On Target to Mars

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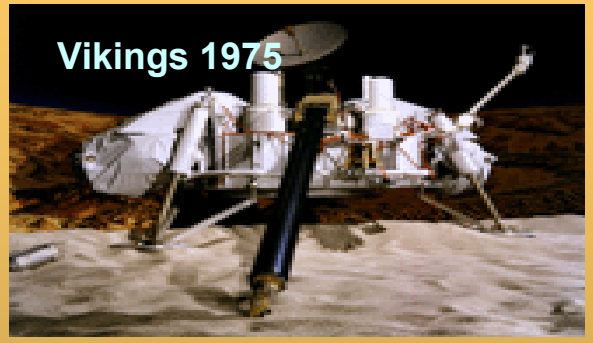
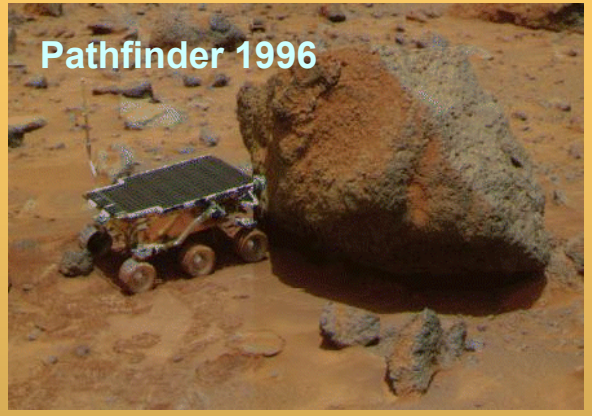
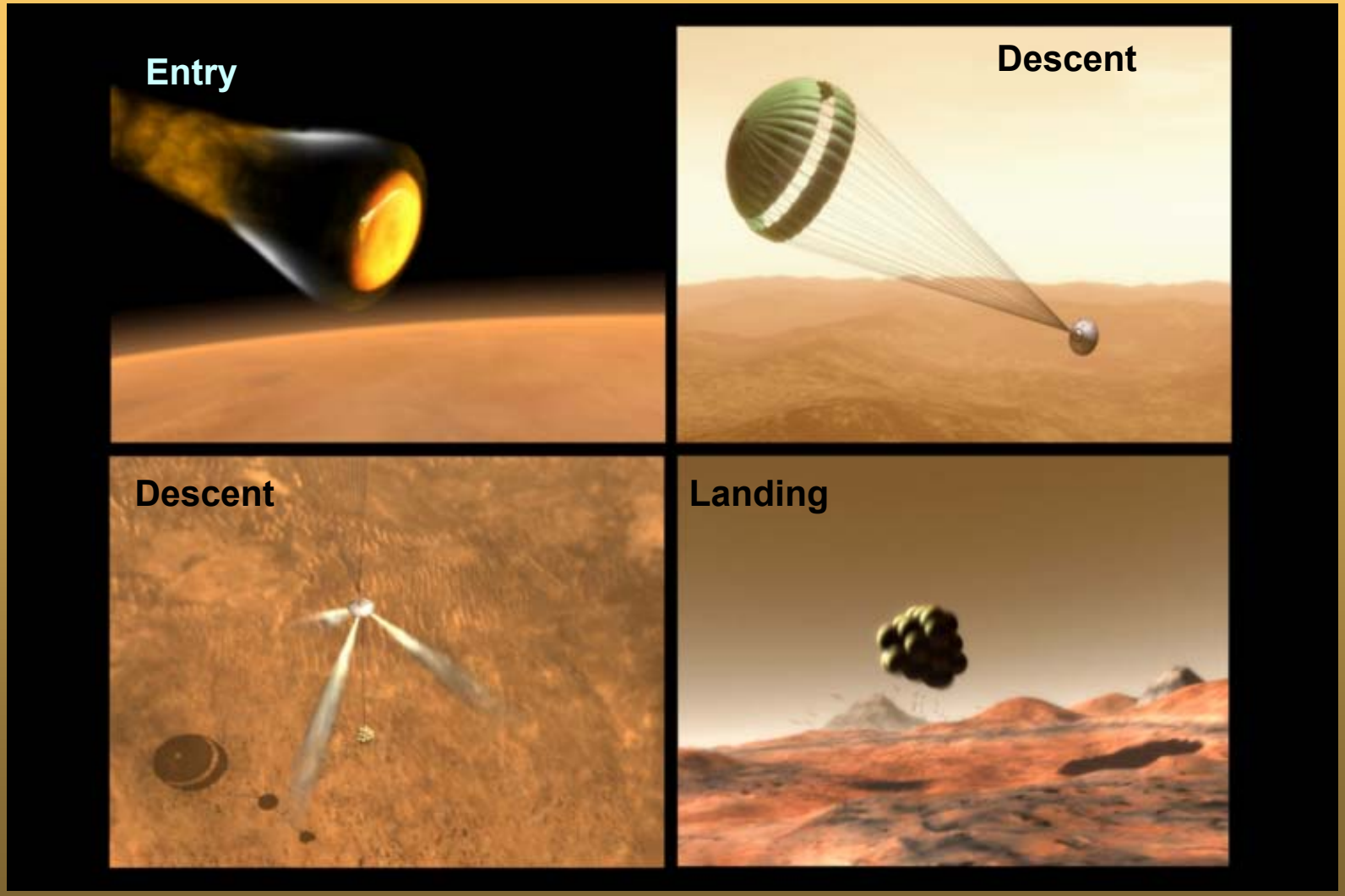
Mars Surface Exploration Past and Current Missions

