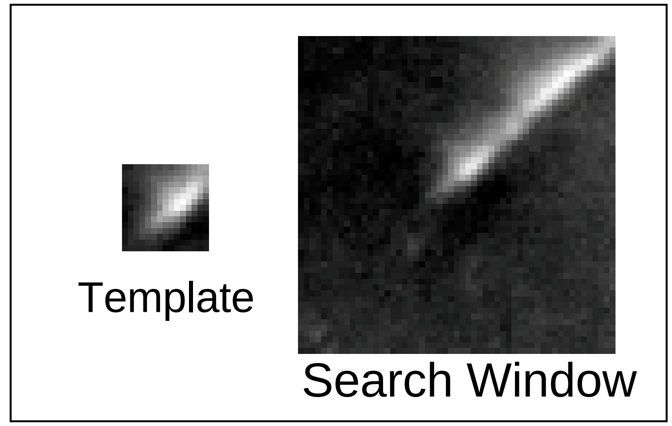
- **Psuedo-normalized correlation**

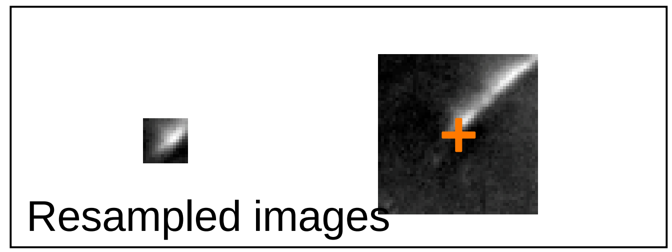
$$R = \left(2\sum_T \tilde{I}_1 * \tilde{I}_2\right) / \left(\sum_T \tilde{I}_1^2 + \sum_T \tilde{I}_2^2\right)$$

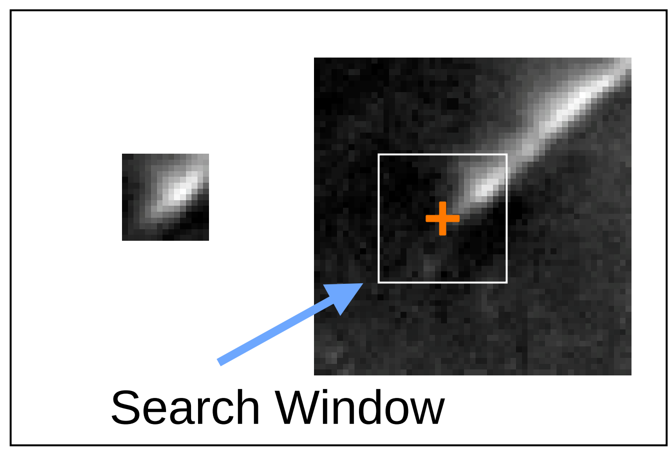
$$\tilde{I}_i = I_i - \sum_T I_i / N$$

- **Speed up correlation by applying it at a coarse and then fine image resolution.**
  1. **Generate coarse data by binning template and search window to 2x2 resolution**
  2. **Correlate coarse template and window to get best and second best match locations**
  3. **Project the best correlation locations into the 1x1 resolution window.**
  4. **Find the best correlations in a smaller window around the projected point.**

- **Results in 2x speed improvement over single stage correlation**

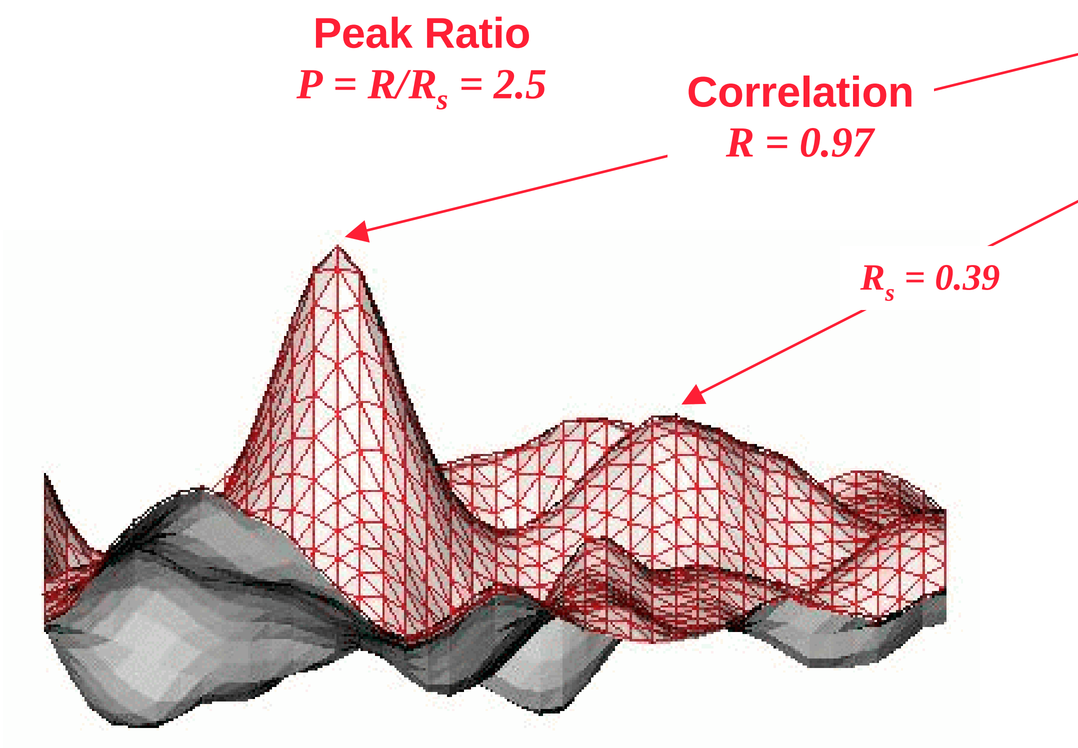


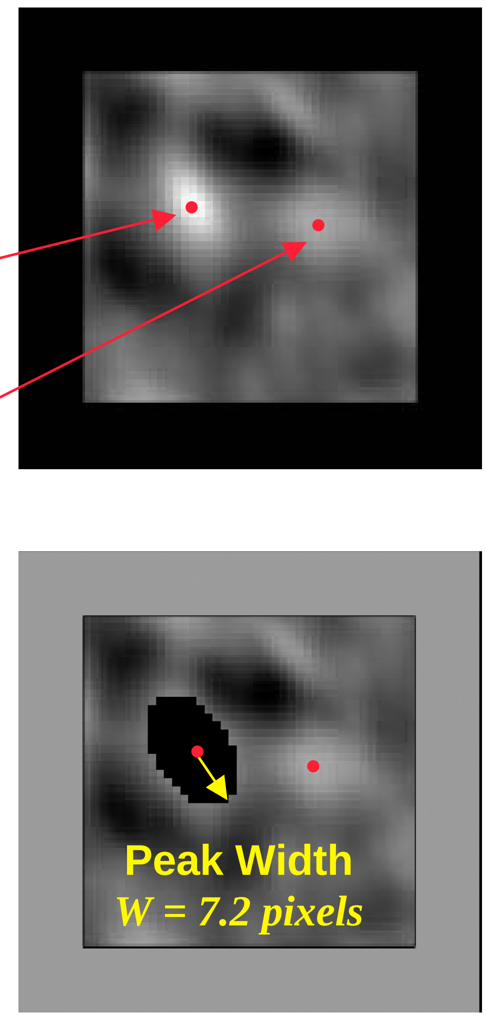




Correlation Performance Metrics

Correlation performance metrics are used to detect false correlations that can lead to incorrect velocity estimates





$V_{err} = (0.6, 0.8)$ m/s

IMU Check on Image Velocities

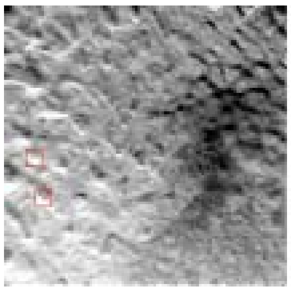


Image Pair 1 Feature Velocity - Image Pair 2 Feature Velocity = Image Delta Velocity

If equal then IMU confirms image velocities

IMU Pair 1 Biased Velocity - IMU Pair 2 Biased Velocity = IMU Delta Velocity

DIMES Logic Diagram

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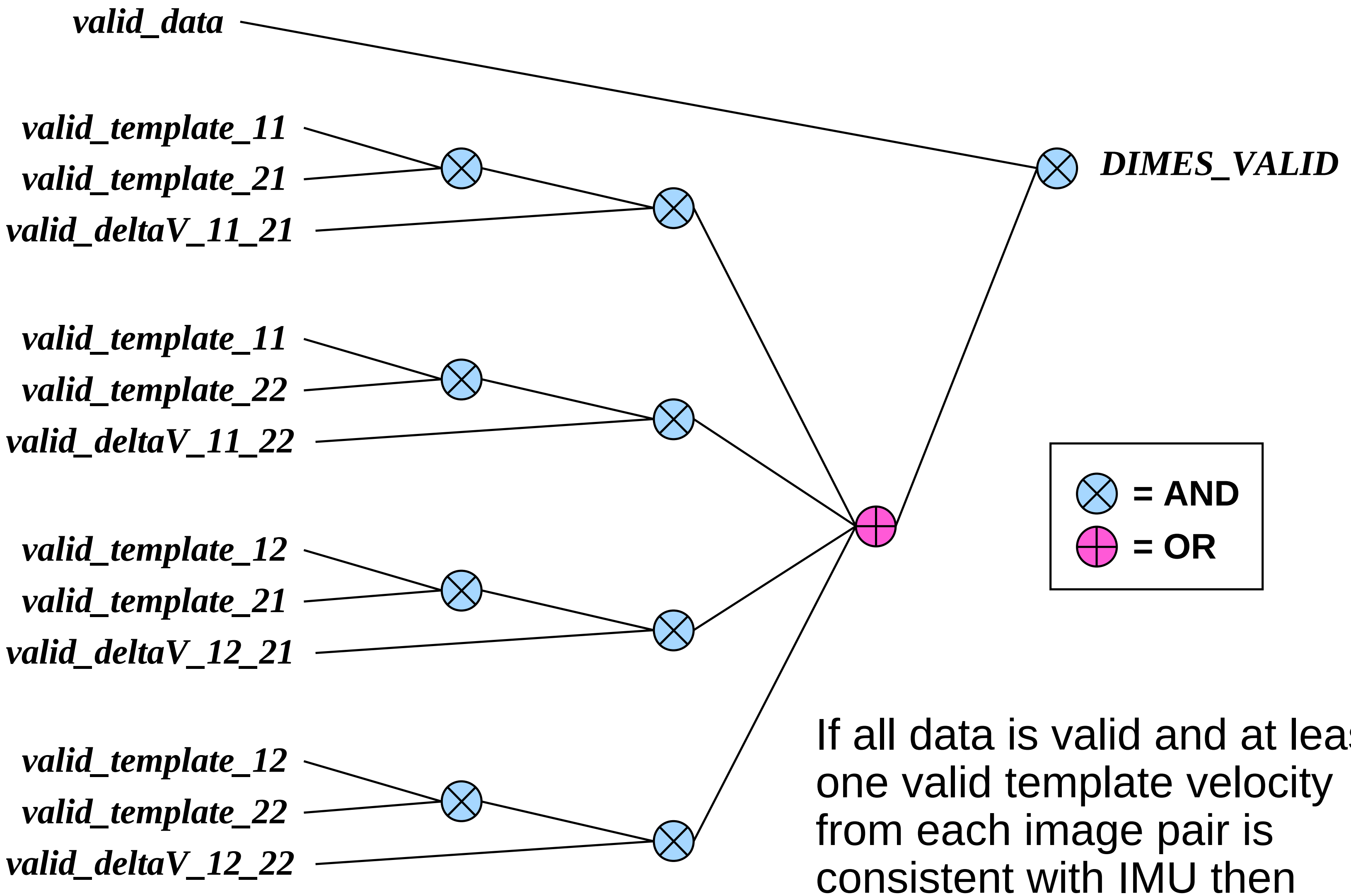


If all data is valid and at least one valid template velocity from each image pair is consistent with IMU then DIMES reports a velocity.

Testing and Verification

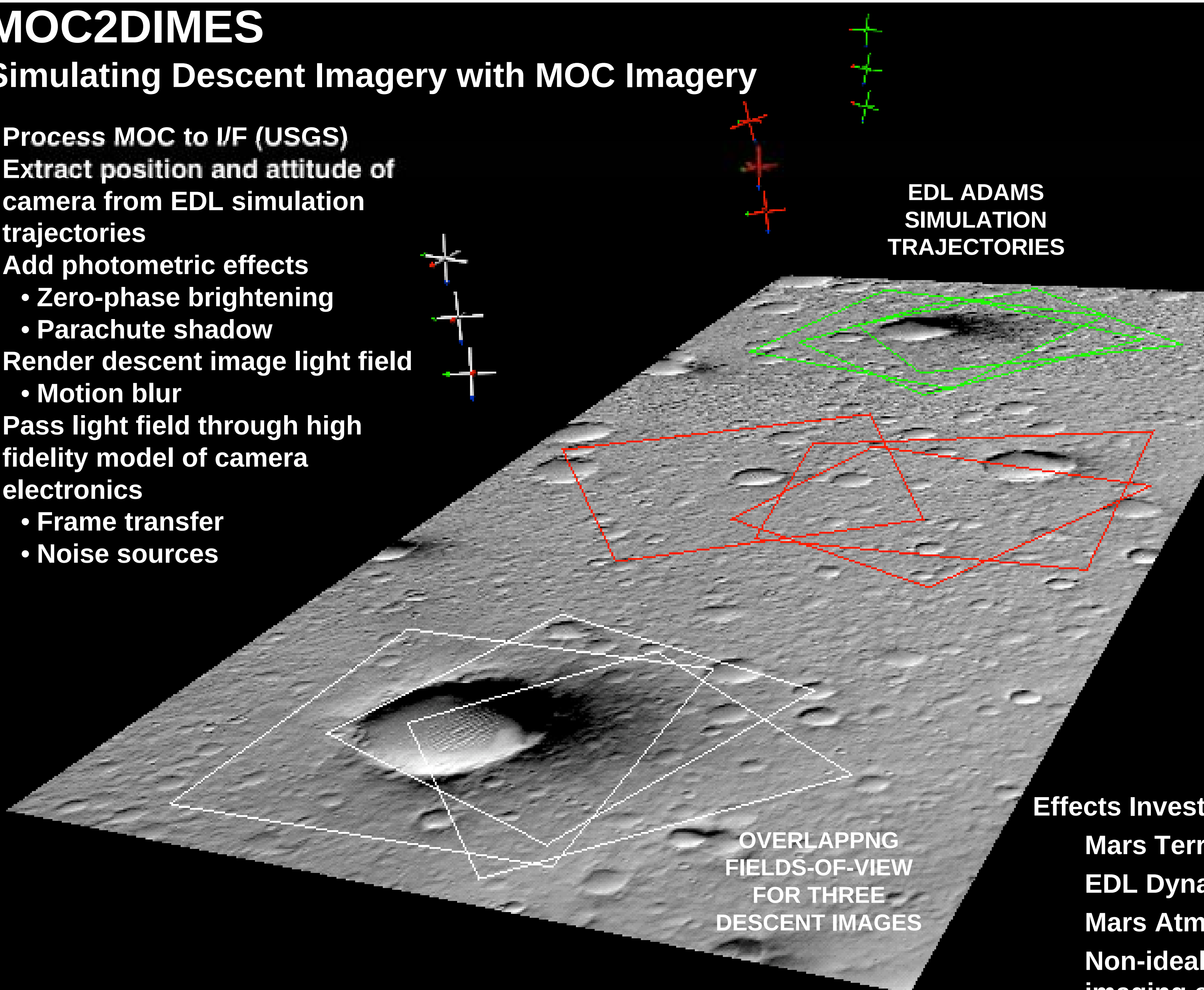
Monte Carlo Simulation with Simulated Imagery

Field Testing with Engineering Model Sensors

MOC2DIMES

Simulating Descent Imagery with MOC Imagery

- Process MOC to I/F (USGS)
- Extract position and attitude of camera from EDL simulation trajectories
- Add photometric effects
  - Zero-phase brightening
  - Parachute shadow
- Render descent image light field
  - Motion blur
- Pass light field through high fidelity model of camera electronics
  - Frame transfer
  - Noise sources

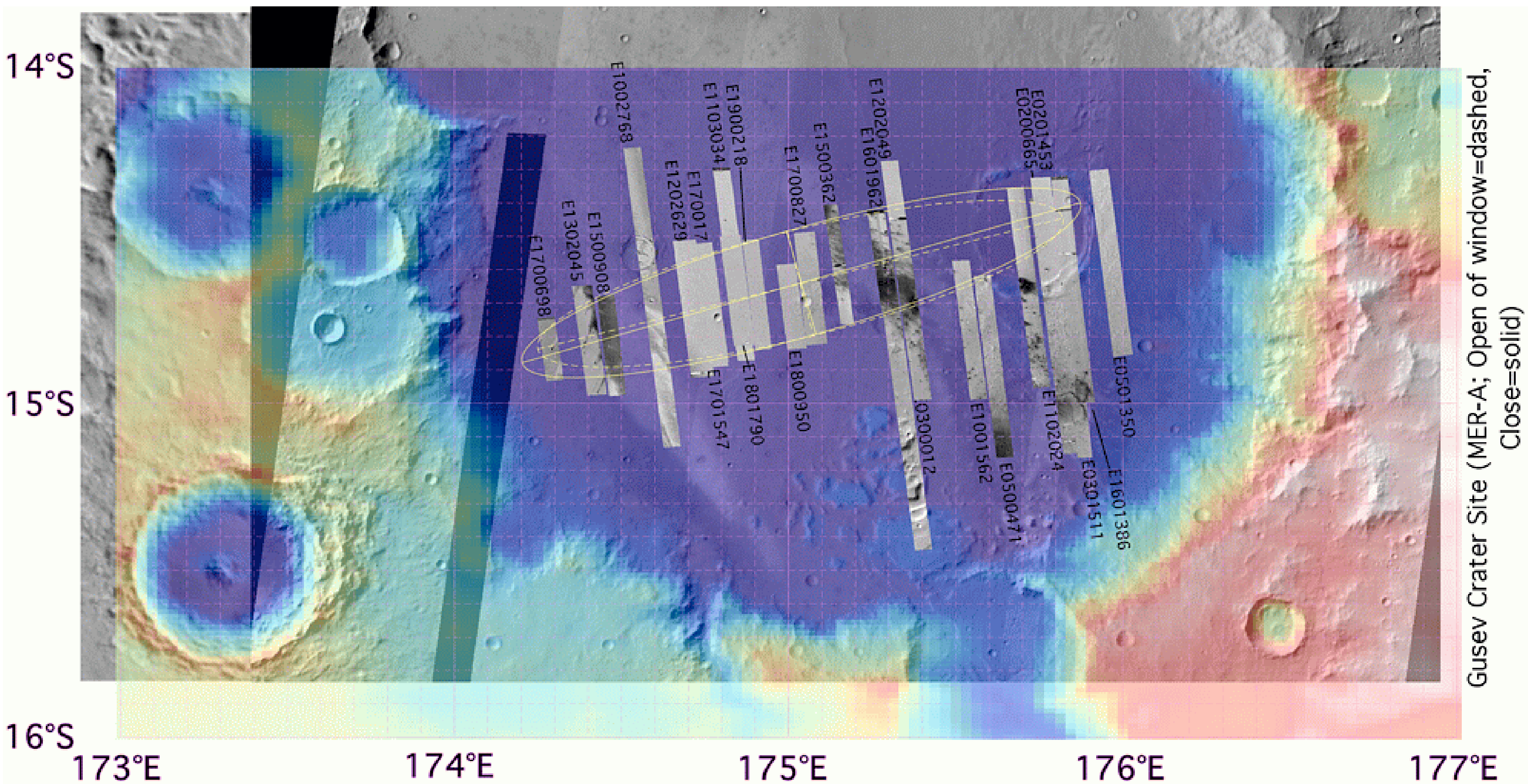


Effects Investigated

- Mars Terrain
- EDL Dynamics
- Mars Atmosphere
- Non-ideal imaging effects

Gusev Crater MOC Coverage for DIMES

Mars Exploration Rover



Ellipse Coverage = 52%

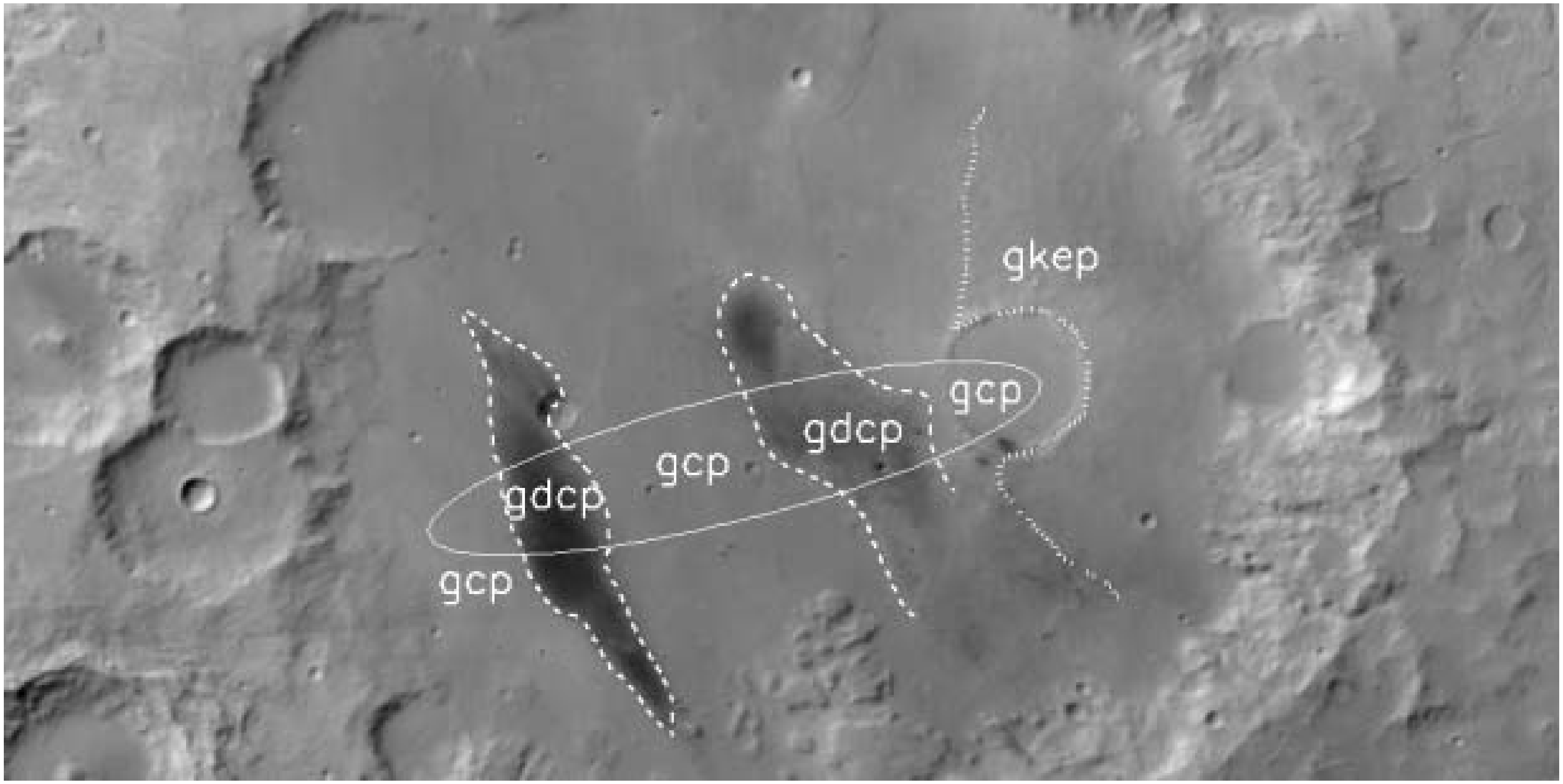
Gusev Crater Appearance Classes

gcp: Gusev cratered plains – higher albedo, smooth plains with few craters, bright crater rims, and low contrast overall
Ellipse Fraction =59%

gdcp: Gusev dark cratered plains– lower albedo, mostly due to linear dark dust devil tracks, cratered plains area

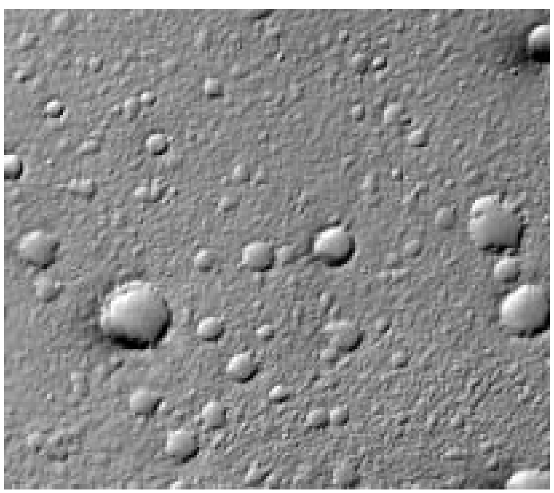
Ellipse Fraction = 41%

gkep: Gusev knobby etched plains – knobs or mesas of positive relief dominate this area surrounding crater at E end of ellipse
Ellipse Fraction = 0%

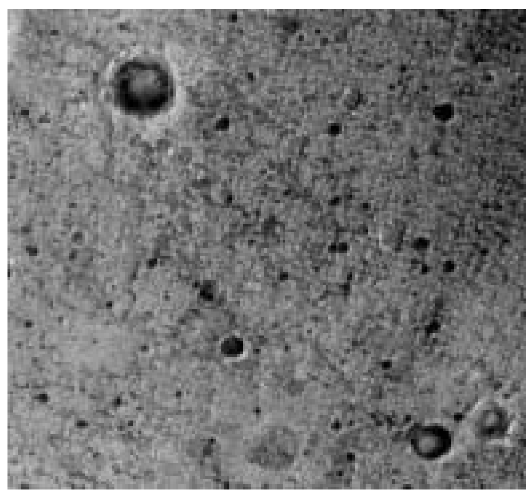


Gusev Crater Overall Performance

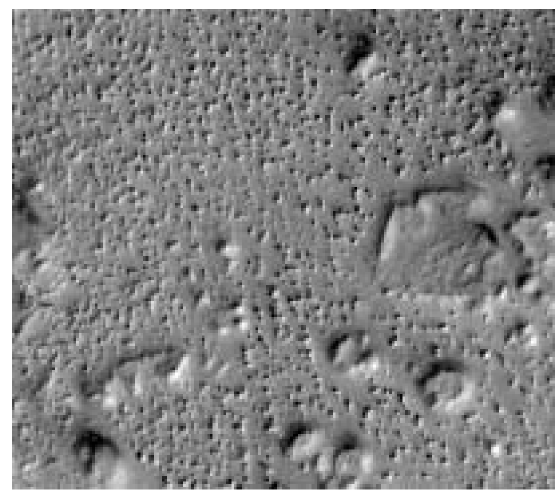
Appearance Class	Number of Cases	Number of valid cases	% valid	Velocity Error (mean + 3 sigma)	% landing ellipse	Total %Valid Contribution	Velocity Error Contribution
gcp	1078	1040	96%	4.05	59%	57%	2.39
gdcp	336	336	100%	3.24	41%	41%	1.33
gkep	523	520.00	99%	3.14	0%	0%	0.00
Gusev	**1937**	**1896**				**98%**	**3.72**



gcp



gdcp



gkep

Meridiani MOC Coverage for DIMES

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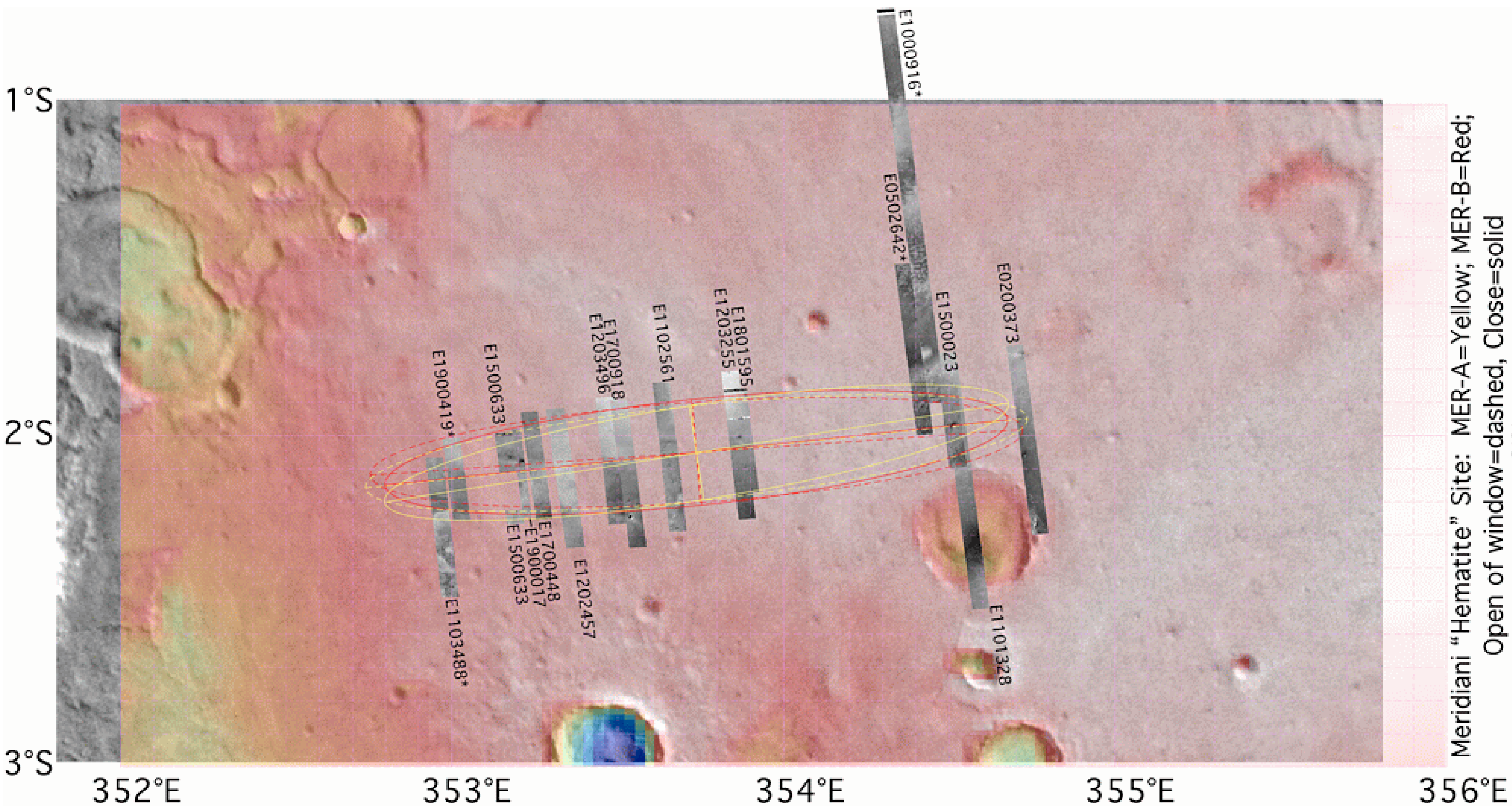


Ellipse Coverage = 31%

Hematite Appearance Classes

hbsp: Hematite bright smooth plains – higher albedo, smooth plains with few craters, low contrast

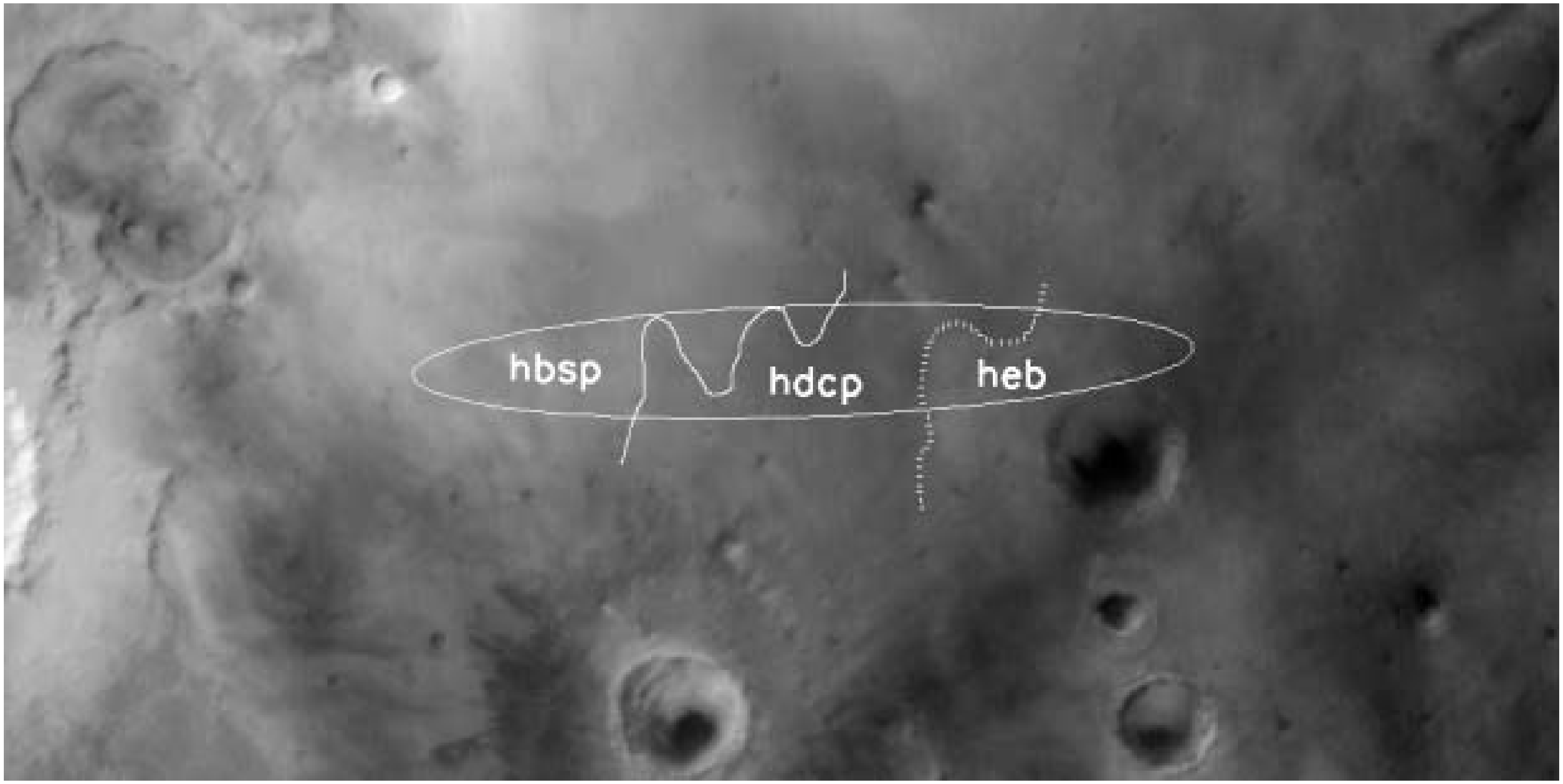
Ellipse Fraction = 34%

hdcp: Hematite dark cratered plains– lower albedo, cratered plains

Ellipse Fraction = 40%

heb: Hematite ejecta blanket – ejecta apron surrounding large crater near E end of ellipse

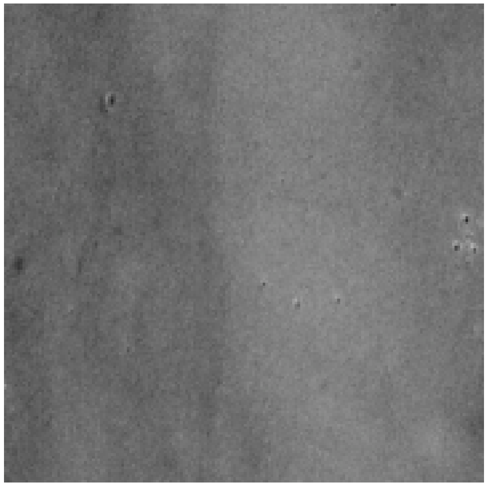
Ellipse Fraction = 26%



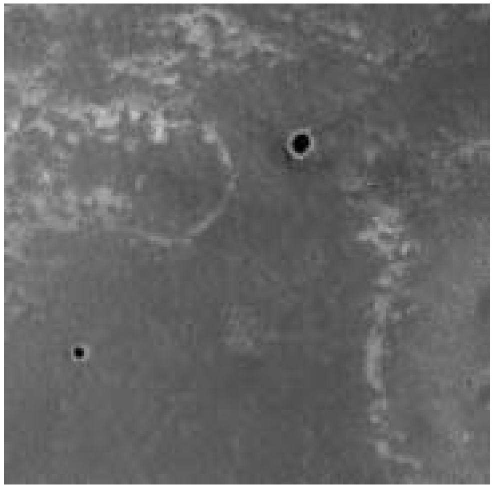
Meridiani Overall Performance

Mars Exploration Rover

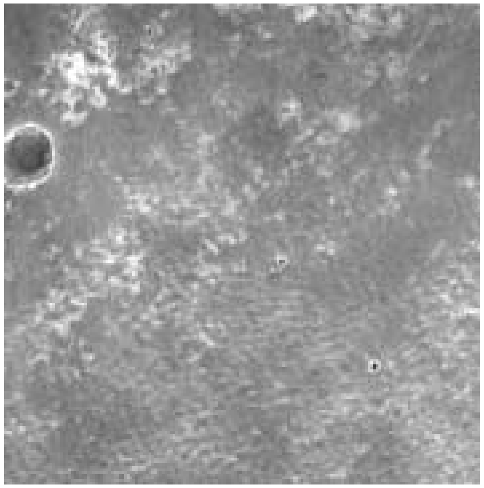
Appearance Class	Number of Cases	Number of valid cases	% valid	Velocity Error (mean + 3 sigma)	% landing ellipse	Total %Valid Contribution	Velocity Error Contribution
hbsp	124	109	88%	2.84	34%	30%	0.96
hdcp	387	349	90%	3.40	40%	36%	1.36
heb	63	63	100%	3.23	26%	26%	0.84
Hematite	**574**	**521**				**92%**	**3.16**



hbsp



hdcp



heb

DIMES Field Test System

Effects Investigated

- Real sensor hardware
- 3D terrain

Digital Elevation Maps

Pisgah Lava Flow

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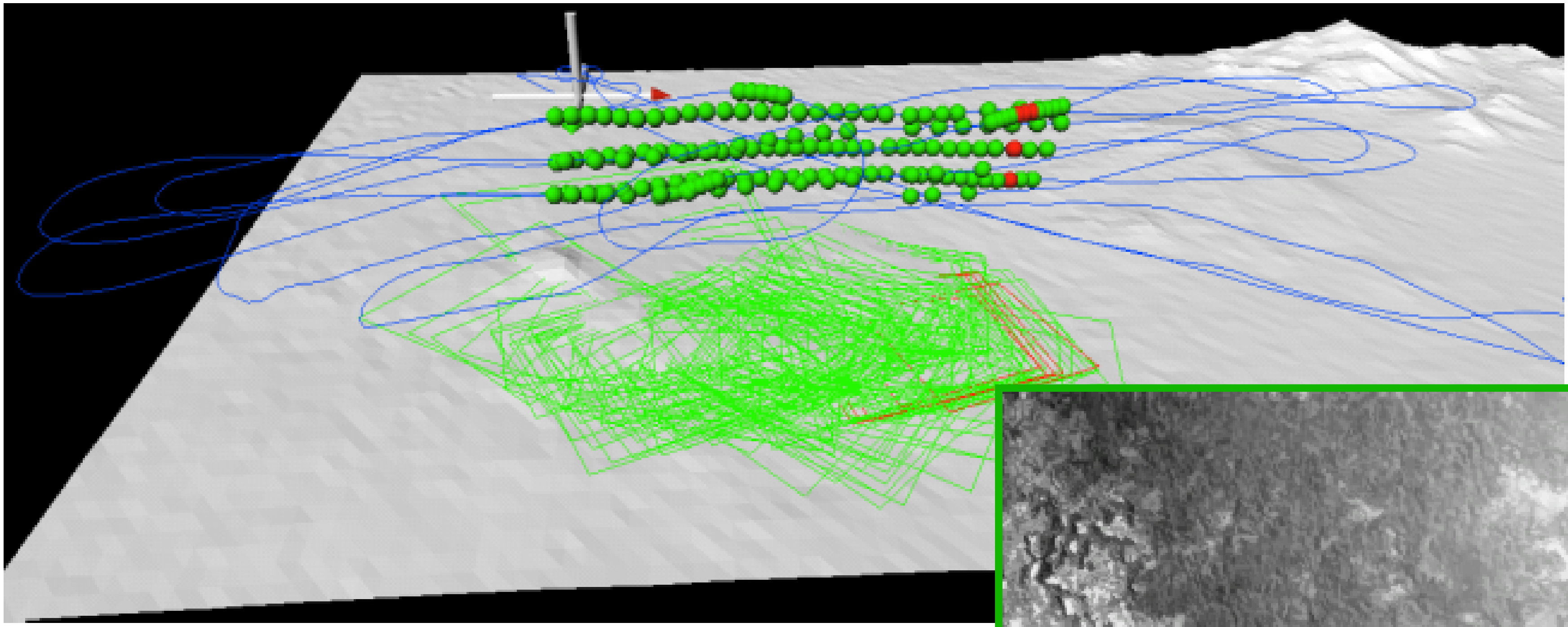
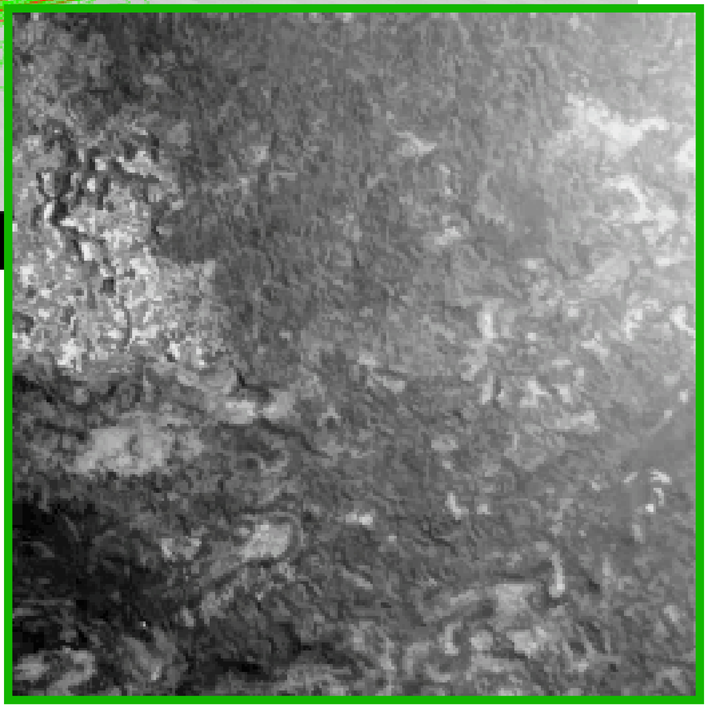
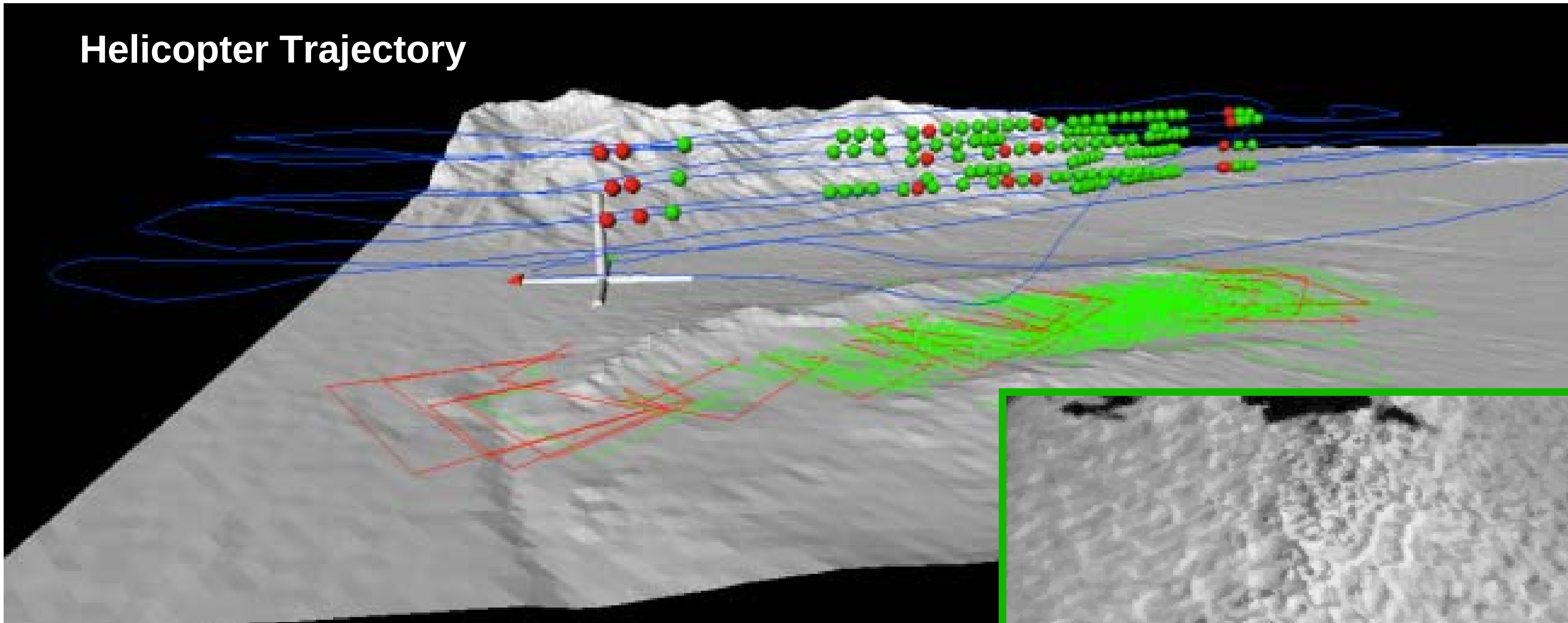
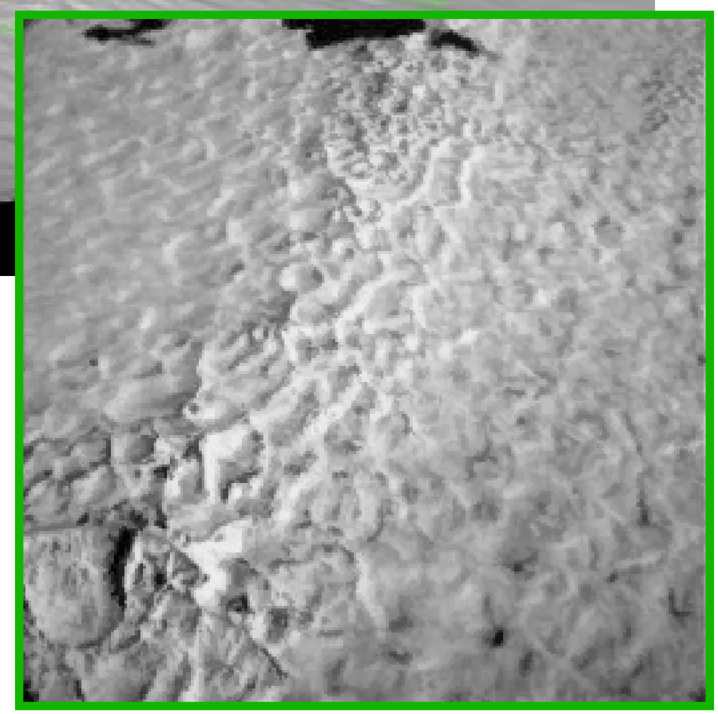