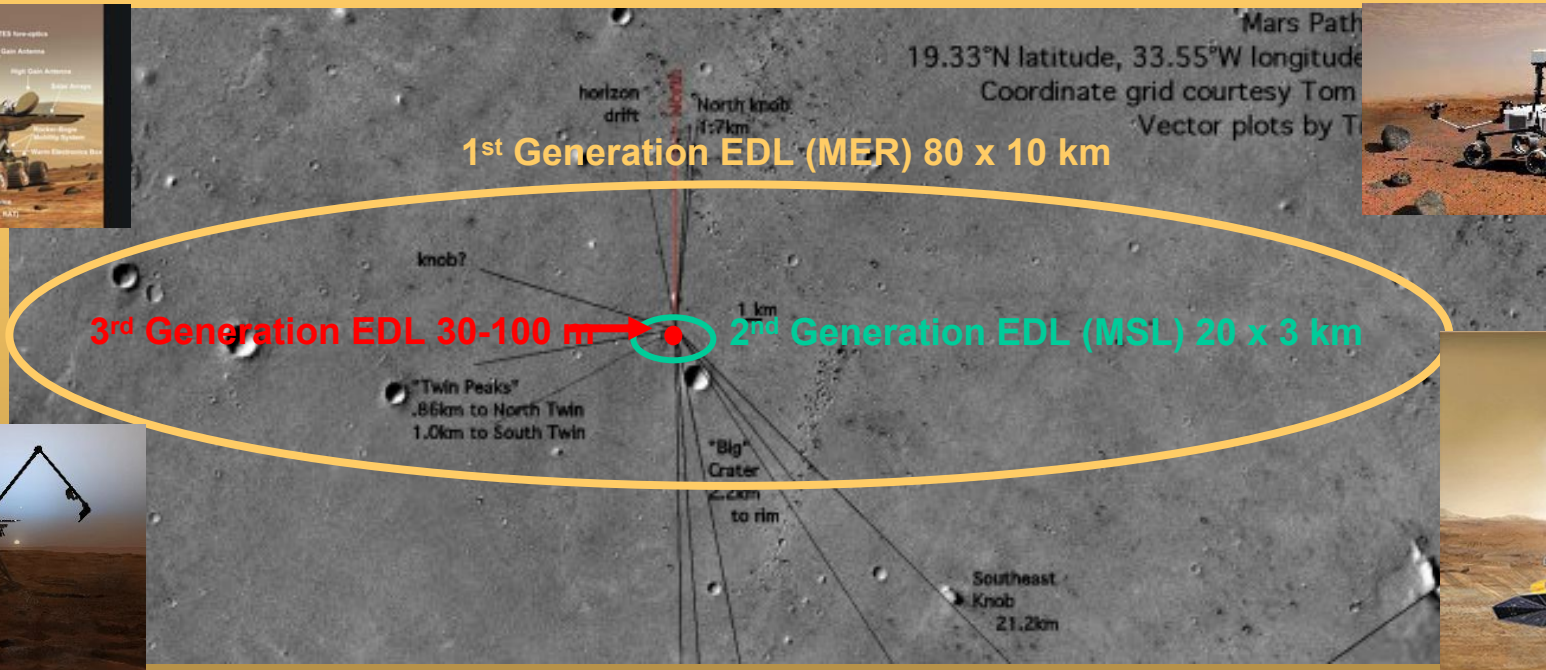




Spacecraft Entry, Descent and Landing (EDL) Scenario

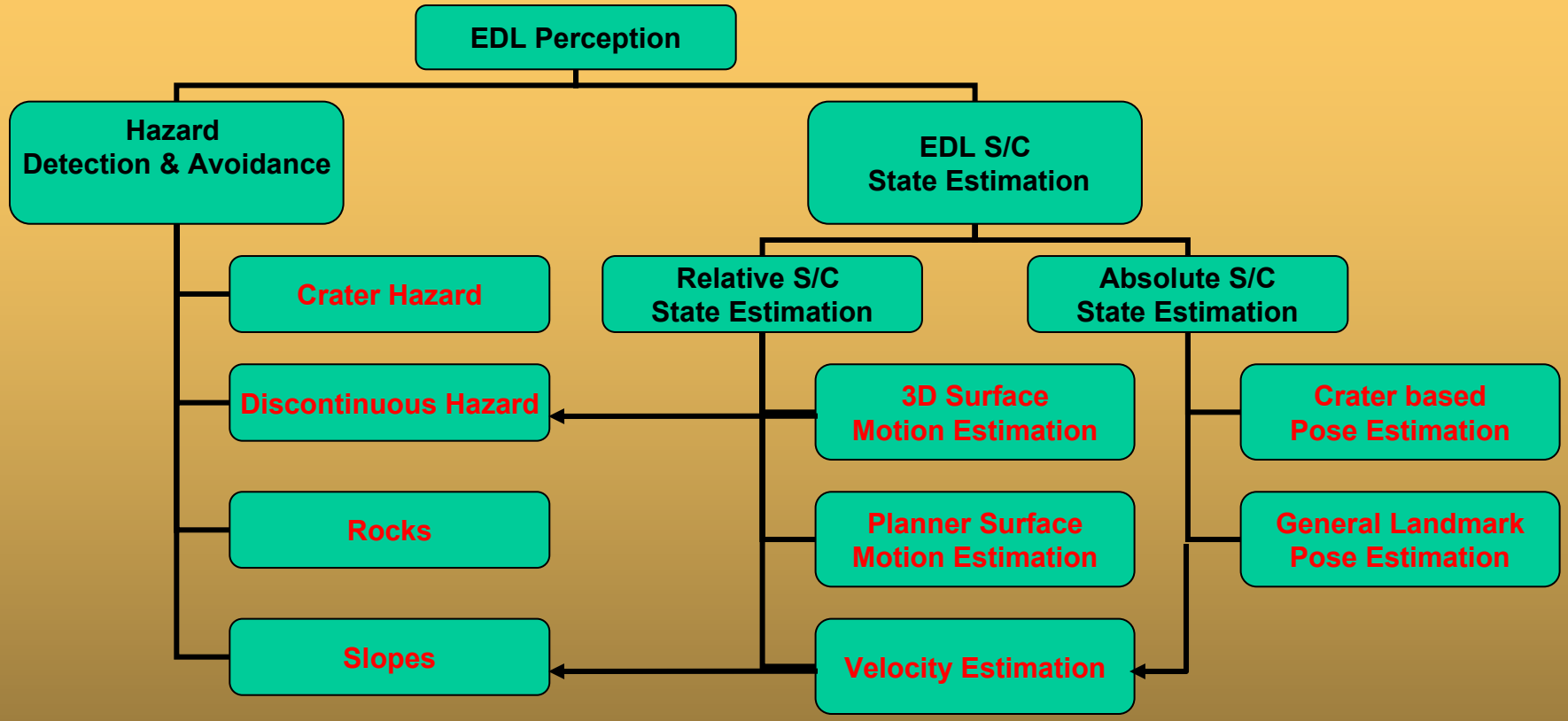


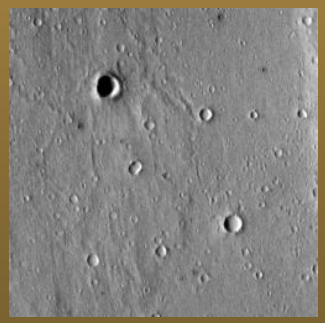
Targeting Errors



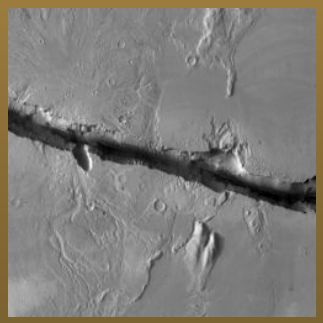
	Time	Accuracy	Key Technologies	Missions
1st Generation	1975-2007	100-300 km	Ballistic entry Hazard tolerance	Viking, MPF, MER, Phoenix
2nd Generation	2009	~10 km	Entry guidance Hazard tolerance	Mars Science Lab.
3rd Generation	2020	30-100 m	Entry guidance, error modeling Propulsion system **Real-time localization**	Mar sample return,