- Dark lava flow
- 10 m terrain variation
- Lowest contrast site

Kelso Sand Dunes





- Repetitive dunes
- 100 m terrain variation
- Highest contrast site

Ivanpah Dry Lake Bed

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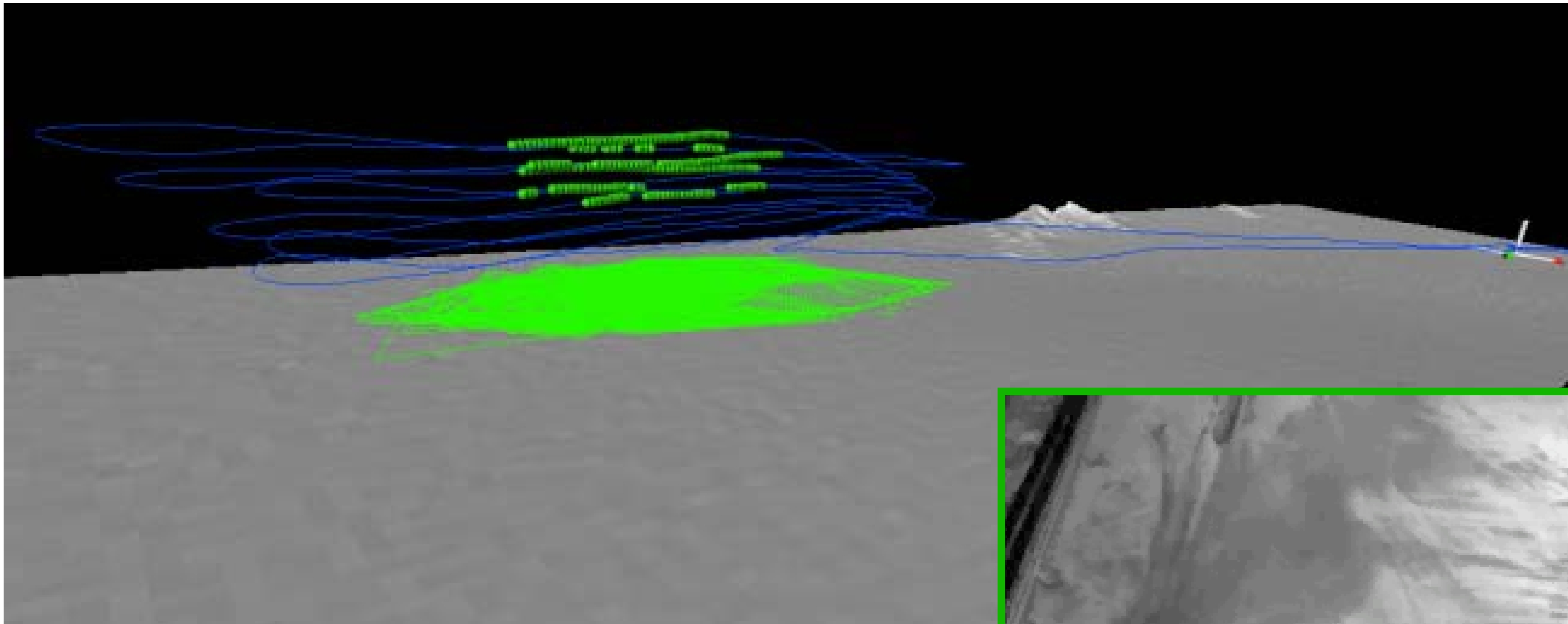
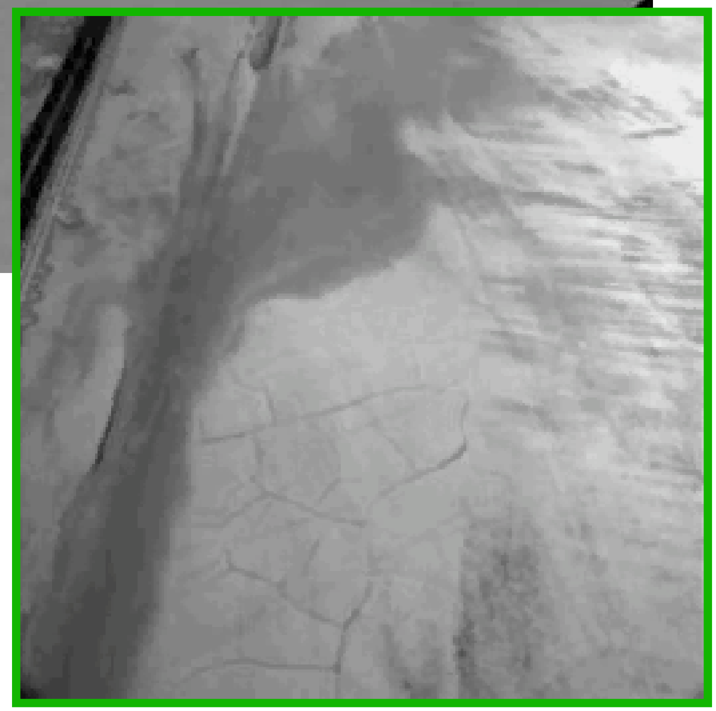
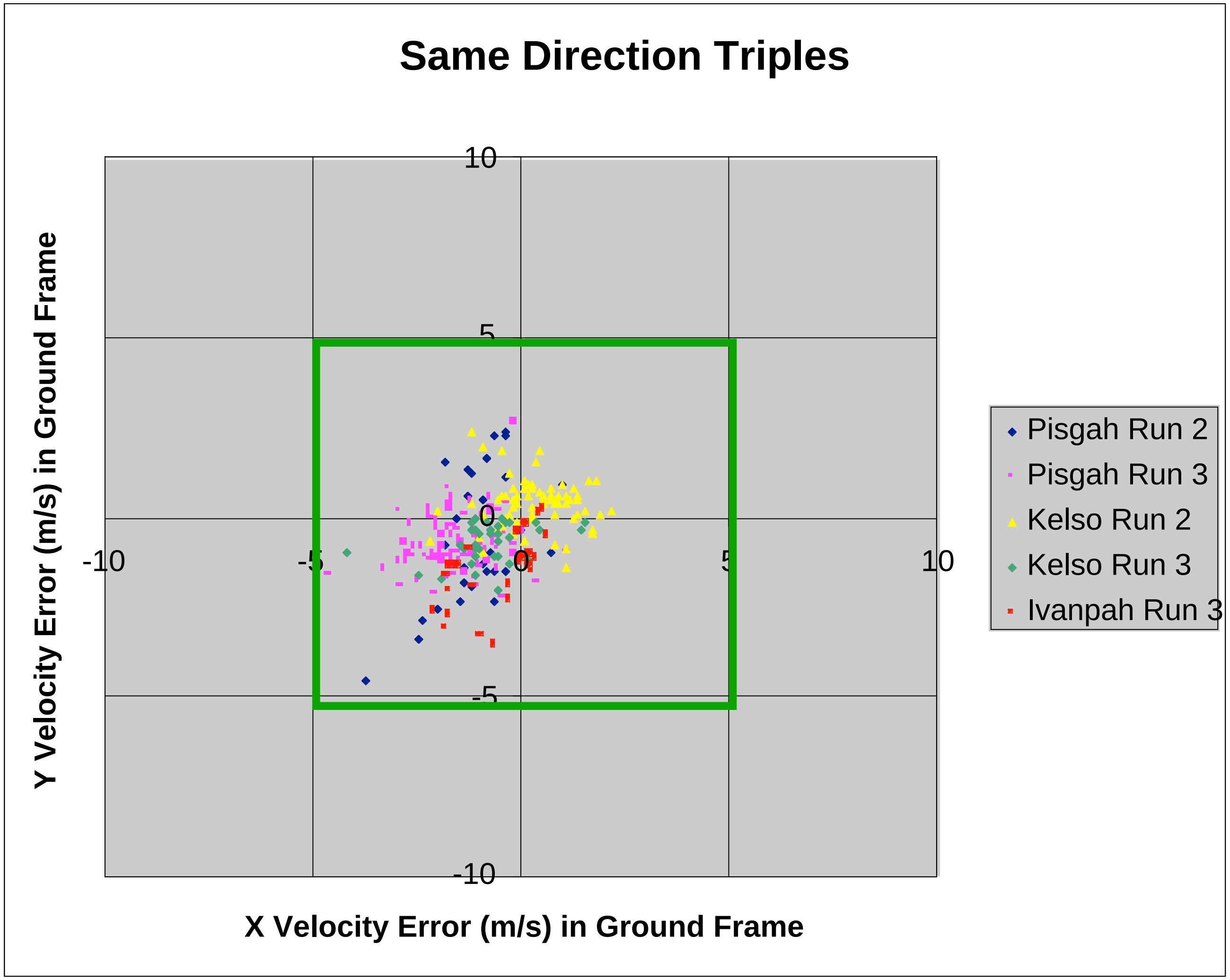


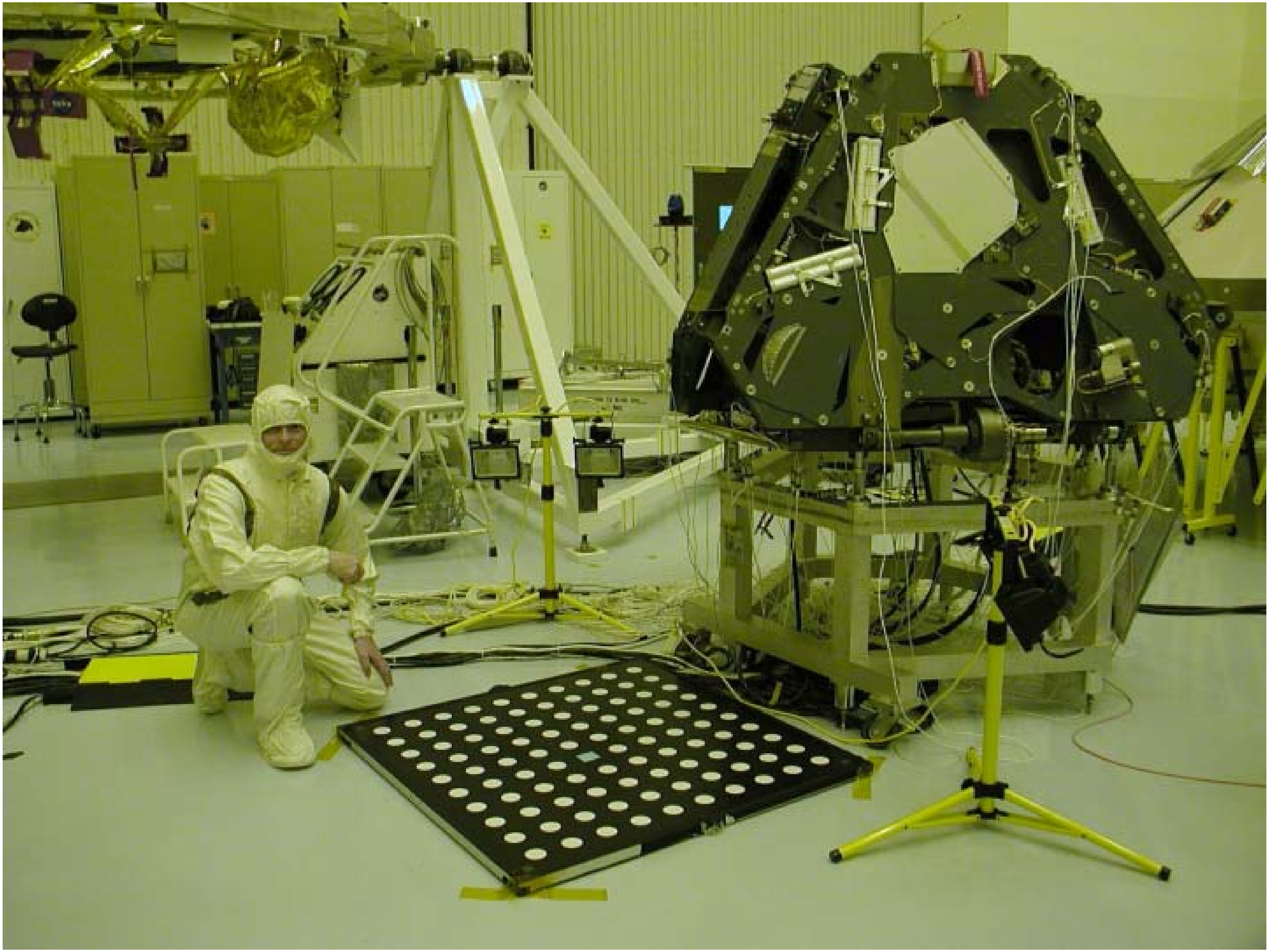


- Bright flat surface
- 1 m terrain variation
- Moderate contrast site
- Man-made features

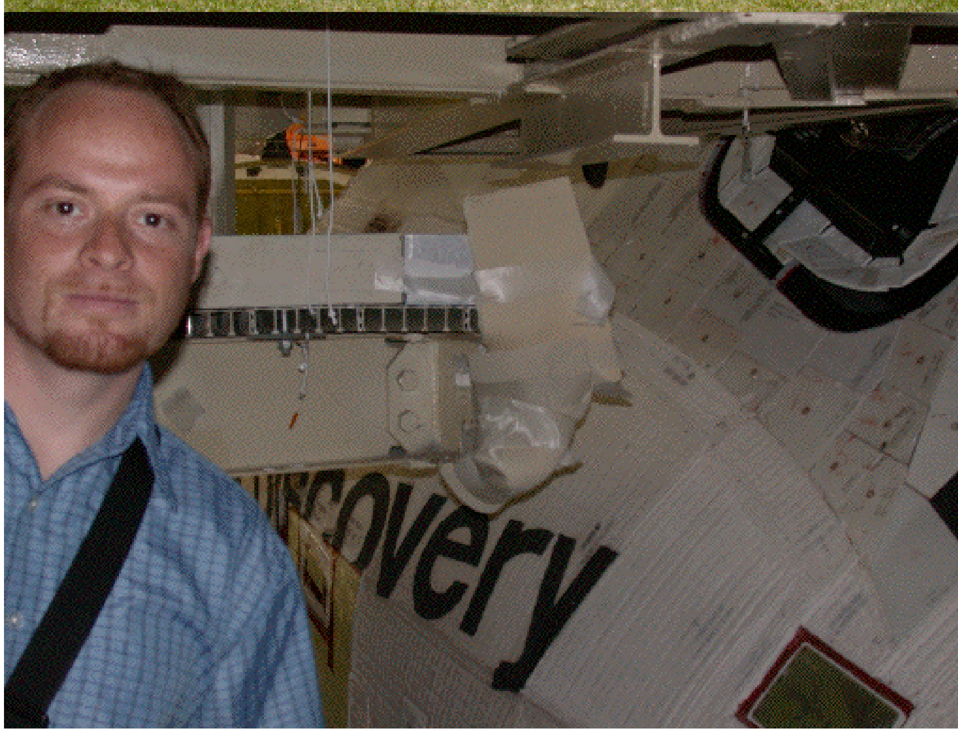
Same Direction Triples

Mars Exploration Rover






USA




USAF
DELTA

Spirit Performance

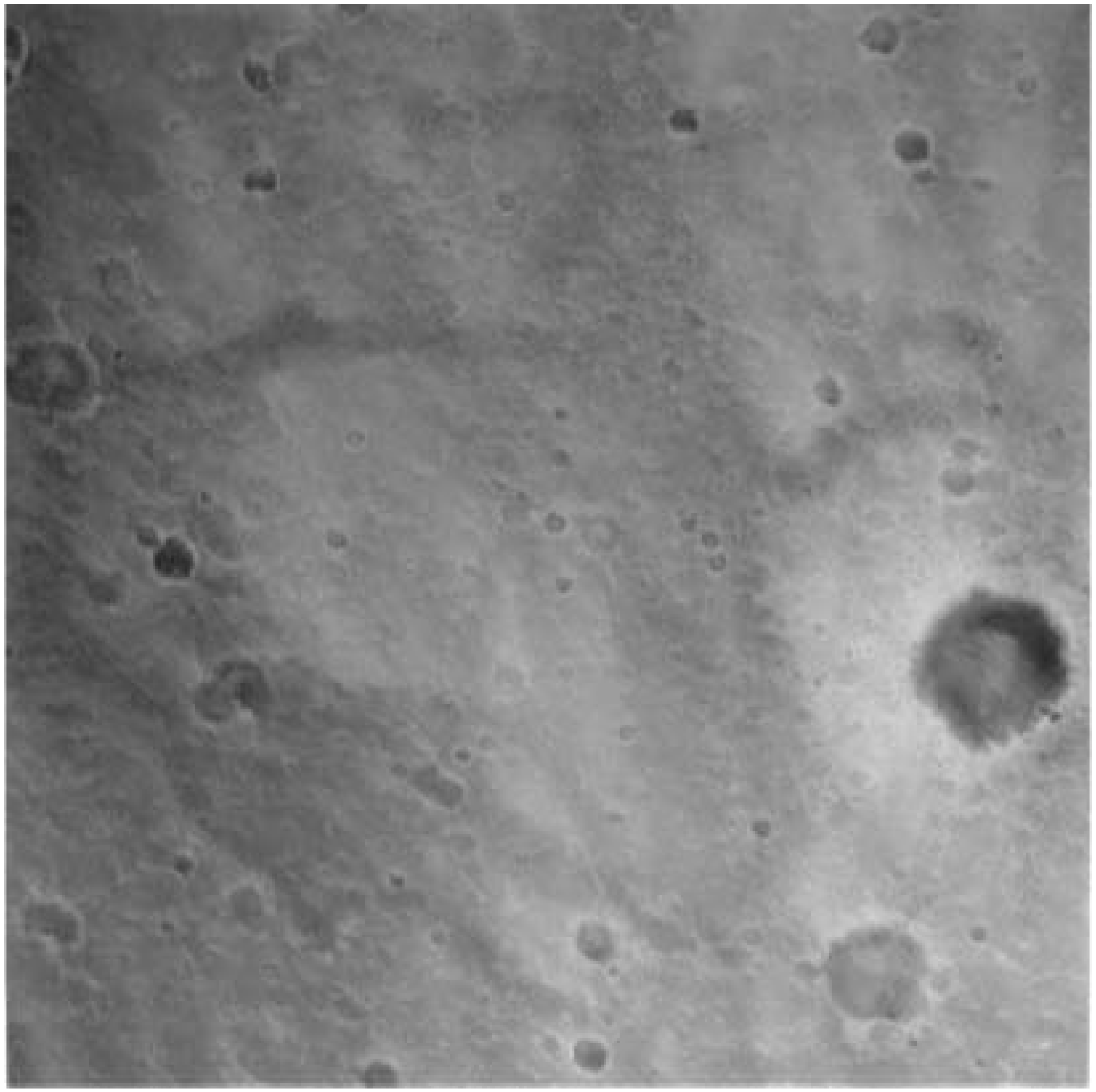
MER-A

Gusev Crater

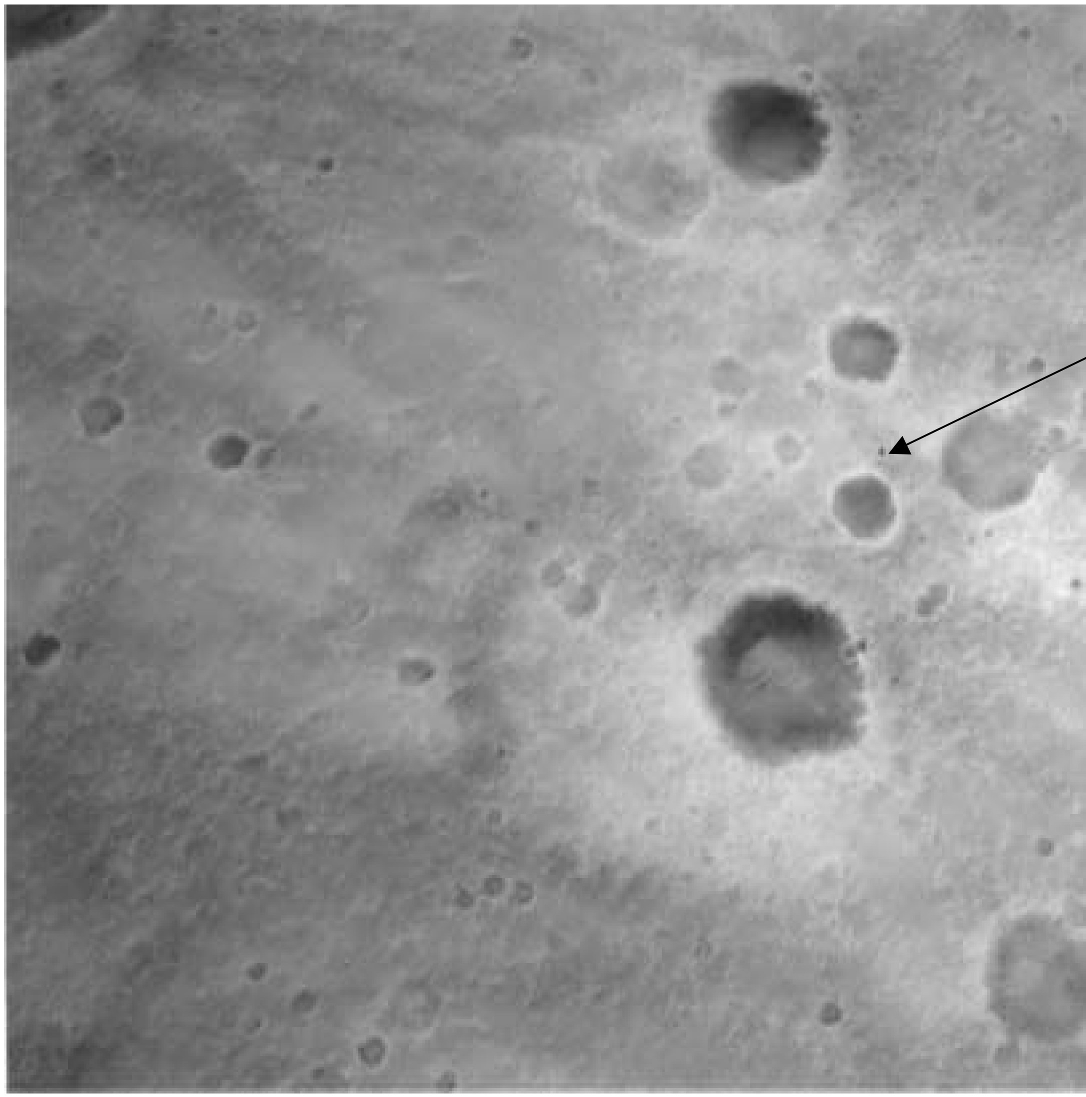
January 3rd, 2004

Spirit First Image (1983 m)

Spirit Second Image (1706 m)



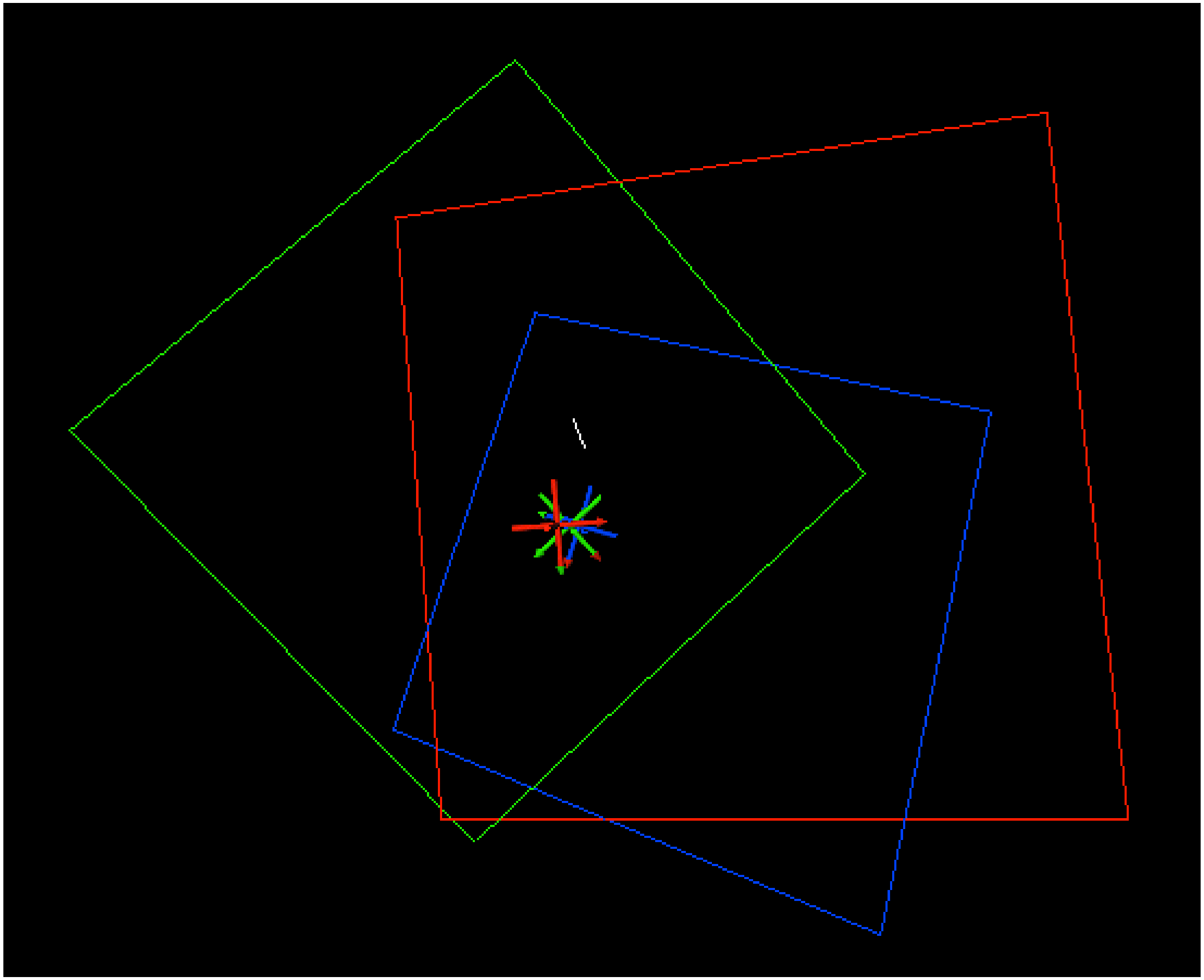
Spirit Third Image (1433 m)



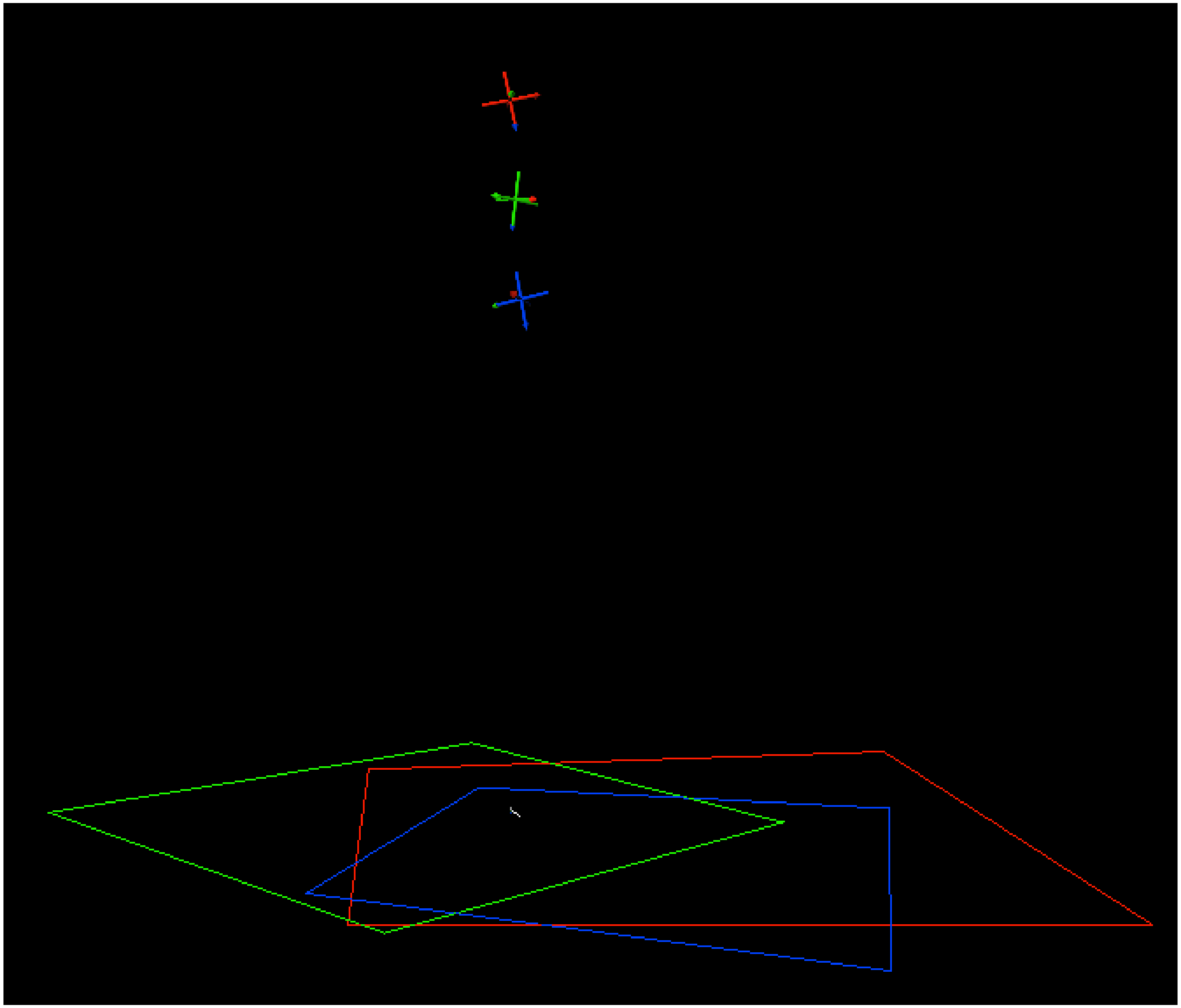
heatshield at
700 m altitude

parachute
shadow

Spirit State Top View

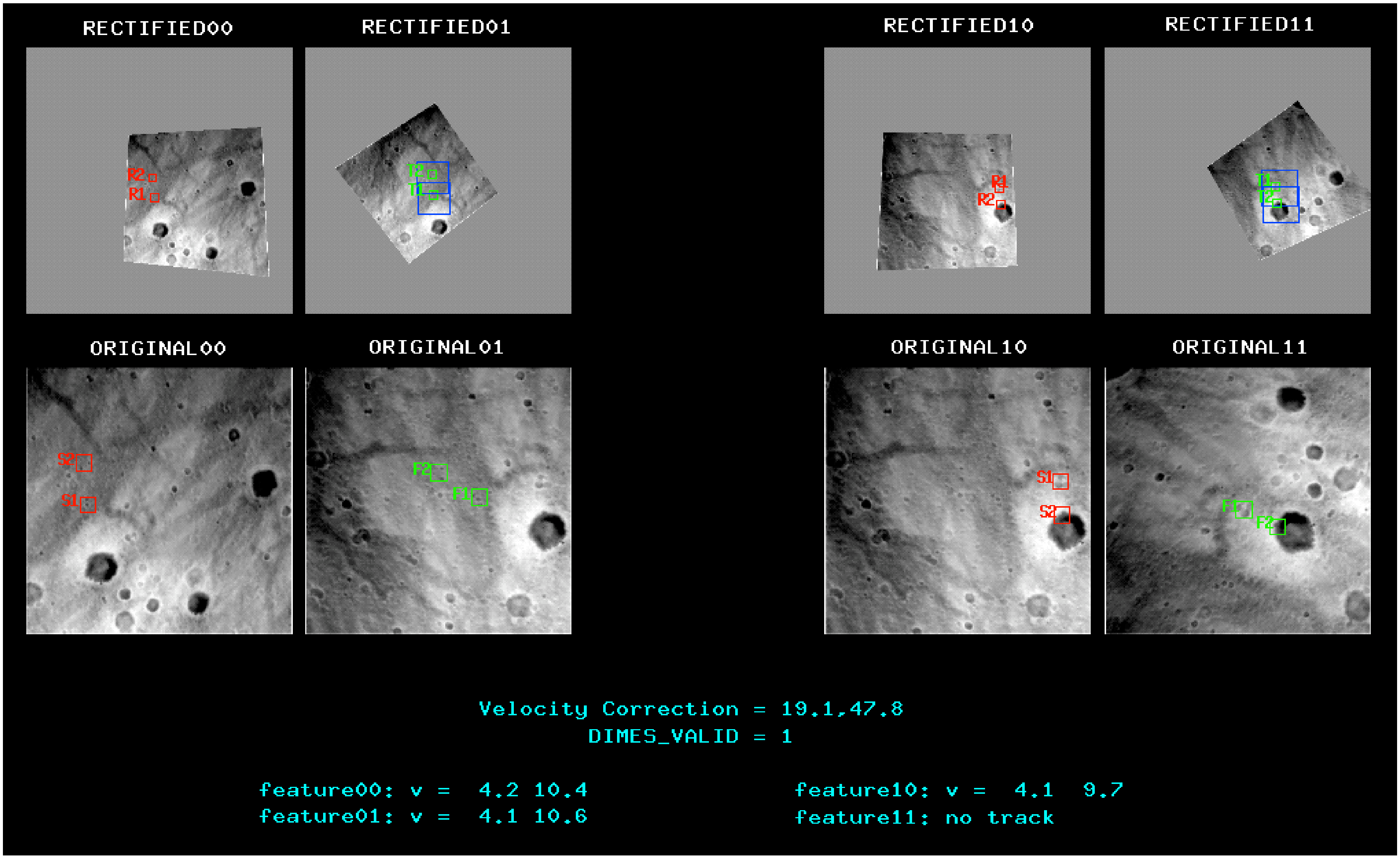


Spirit State Side View



Spirit Velocity Result

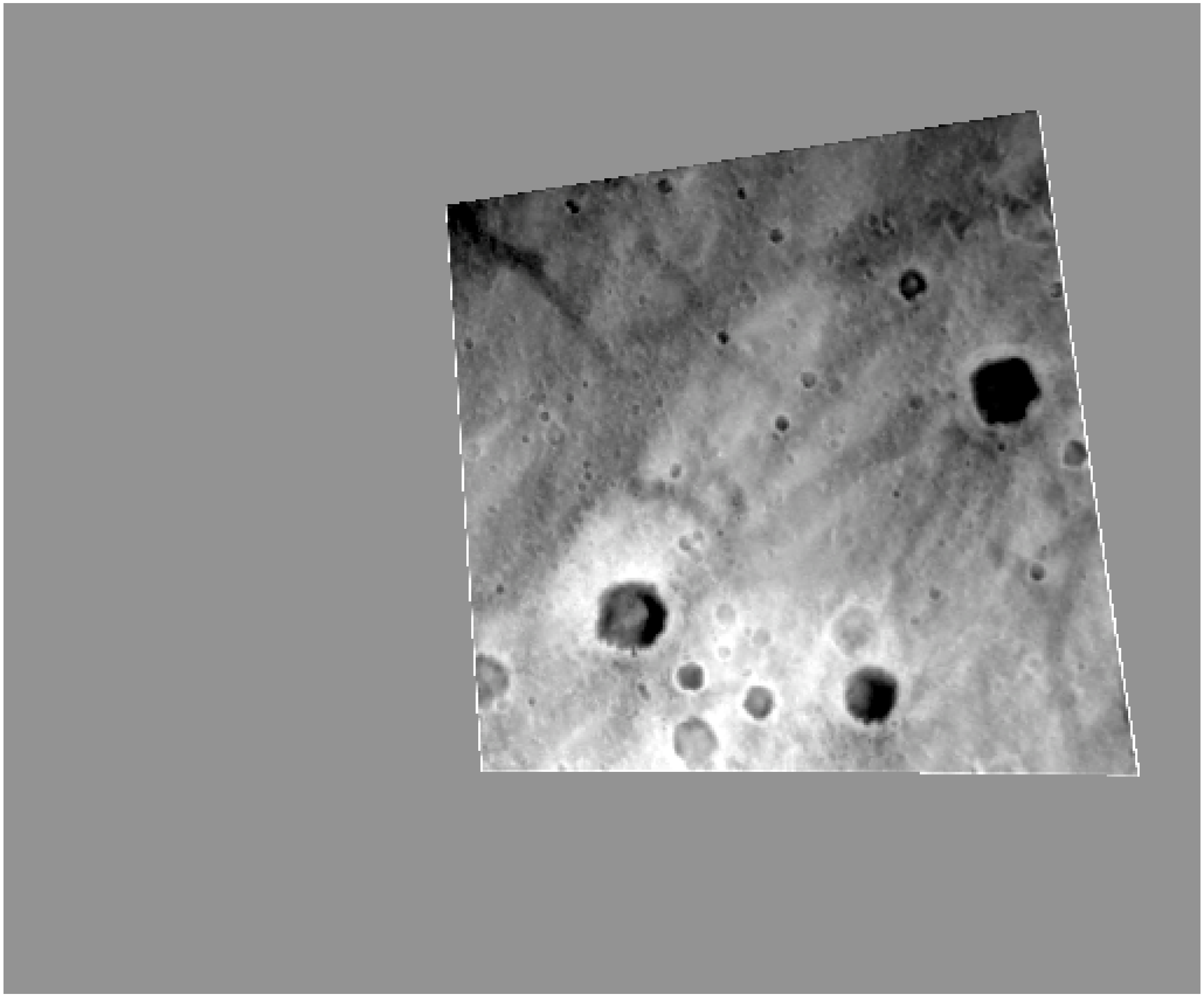
Mars Exploration Rover



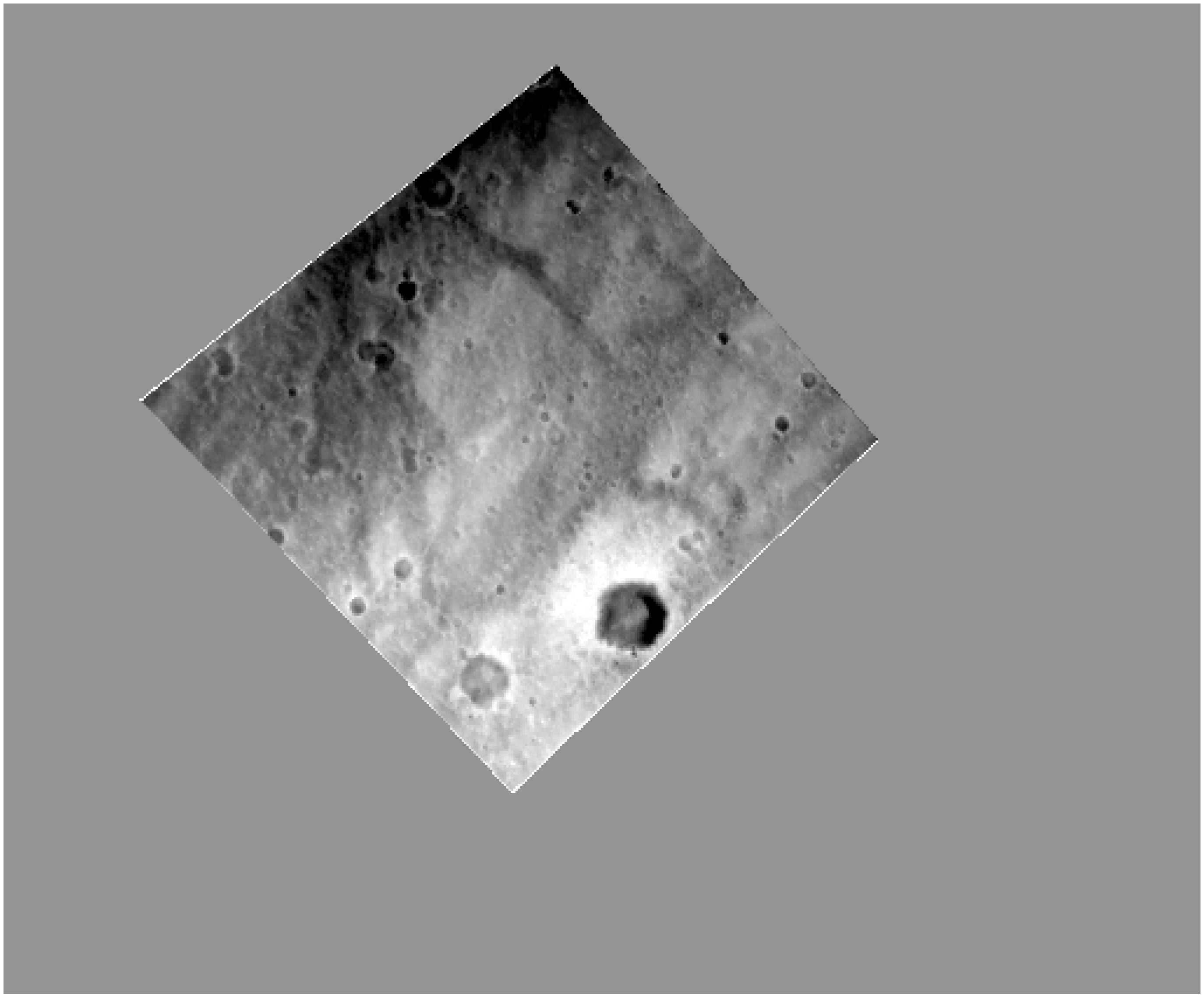
DIMES Verification

- The 3 images on the following pages are the DIMES images rectified to the local level frame. The position and attitude for rectification come from onboard measurements: attitude from IIT, altitude from RAS, horizontal motion from DIMES. For the images, North is left and East is down.
- As you flip through the pages, you will see that in the overlap there is very little shift in image data. Qualitatively, this indicates that all of the measurements are consistent and specifically that the horizontal velocity computed by DIMES was correct.