The Roles of Perception to Spacecraft Landing

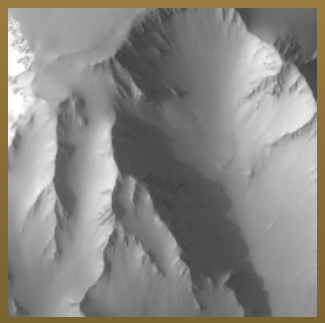




Craters



Discontinuity



Slope

Rocks

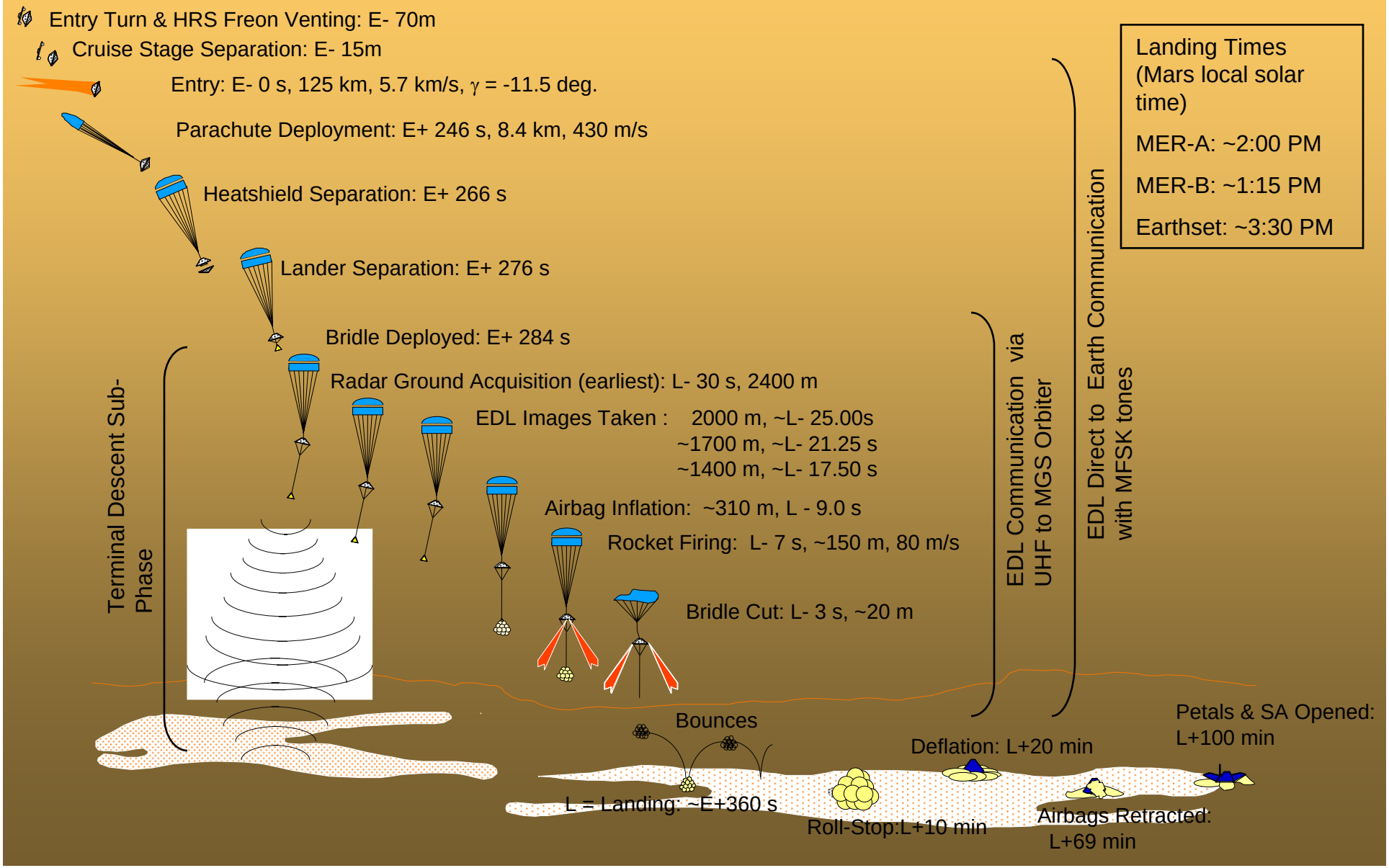
Outline of this Presentation

- Spacecraft relative state estimation
  - Descent Image Motion Estimation System (DIMES) for MER (past)
- Hazard detection and avoidance (HDA) for Spacecraft safe landing (present)
- Spacecraft absolute state estimation for pinpoint landing
  - Real-time landmark (crater & general landmark) based position estimation system for spacecraft pinpoint landing (future)
    - Landmark detection
    - Landmark matching
    - Pose estimation
- Future work and open issues
- Conclusions
- Q&A

Spacecraft Relative State Estimation

MER Descent Image Motion Estimation System
(DIMES)

MER Entry, Descent & Landing Scenario



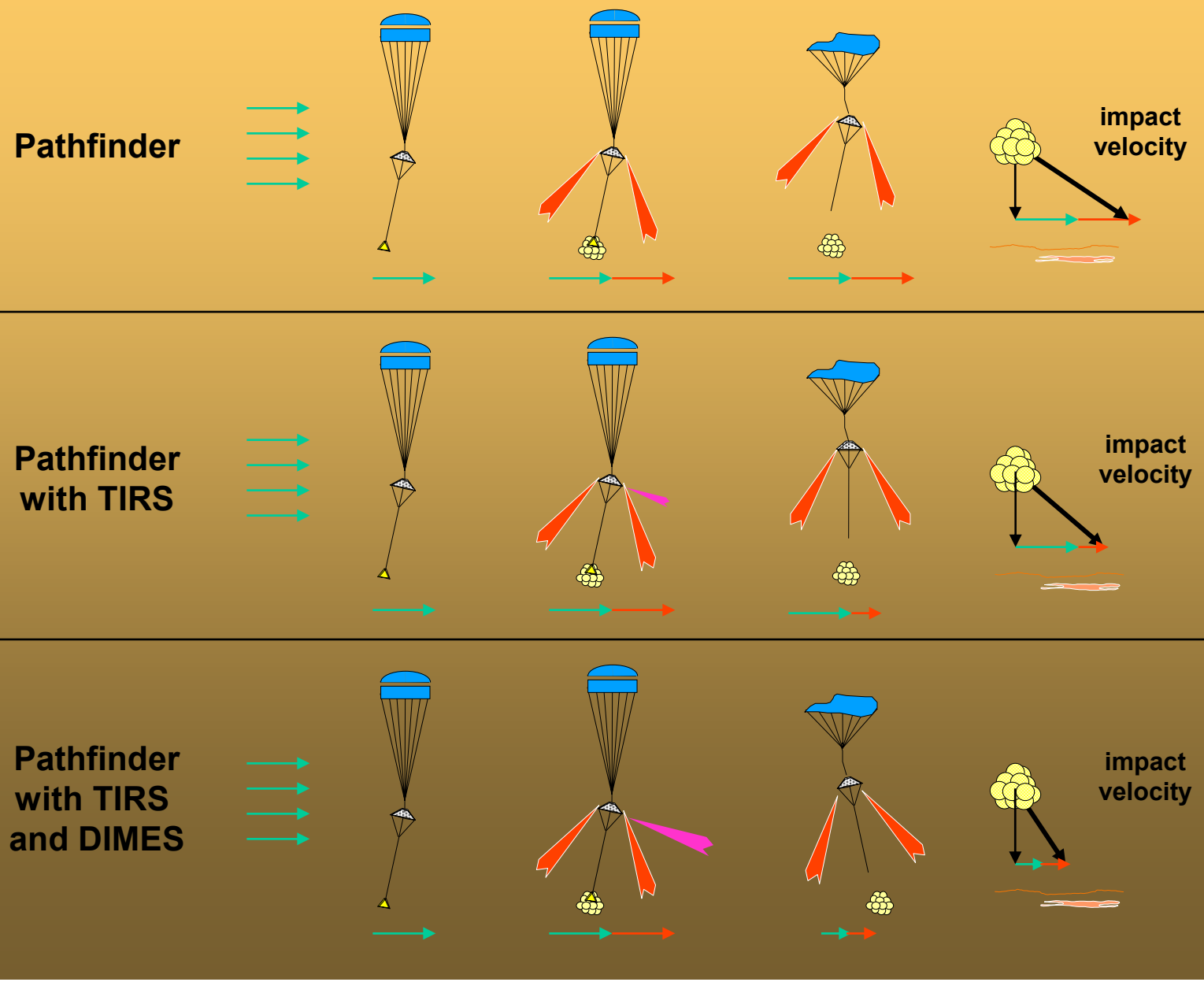
Landing Times (Mars local solar time)