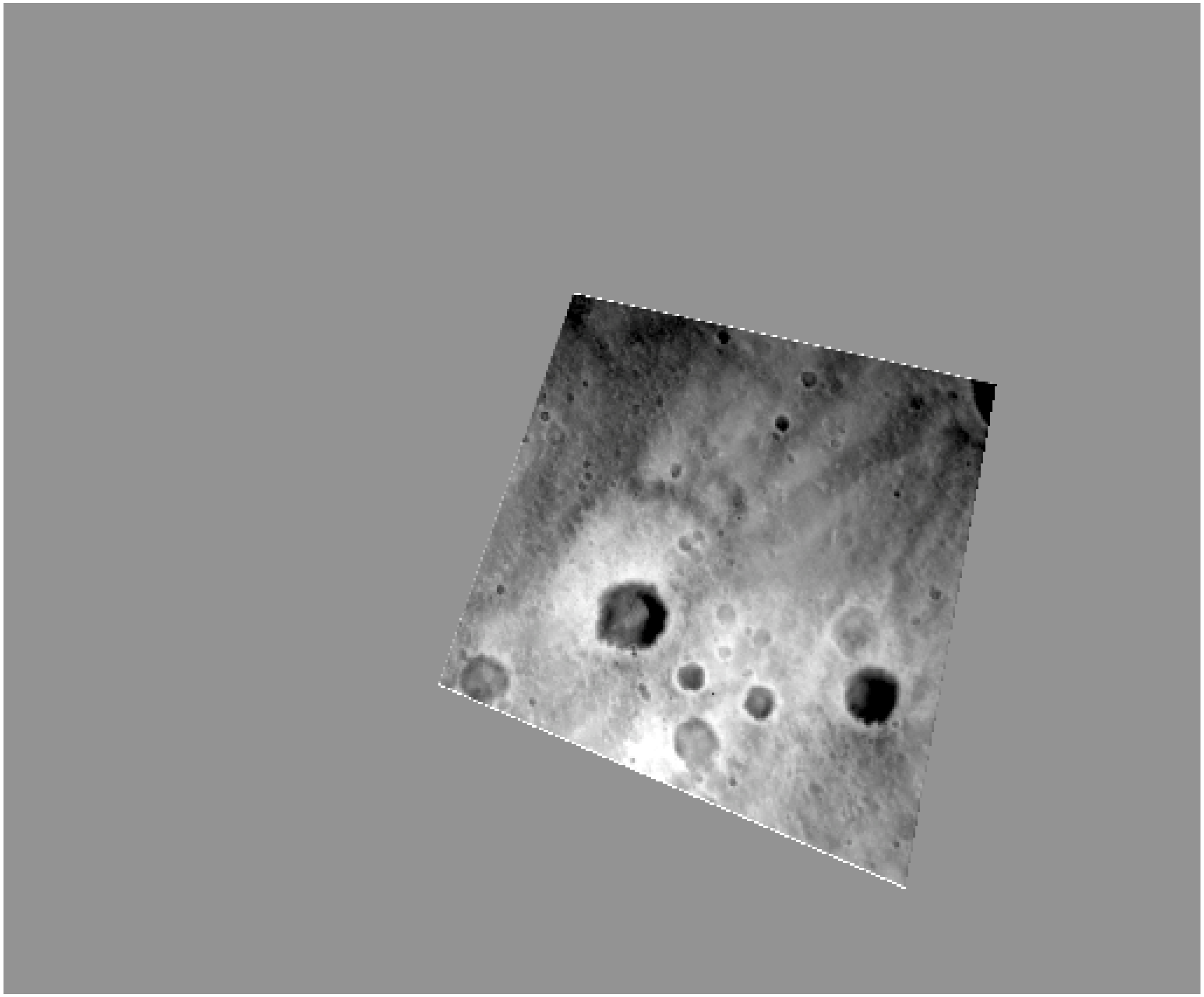
First Spirit Image Mapped to Local Level



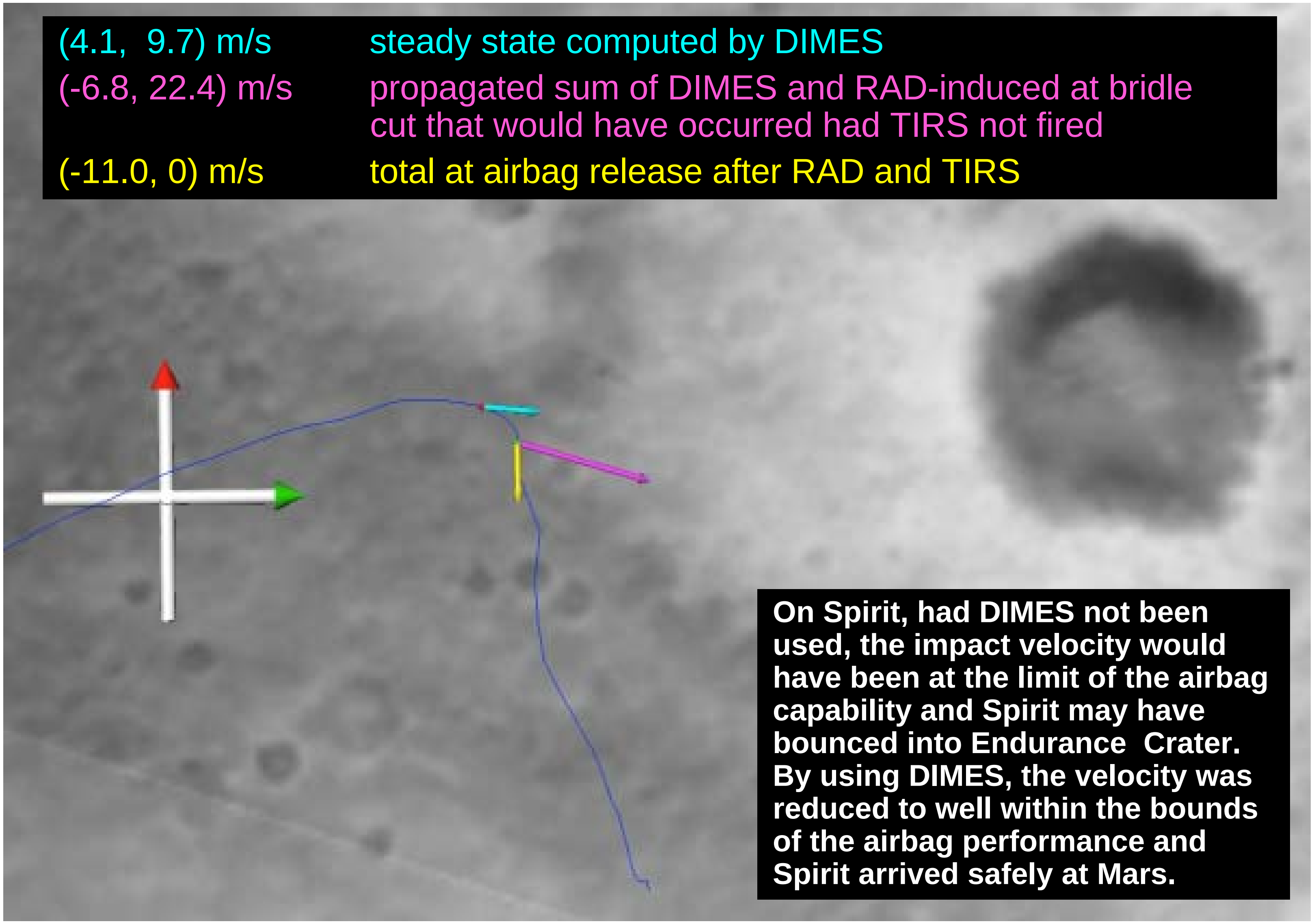
Second Spirit Image Mapped to Local Level



Third Spirit Image
Mapped to Local Level



Spirit DIMES/TIRS Vector Diagram



Opportunity Performance

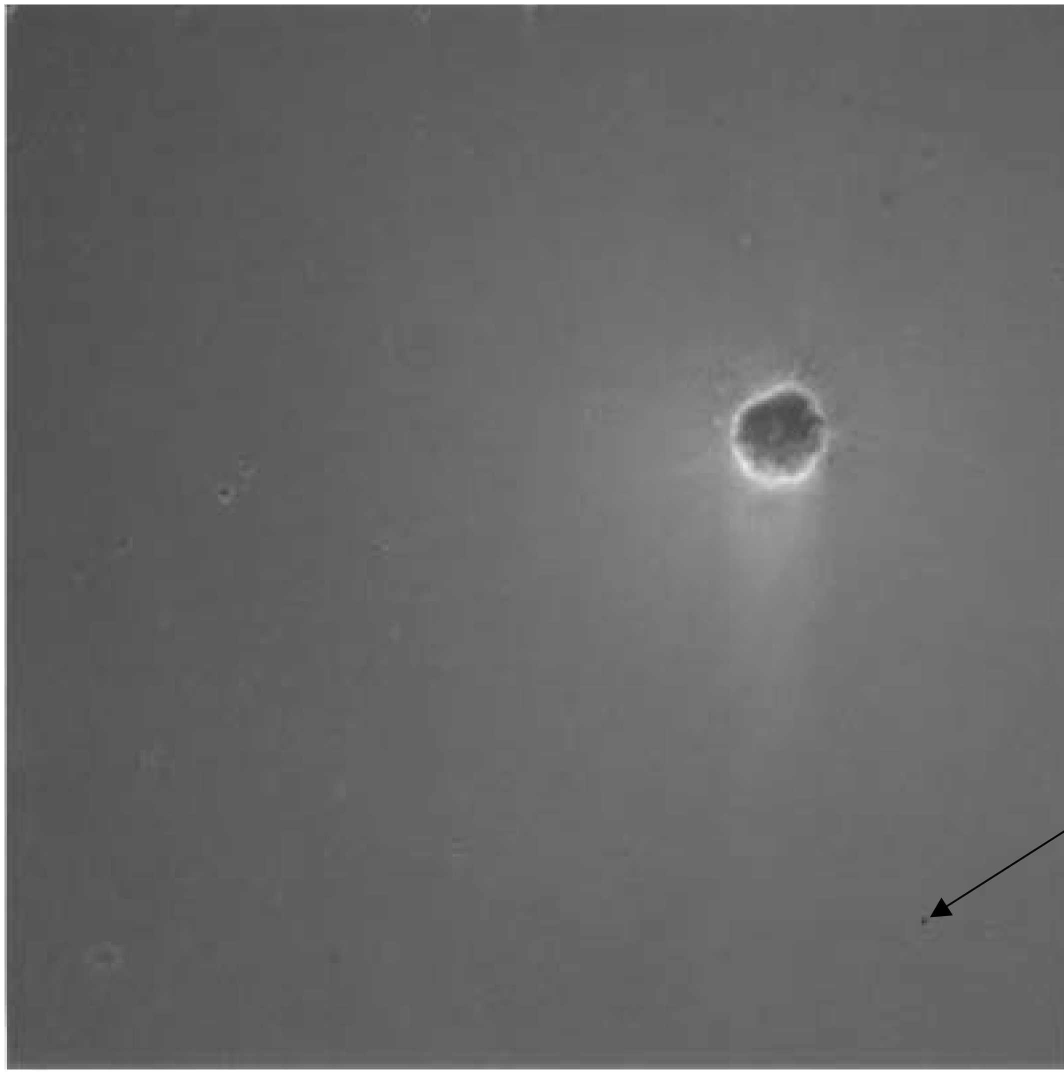
MER-B

Meridiani Planum

January 23th, 2004

First Opportunity Image (1986 m)

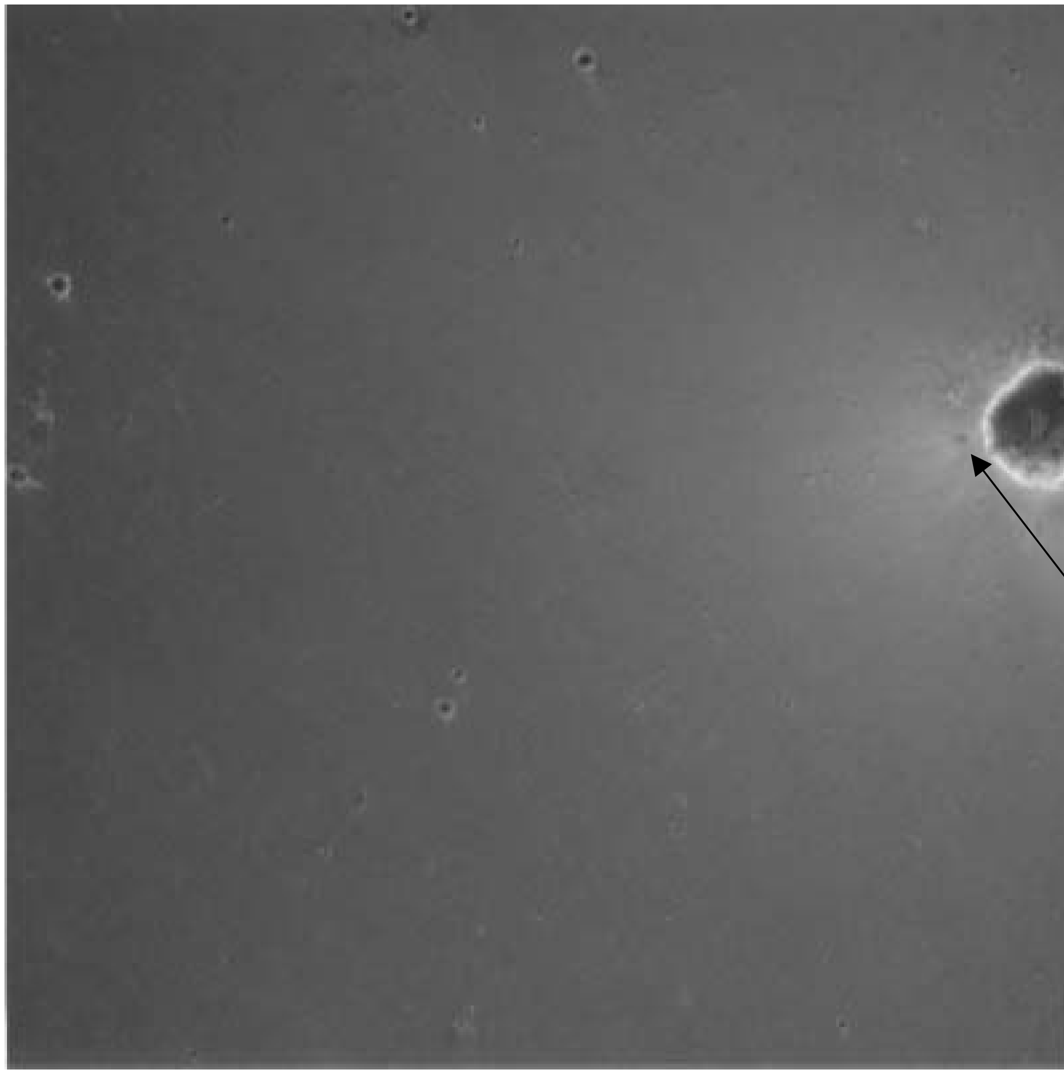
Mars Exploration Rover



heatshield at
1257 m altitude

Second Opportunity Image (1690 m)

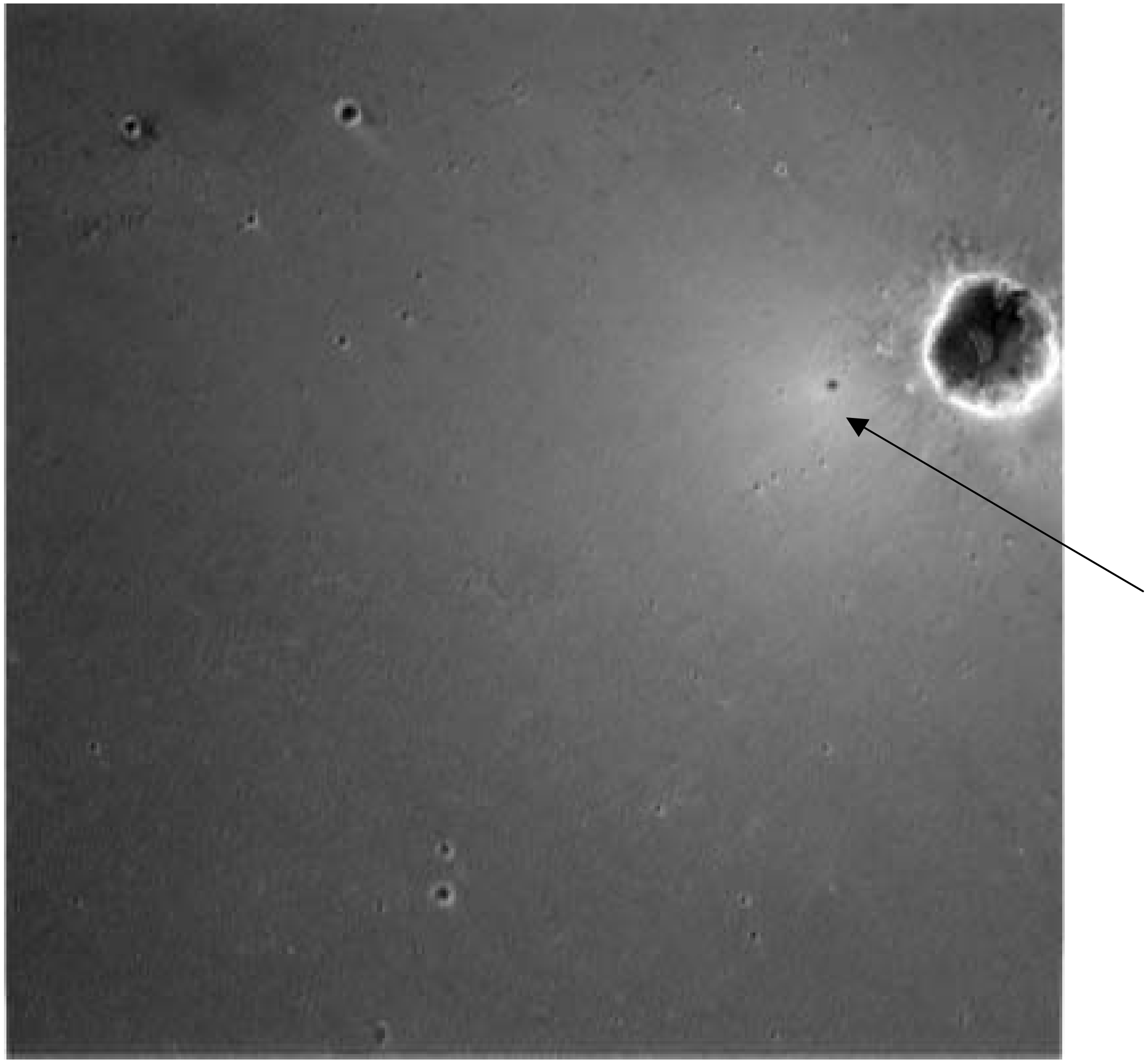
Mars Exploration Rover



parachute shadow and opposition effect

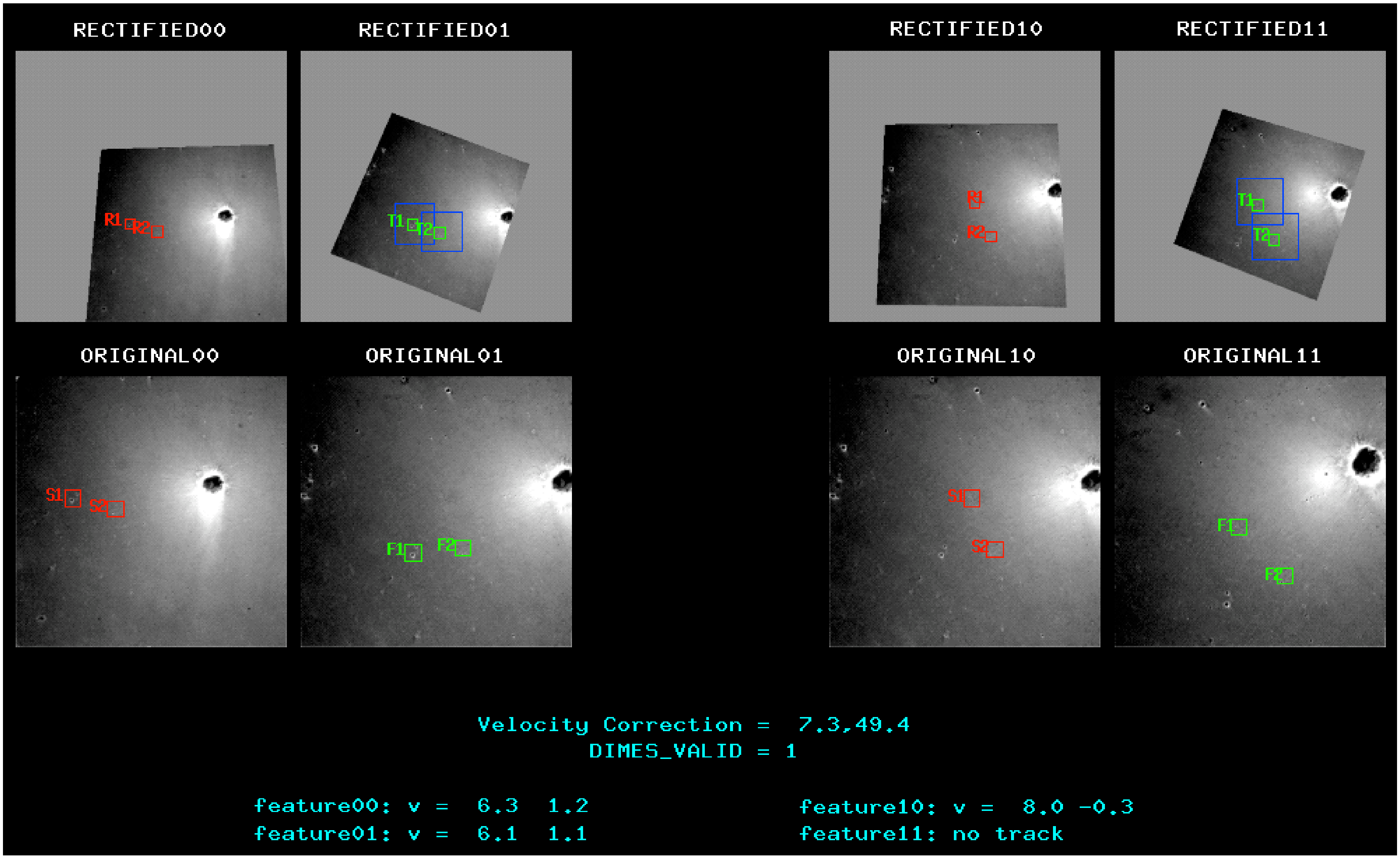
Third Opportunity Image (1404 m)