MER-A: ~2:00 PM

MER-B: ~1:15 PM

Earthset: ~3:30 PM

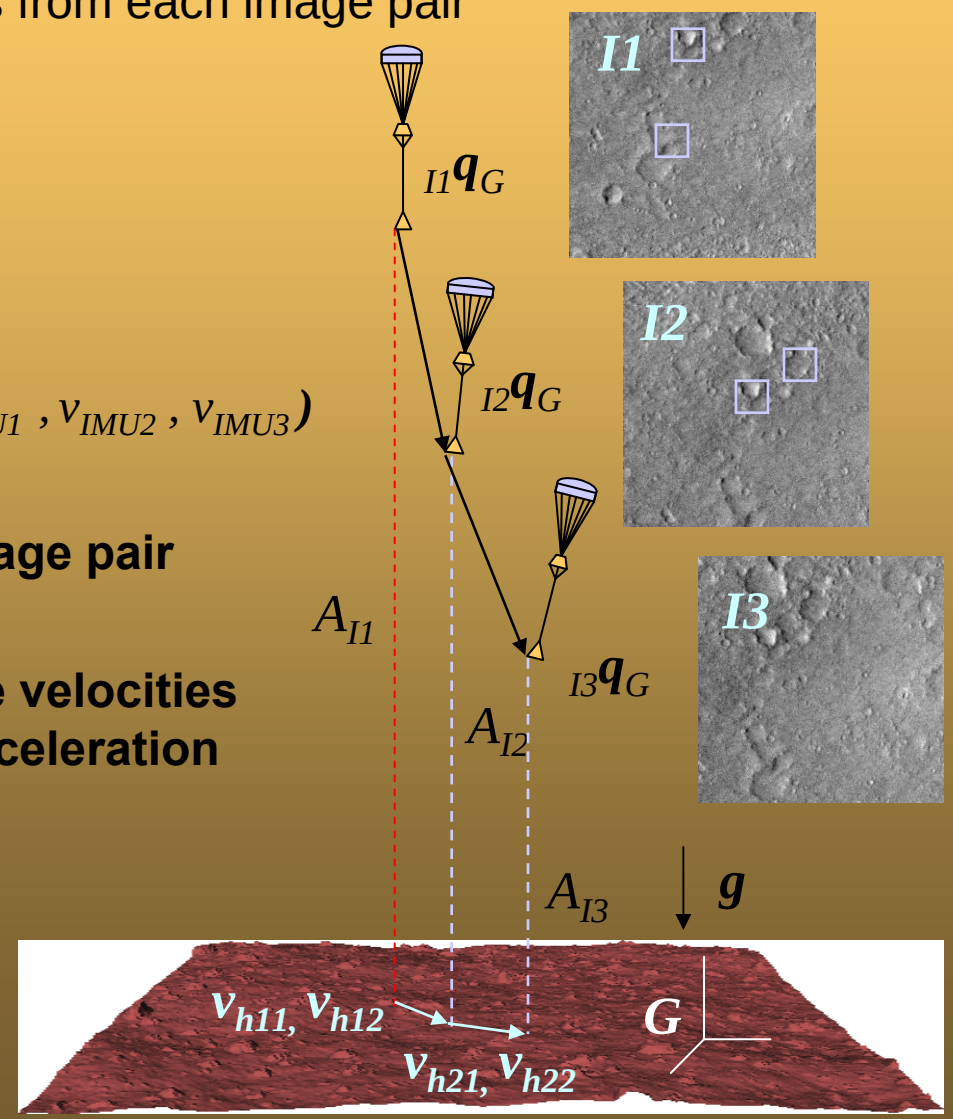
Effect and Mitigation of Winds



DIMES Algorithm