Mars Exploration Rover

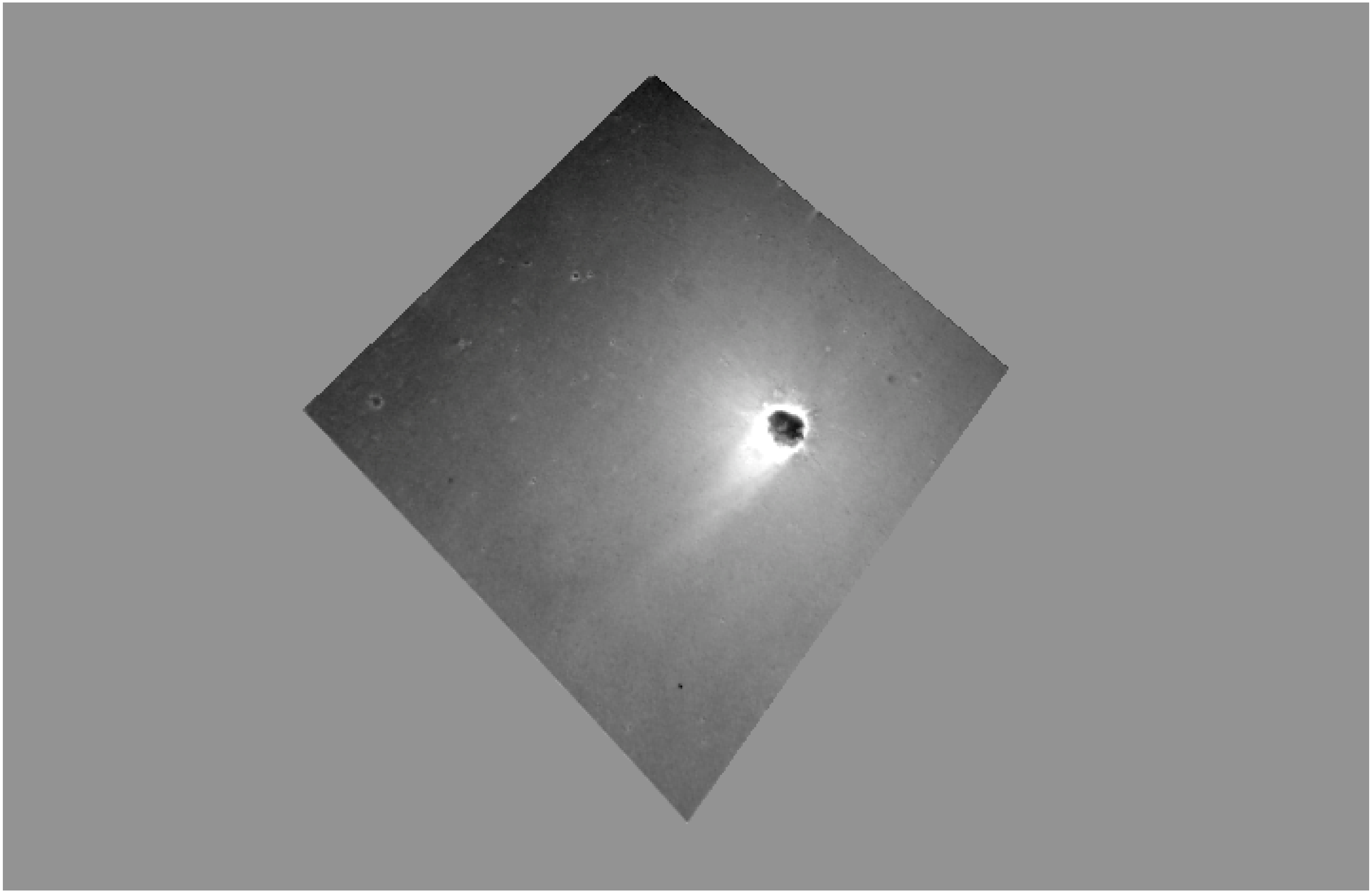


Opportunity Velocity Result

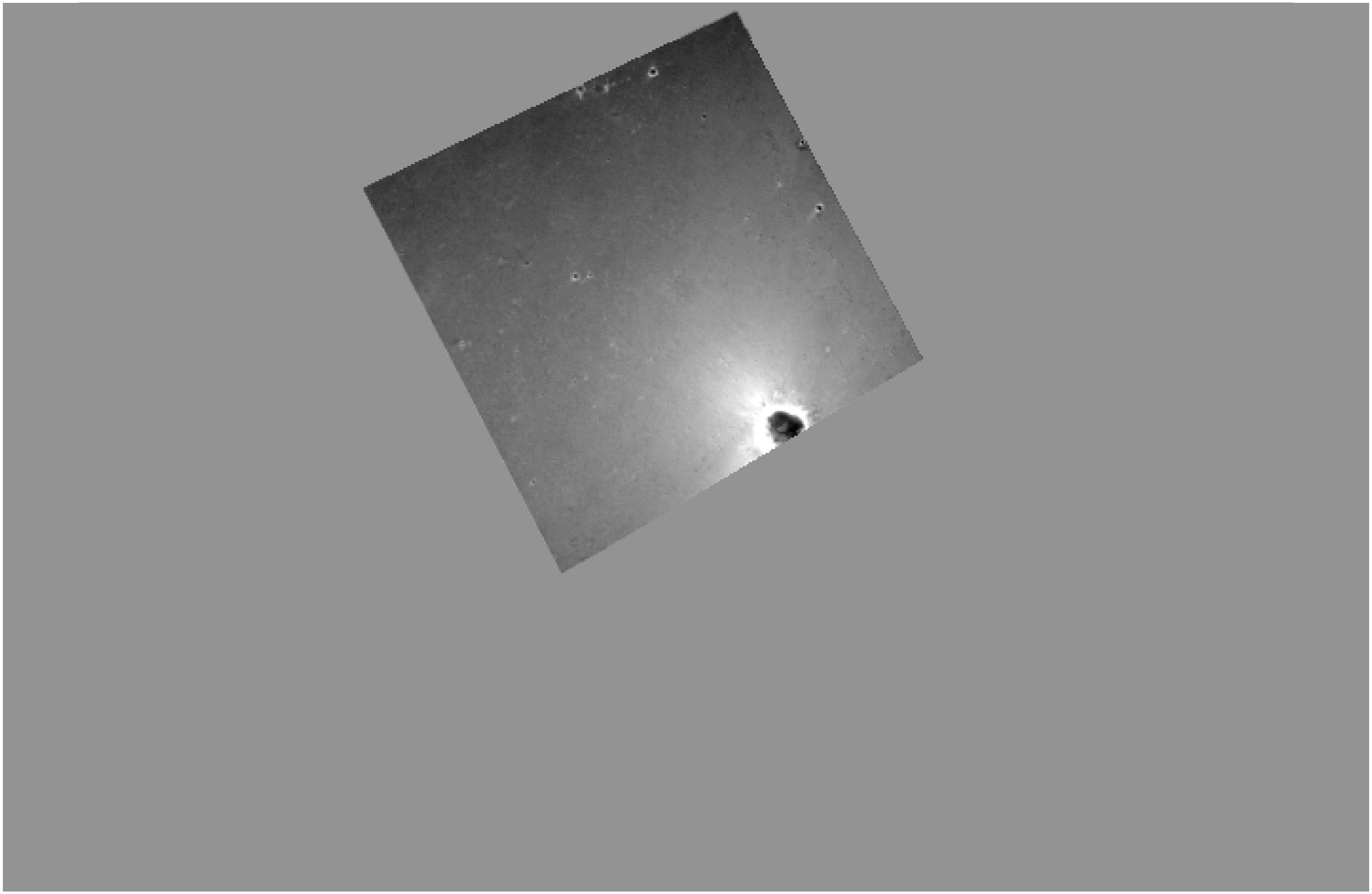
Mars Exploration Rover



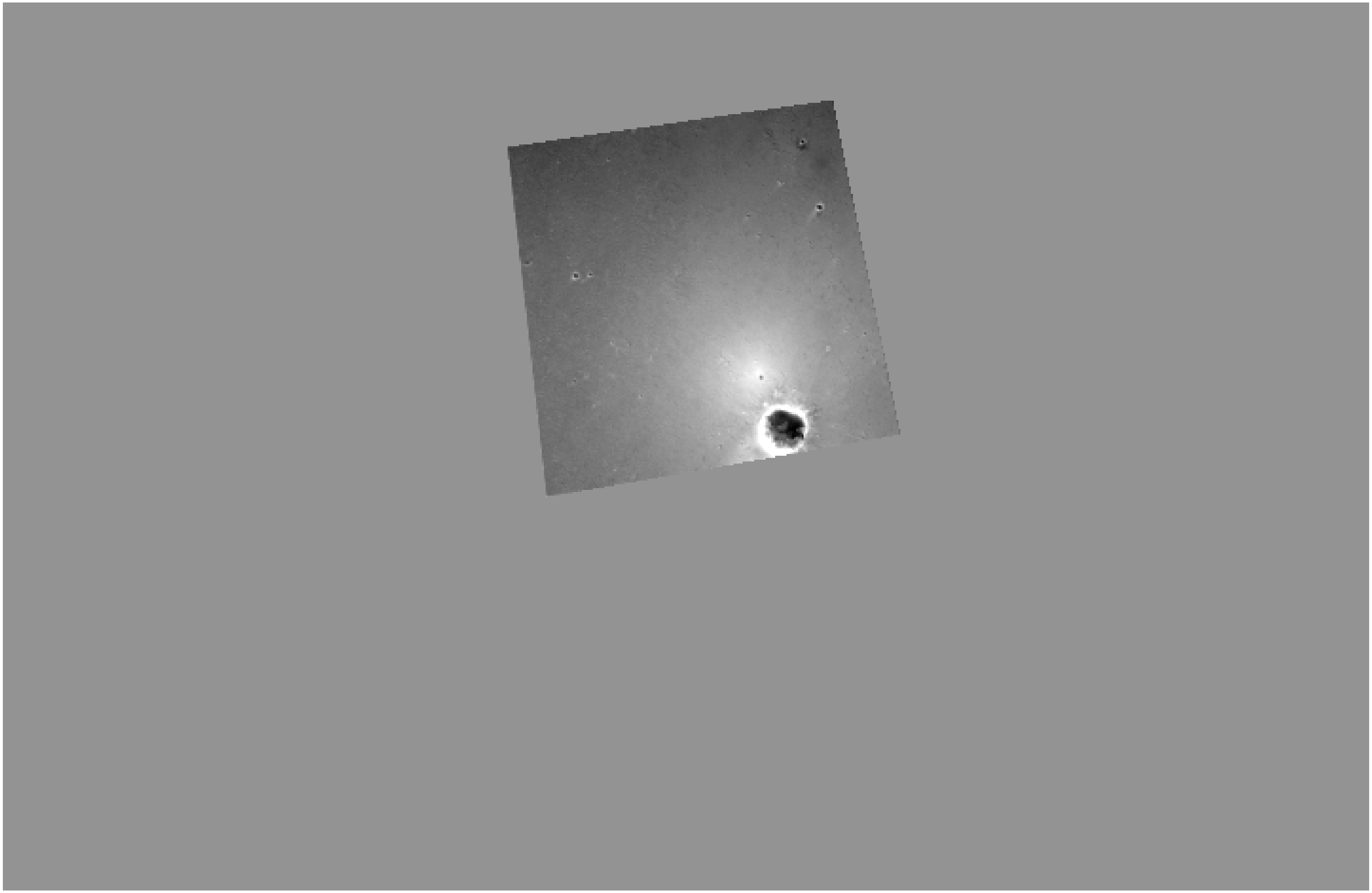
First Opportunity Image
Mapped to Local Level



Second Opportunity Image Mapped to Local Level



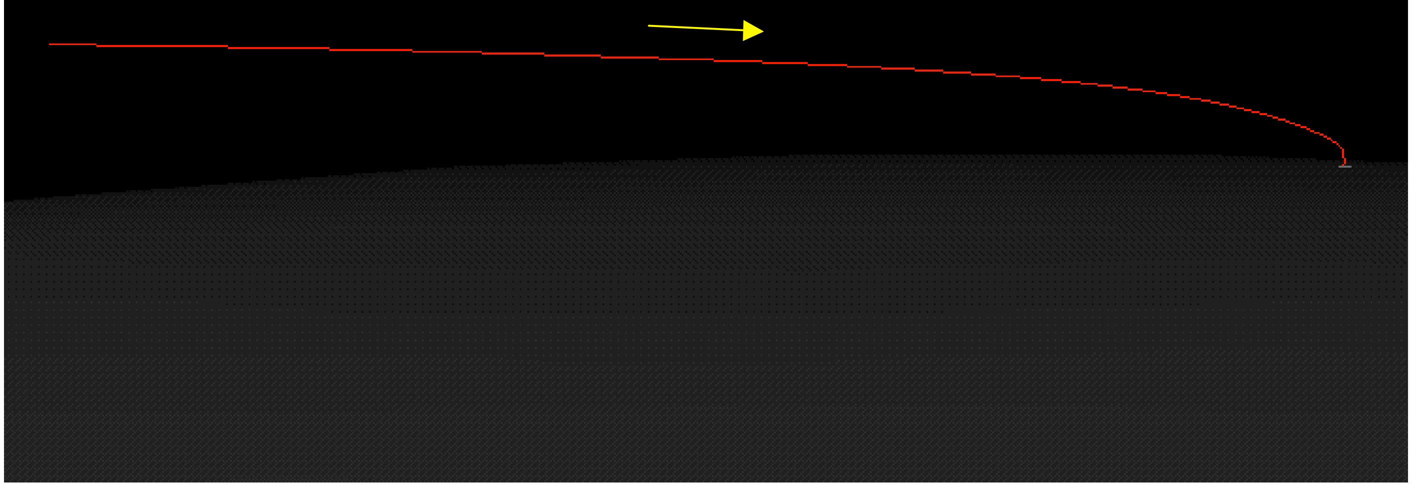
Third Opportunity Image
Mapped to Local Level



View of Entry Trajectory

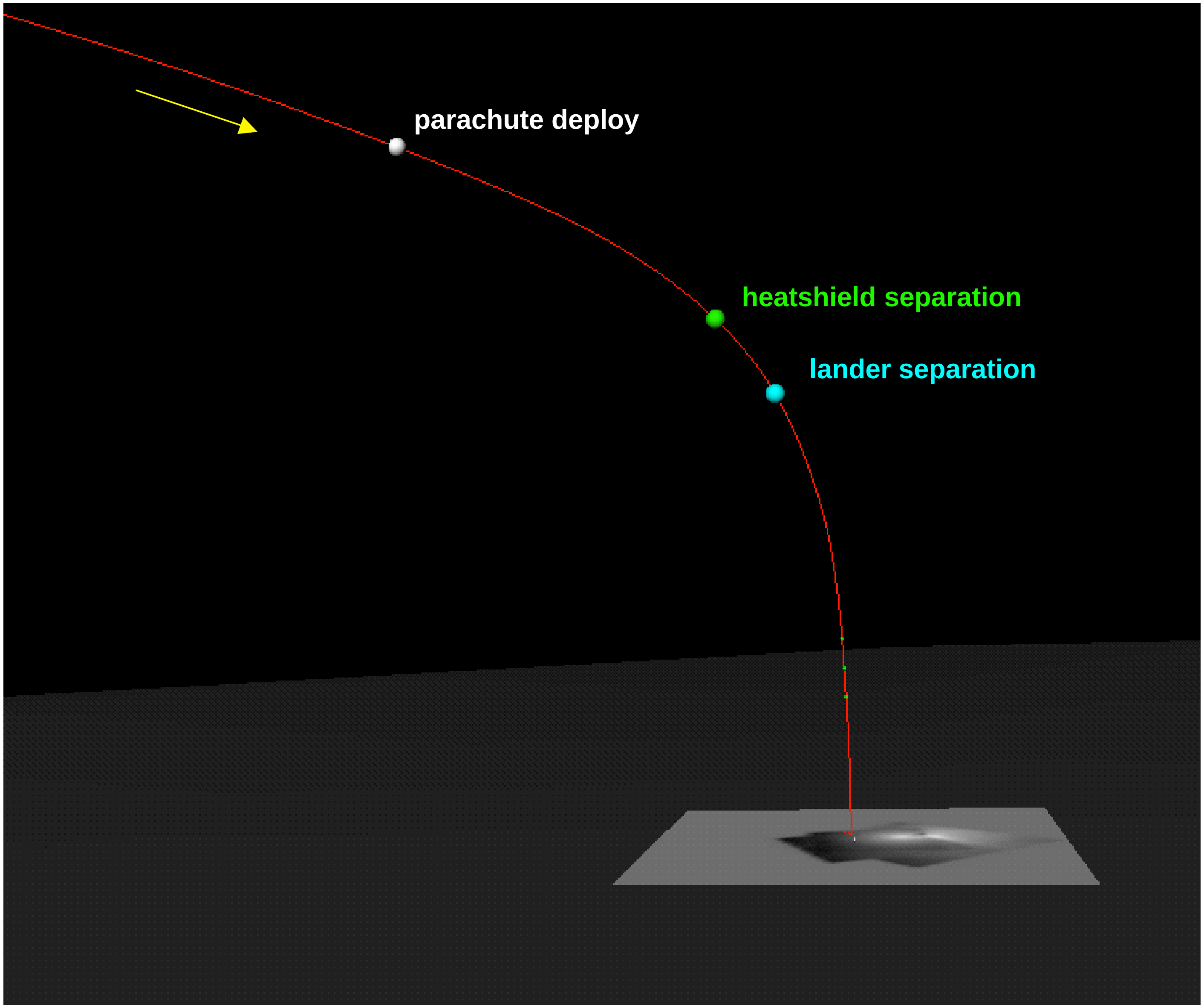
The next 6 slides show different views of the EDL trajectory superimposed on a mosaic of the DIMES images.

- **This visualization is one of several pieces of information used to determine the location of Opportunity on the surface.**
- **The EDL trajectory is a straight integration of acceleration using the DIMES velocity as an initial condition.**
- **The DIMES images are mosaiced using IIT attitude, RAS altitude and DIMES horizontal motion estimates.**