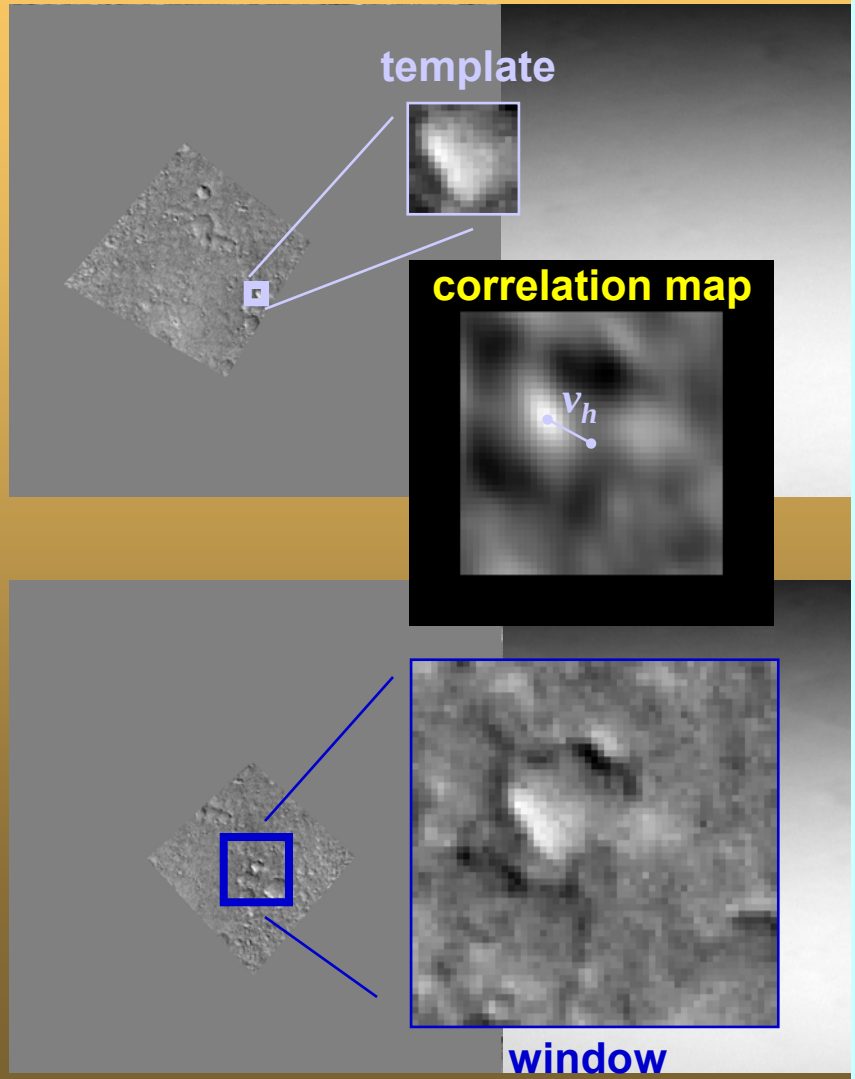
Using three images and two templates from each image pair improves overall DIMES robustness