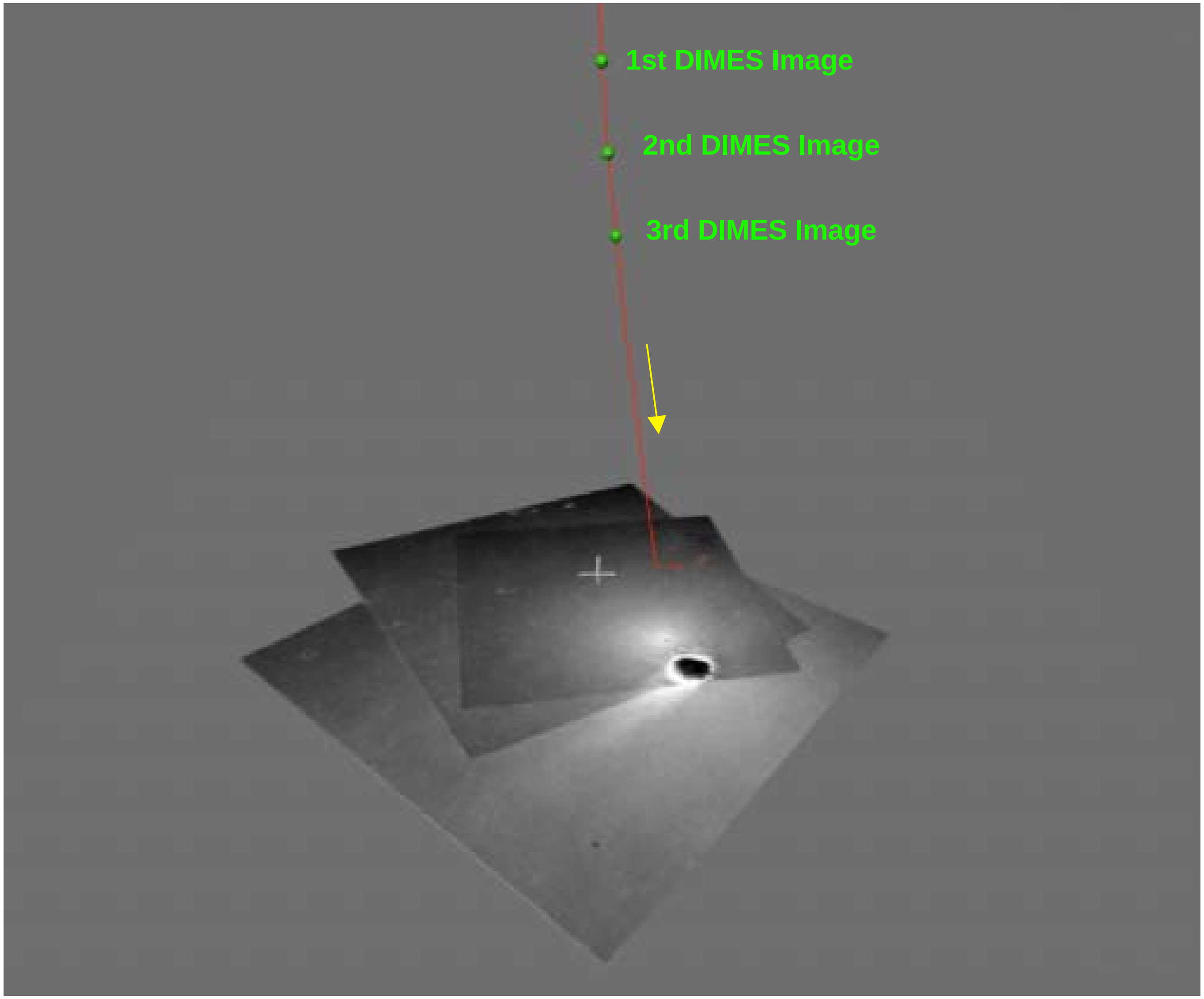


A Closer View of Entry

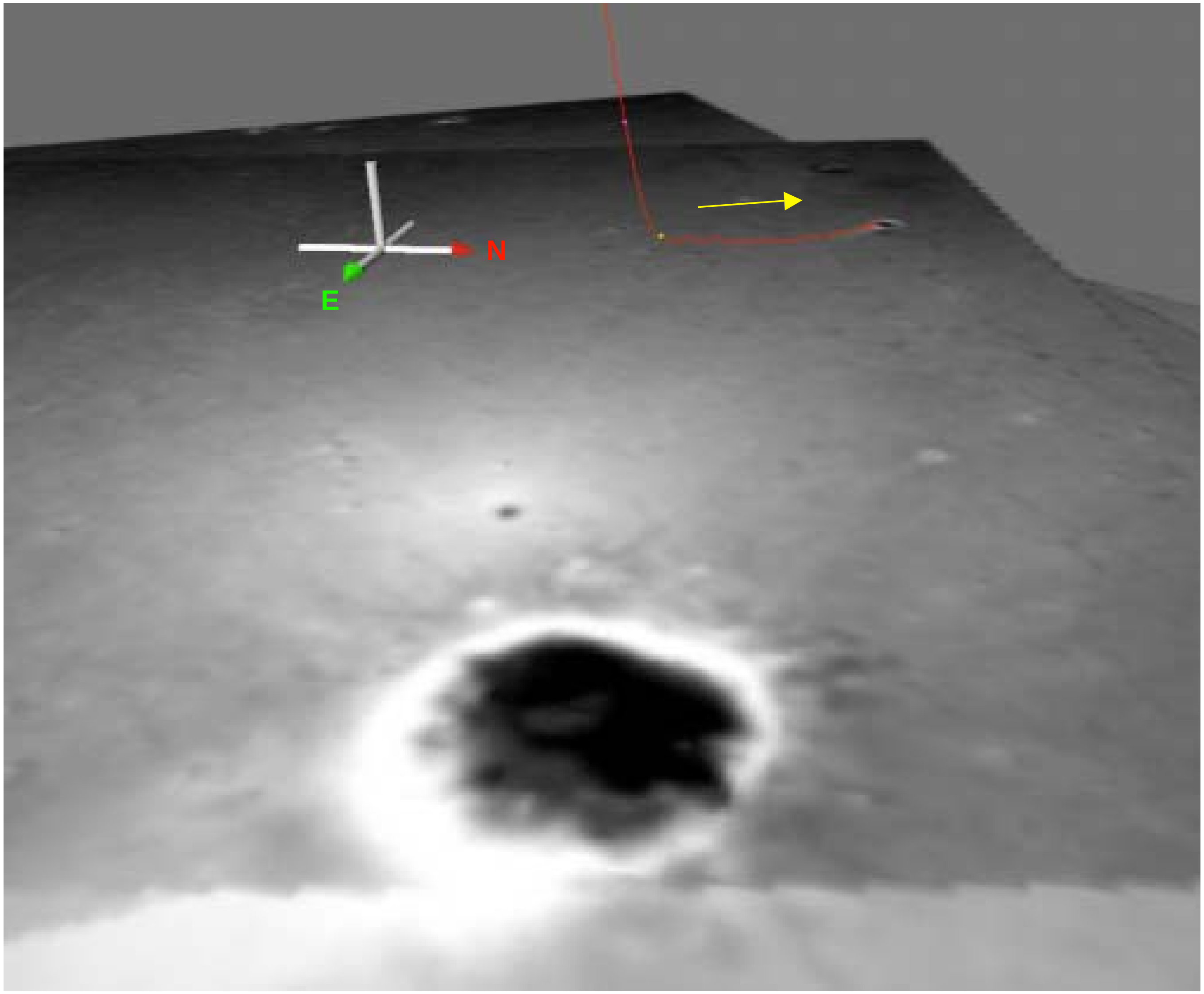
Mars Exploration Rover



Descent and DIMES Images

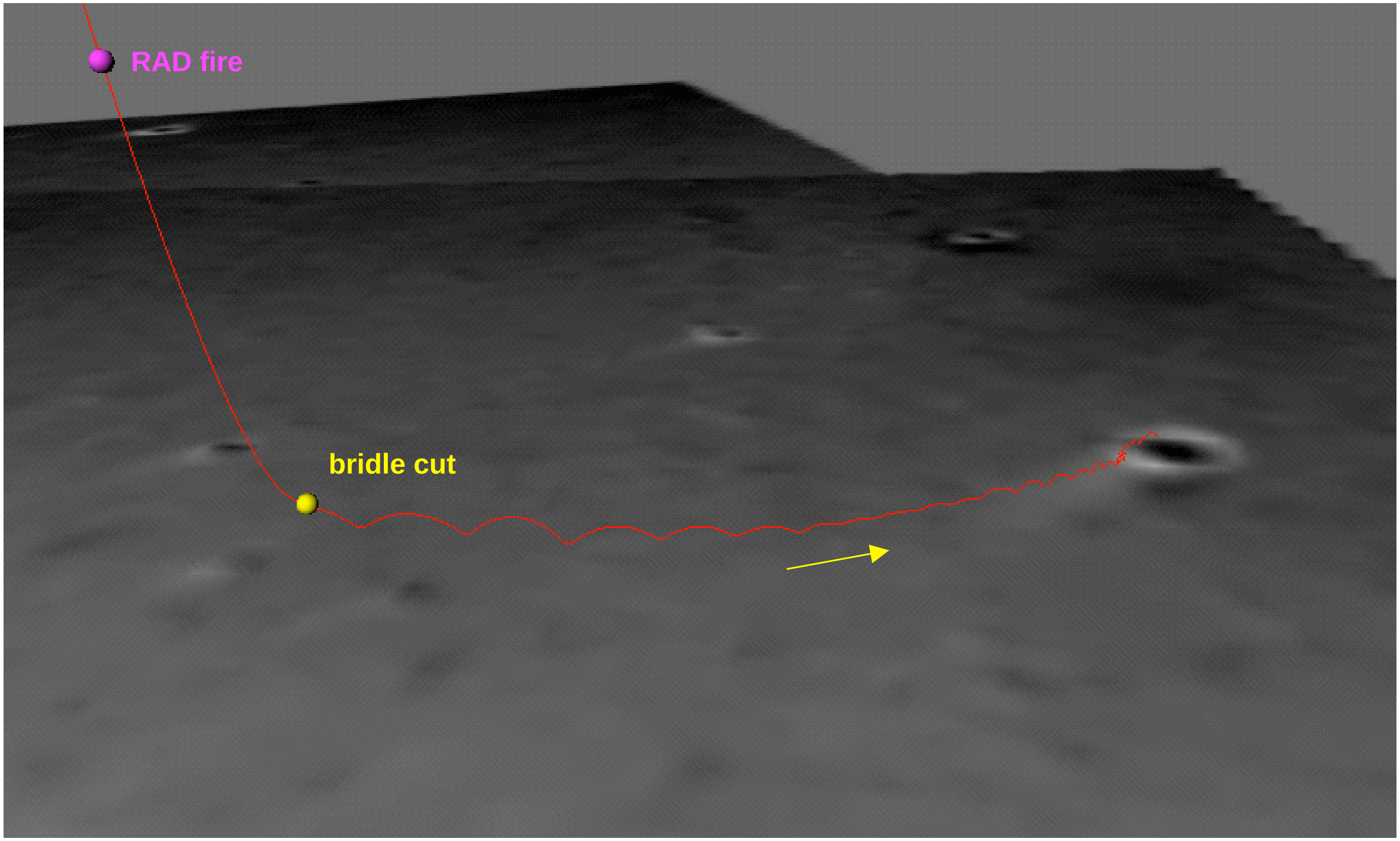


Direction of Bouncing



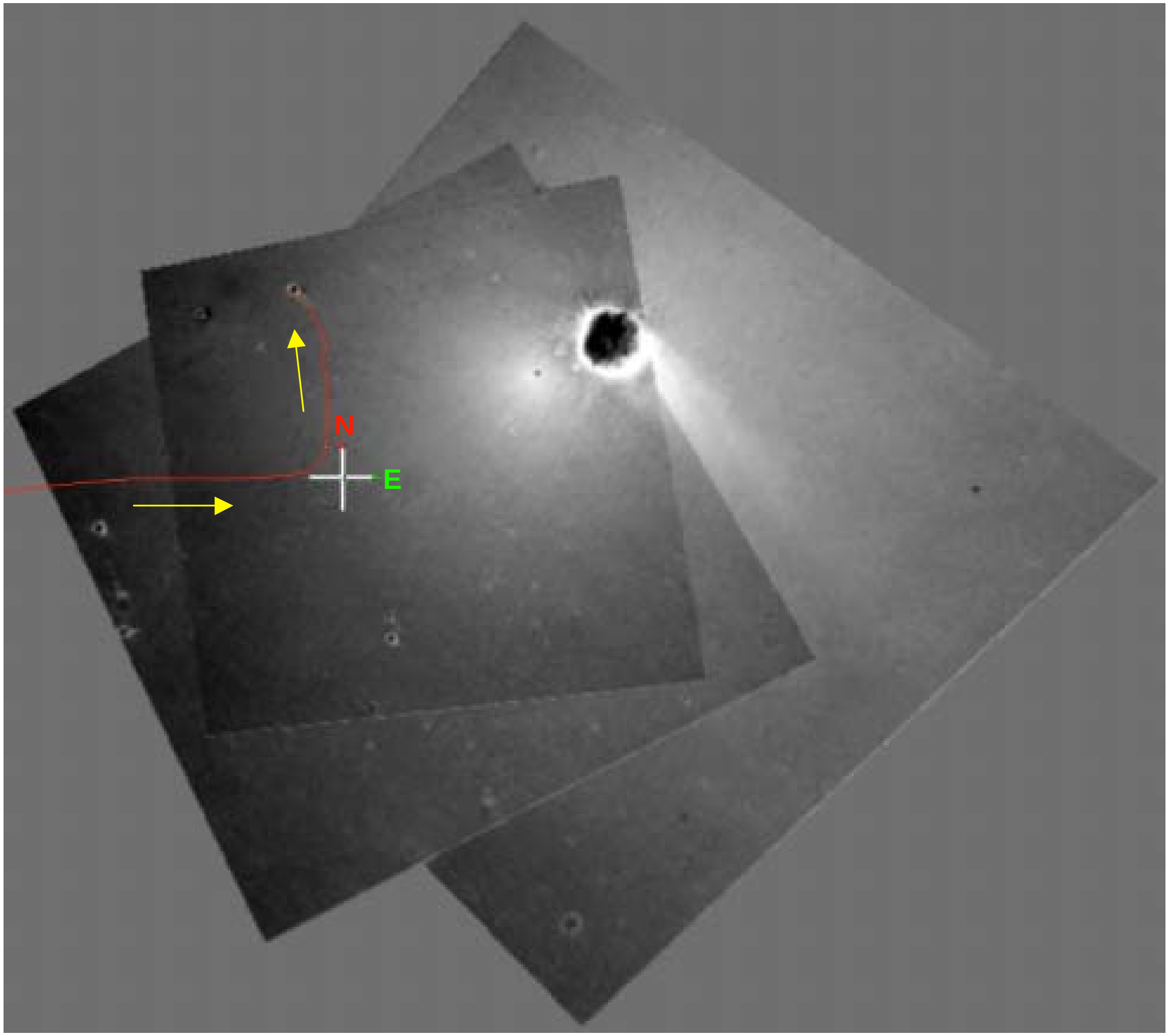
Side View of Bouncing

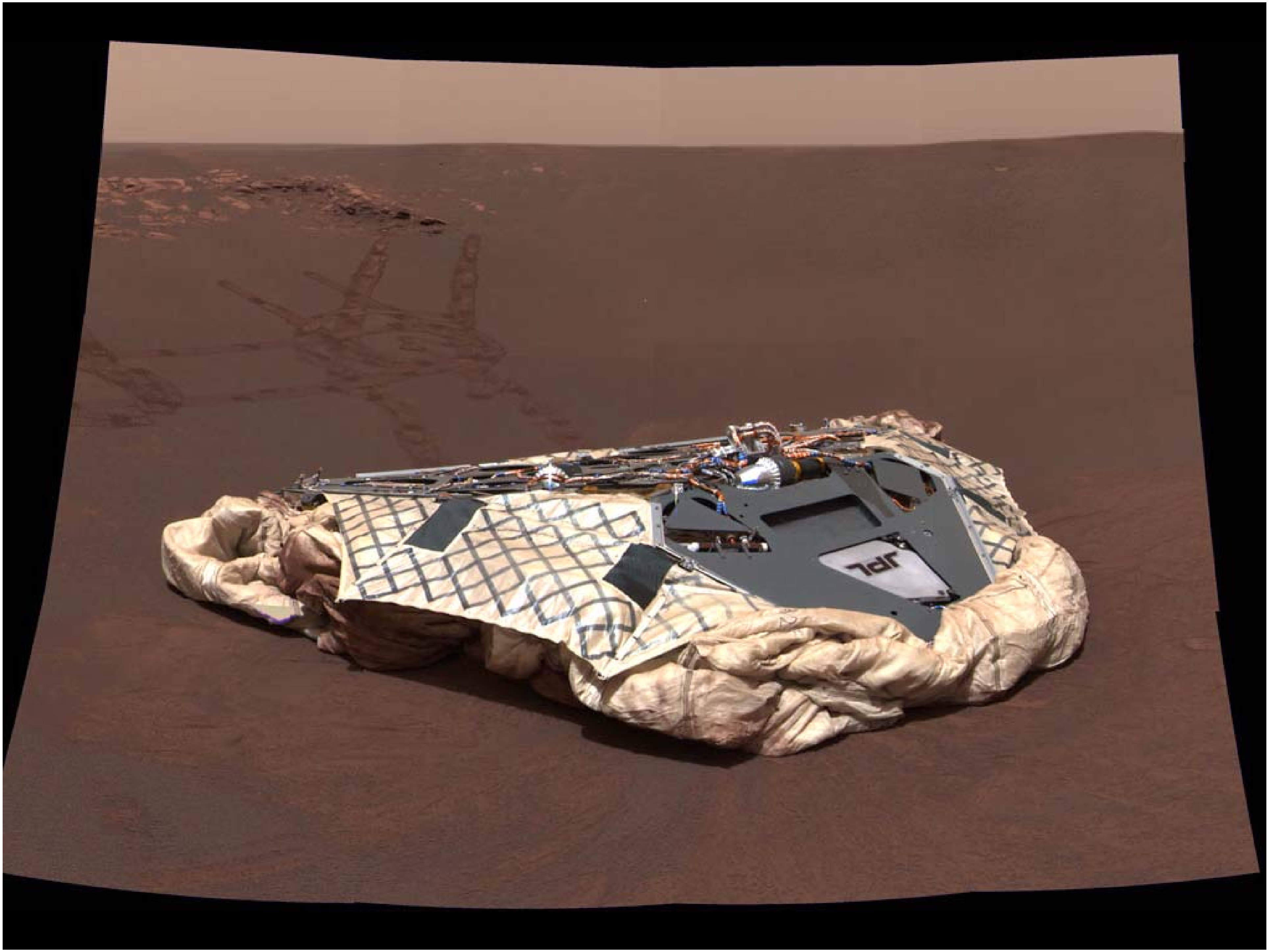
Mars Exploration Rover

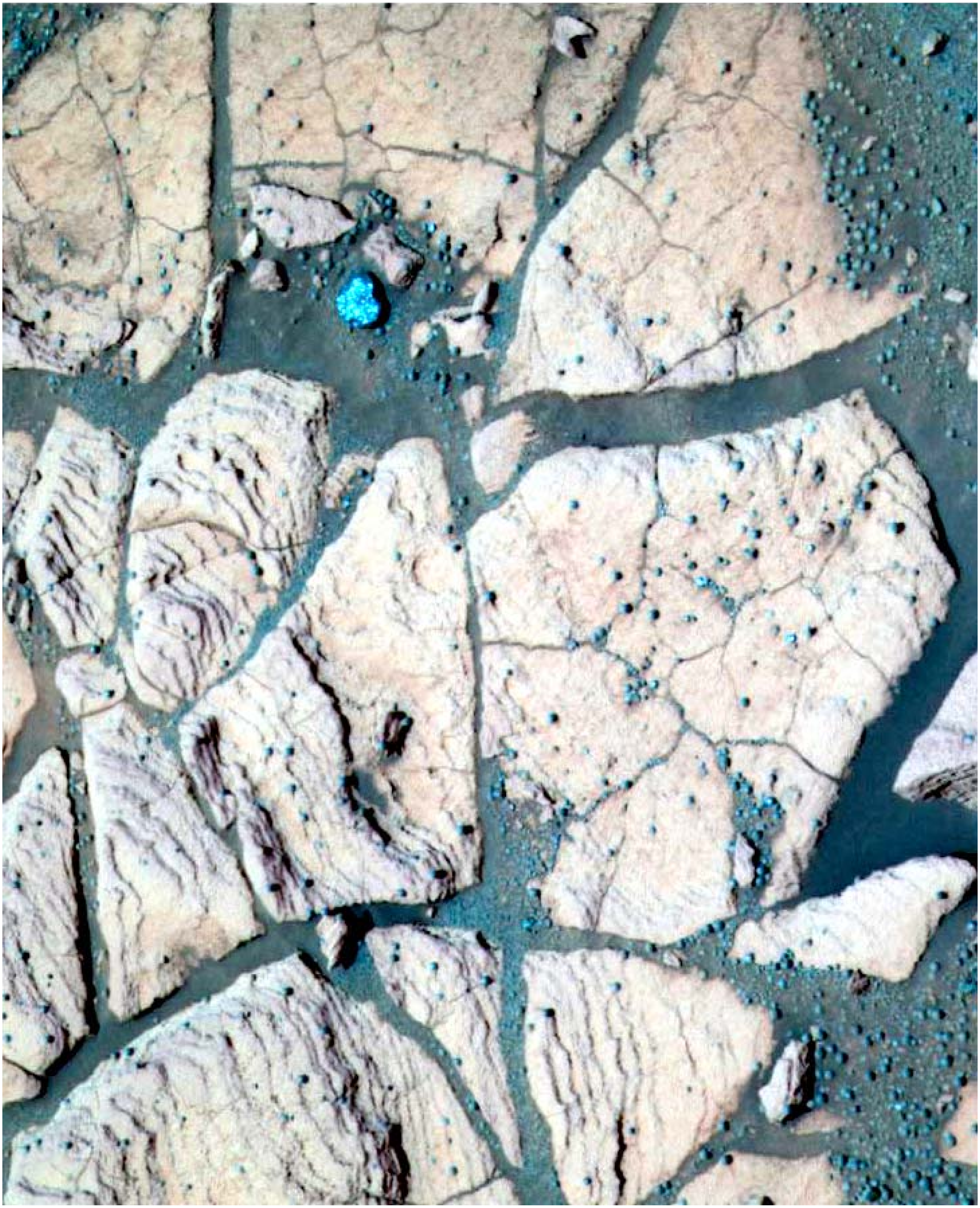


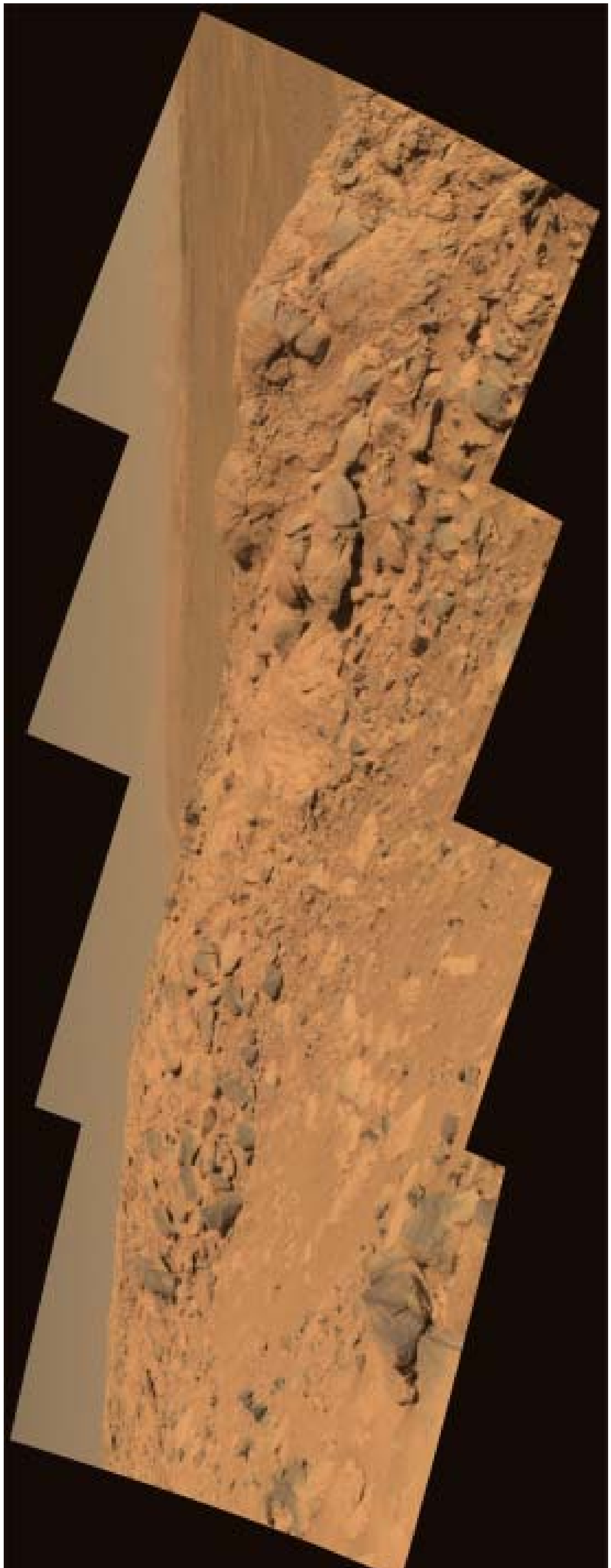
Overhead View of Trajectory

Mars Exploration Rover





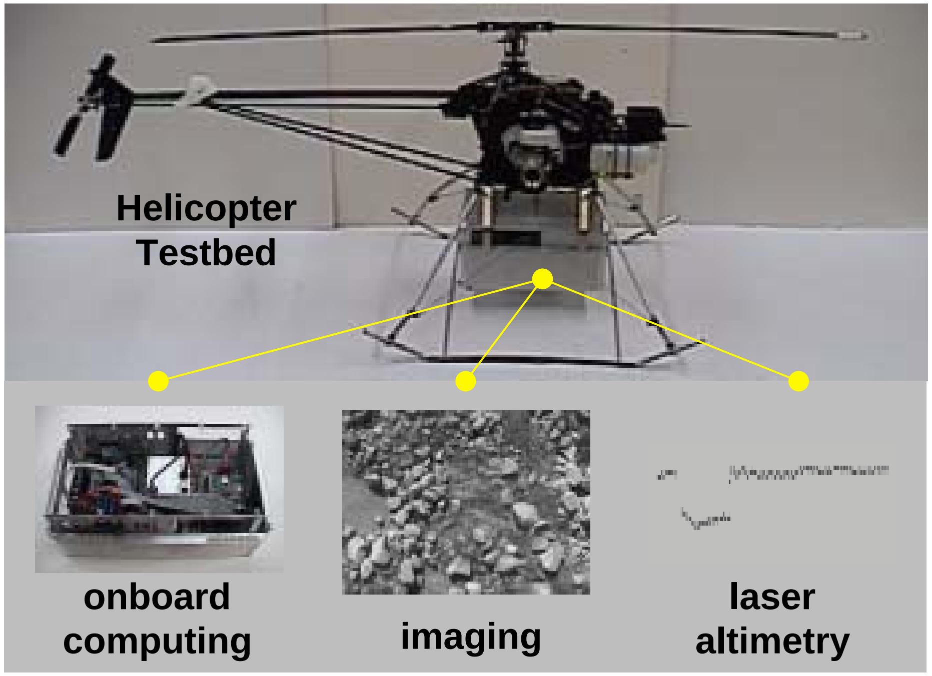




Current and Future Work

JPL Autonomous Helicopter Testbed

Mars Exploration Rover



Commercial Model Helicopter

- 9 kg payload capacity
- 1.8 meter main rotor diameter
- Twin cylinder engine, runs on gas/oil mixture
- 15-20 minute flight on single tank of fuel (can extend flight time with additional/larger tanks)

Sensors

- CCD imager (640x480 grayscale)
- Laser altimeter
- IMU
- DGPS (2 cm CEP accuracy)
- Compass/Inclinometer

Onboard Computing

- PC/104+ architecture
- 700 MHz PIII CPU with 128Mb DRAM and 128 Mb flash disk
- Framegrabber
- Timer/counter and DIO
- Quad serial card

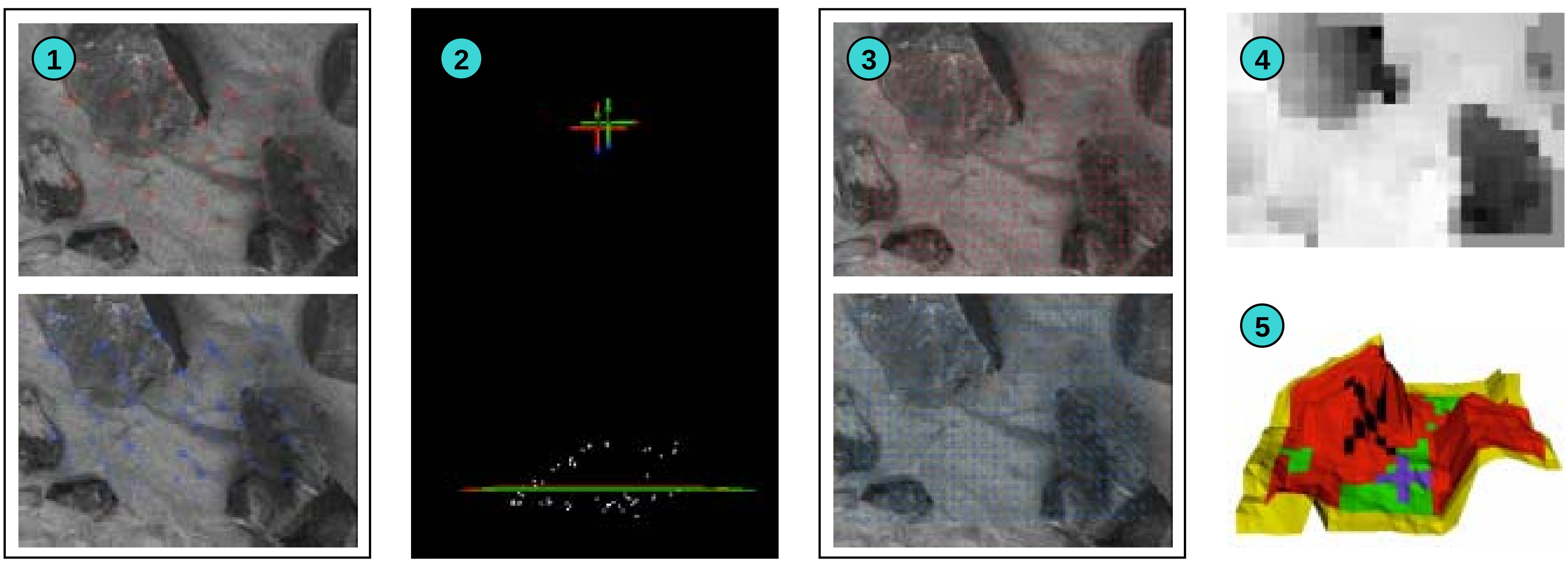
Communication and Control

- 11 Mbit/s wireless ethernet link
- Laptop for robot control and telemetry display

Dense Structure From Motion
Landing Hazard Avoidance Algorithm

Mars Exploration Rover

1. Select and track features between two images
2. Estimate motion and coarse topography
3. Track dense feature grid using motion and coarse topography to reduce search
4. Construct terrain map
5. Apply slope and roughness hazard detection and avoidance

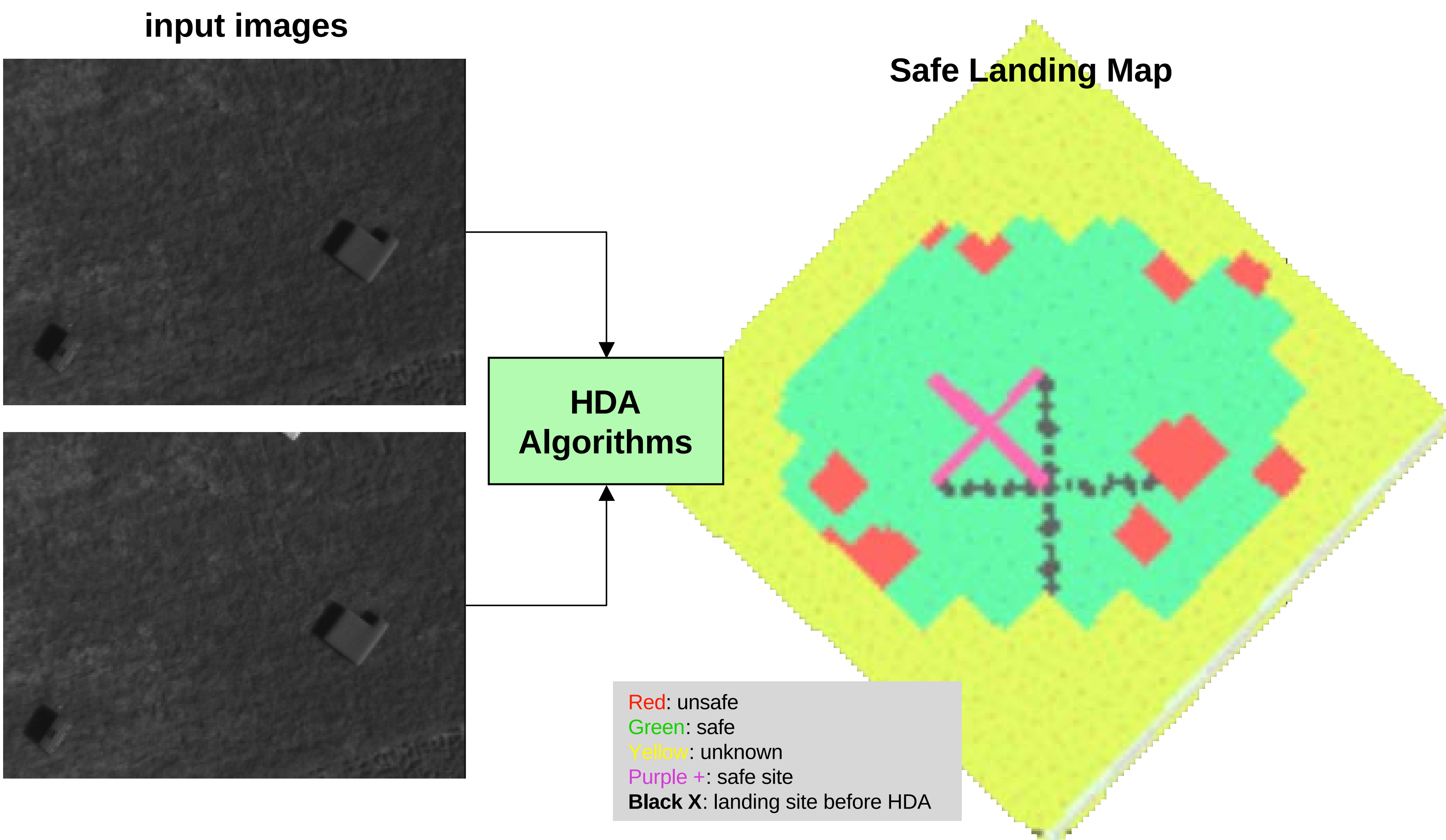


Autonomous Landing in Hazardous Terrain

Helicopter Flight 23-Nov-03

Autonomous Landing in Hazardous Terrain
Flight Data 23-Nov-03

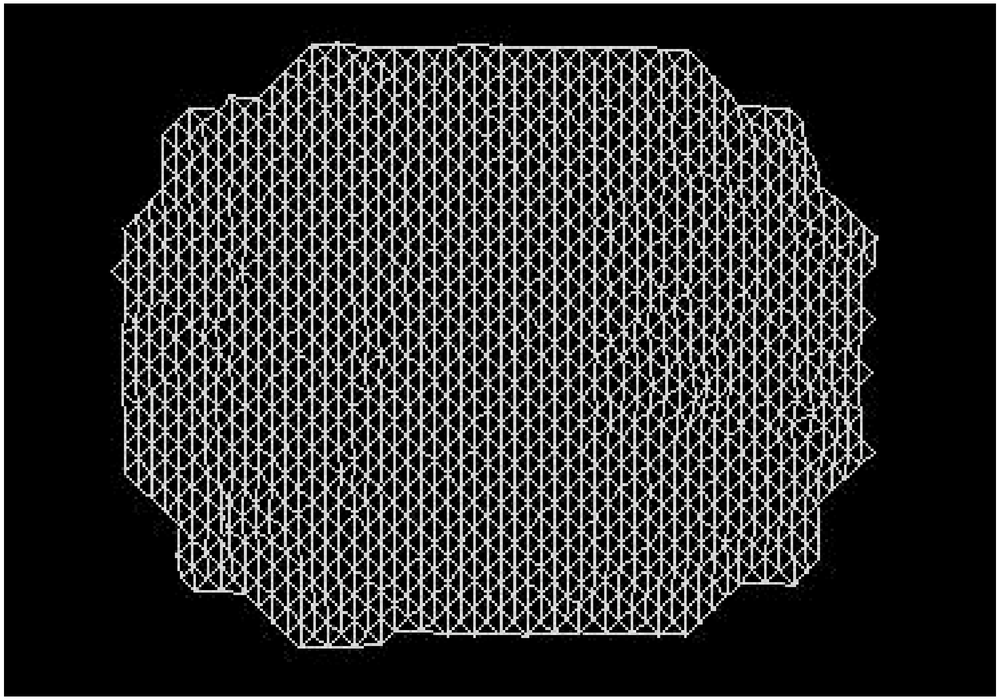
Mars Exploration Rover



Autonomous Landing in Hazardous Terrain

Terrain and Safe Landing Maps 23-Nov-03

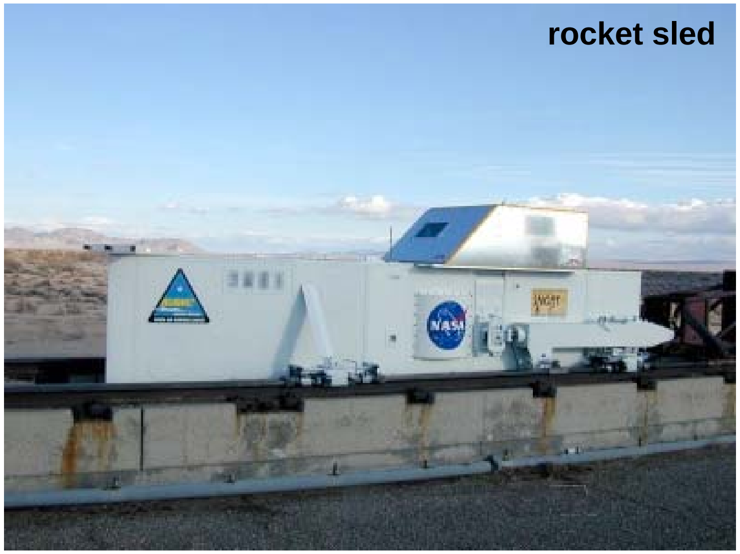
Mars Exploration Rover

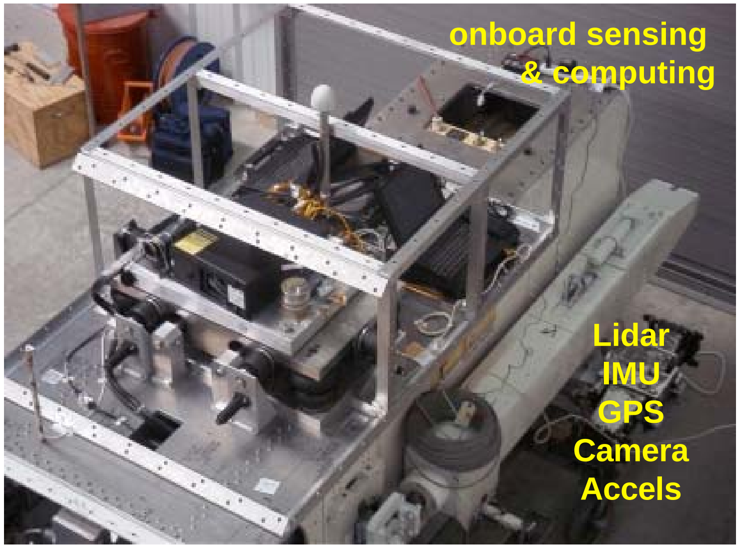


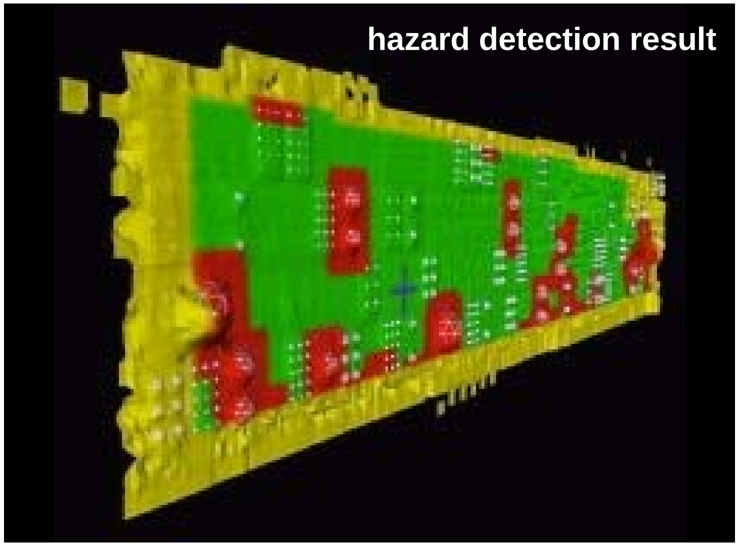
Red: unsafe
Green: safe
Yellow: unknown
Purple +: safe site
Black X: landing site before HDA

Lidar Hazard Detection Field Testing

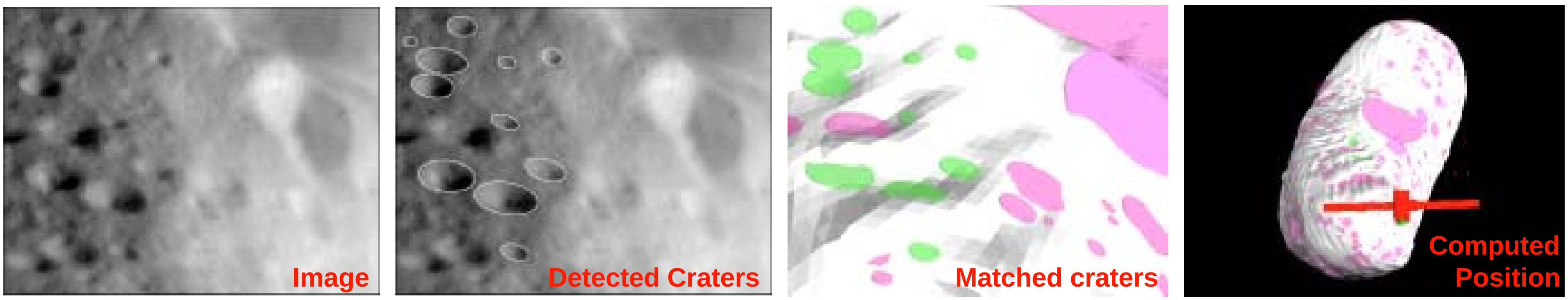
Mars Exploration Rover

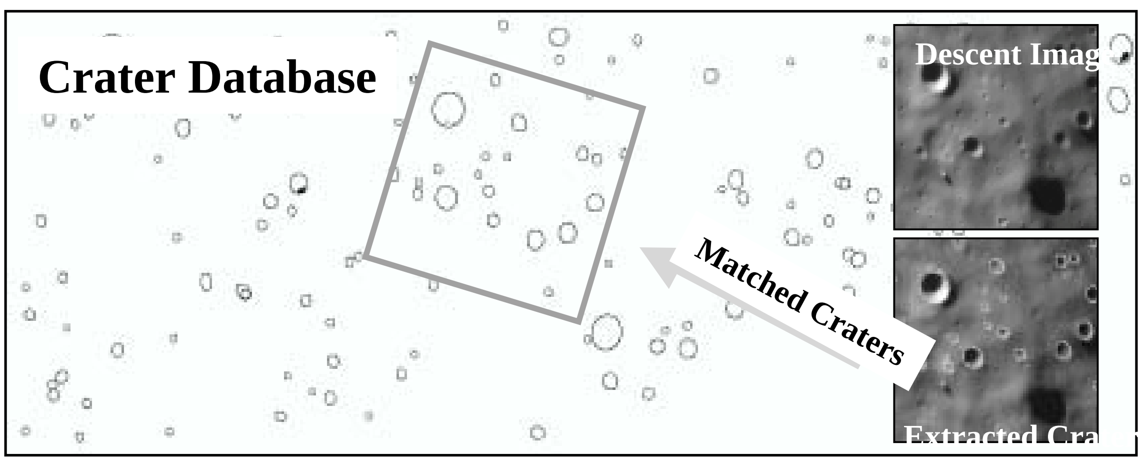


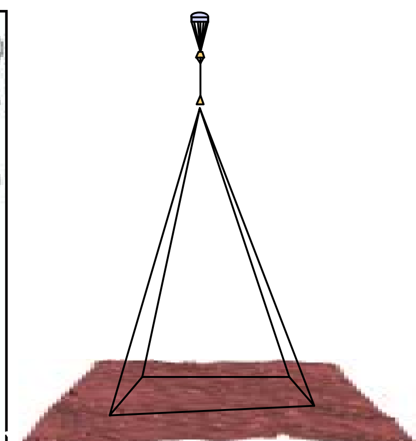




Crater Identification for Pin-Point Landing





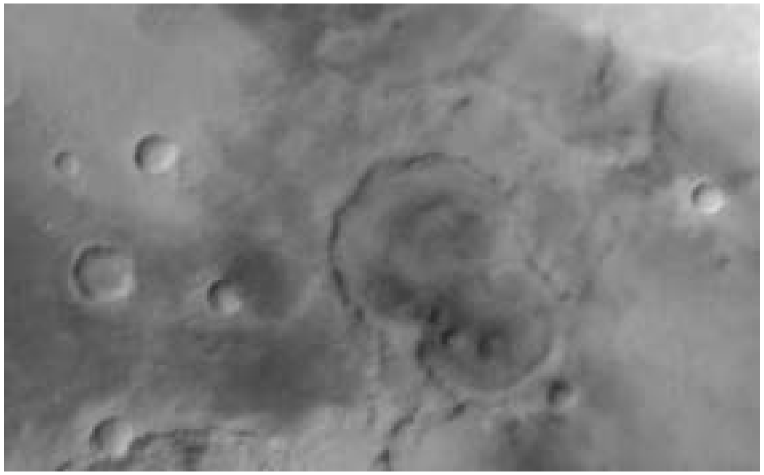


Thermal Imaging for Autonomous Night Landing

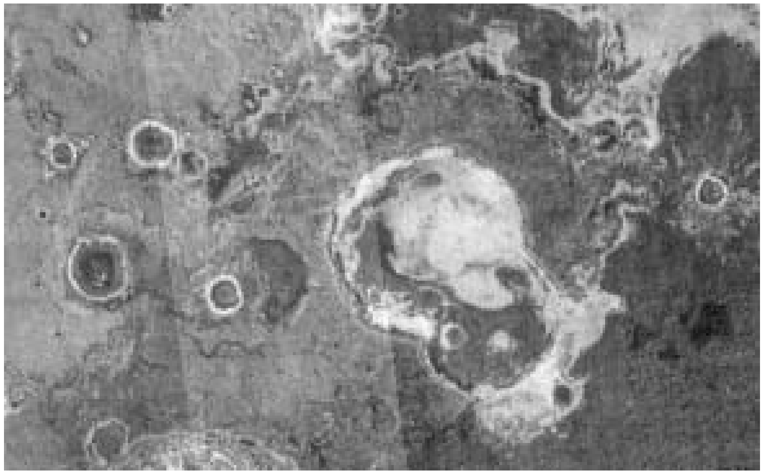
Mars Exploration Rover

Comparison of Visible Imaging to Nighttime Thermal IR

MOC WA Visible Image



THEMIS Nighttime Thermal IR Mosaic

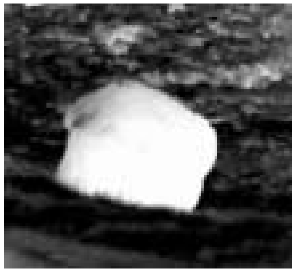


Thermal IR Sensors

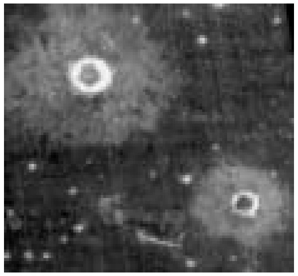
Commercial microbolometerB

JPL QWIP

Terrain Hazards in Thermal IR



rock



craters

Jupiter Icy Moons Landmark Identification for Orbit Determination