- 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 Motion Estimation Concept

(not the actual optimized order of operations)



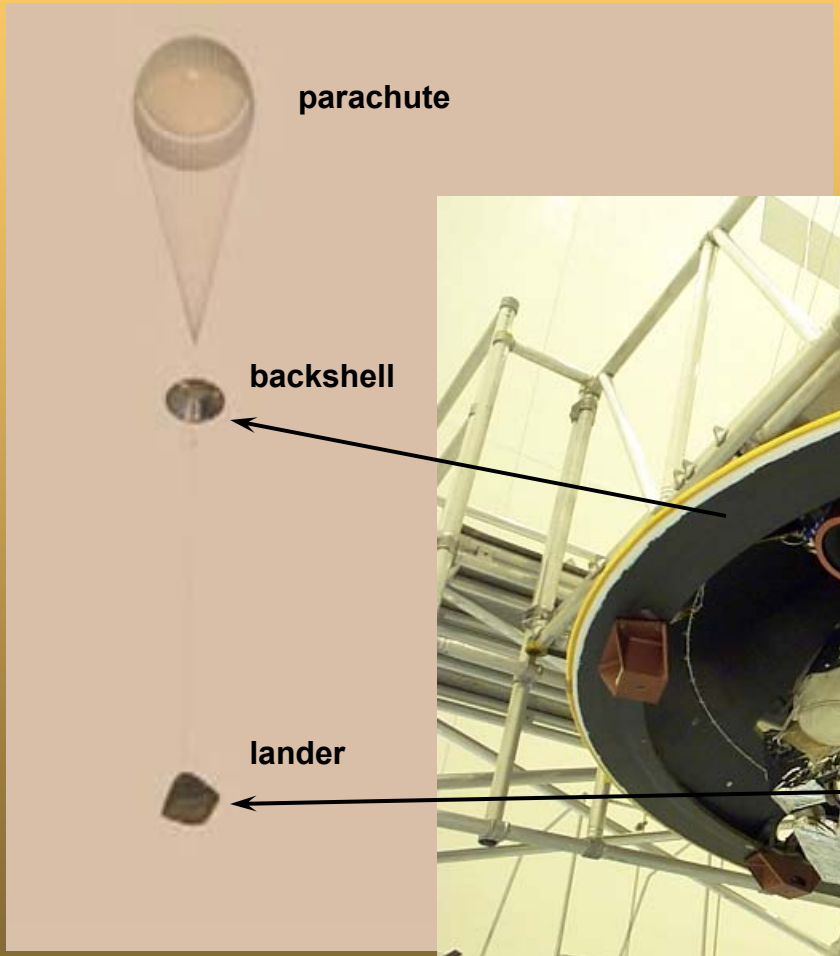
Correct Images

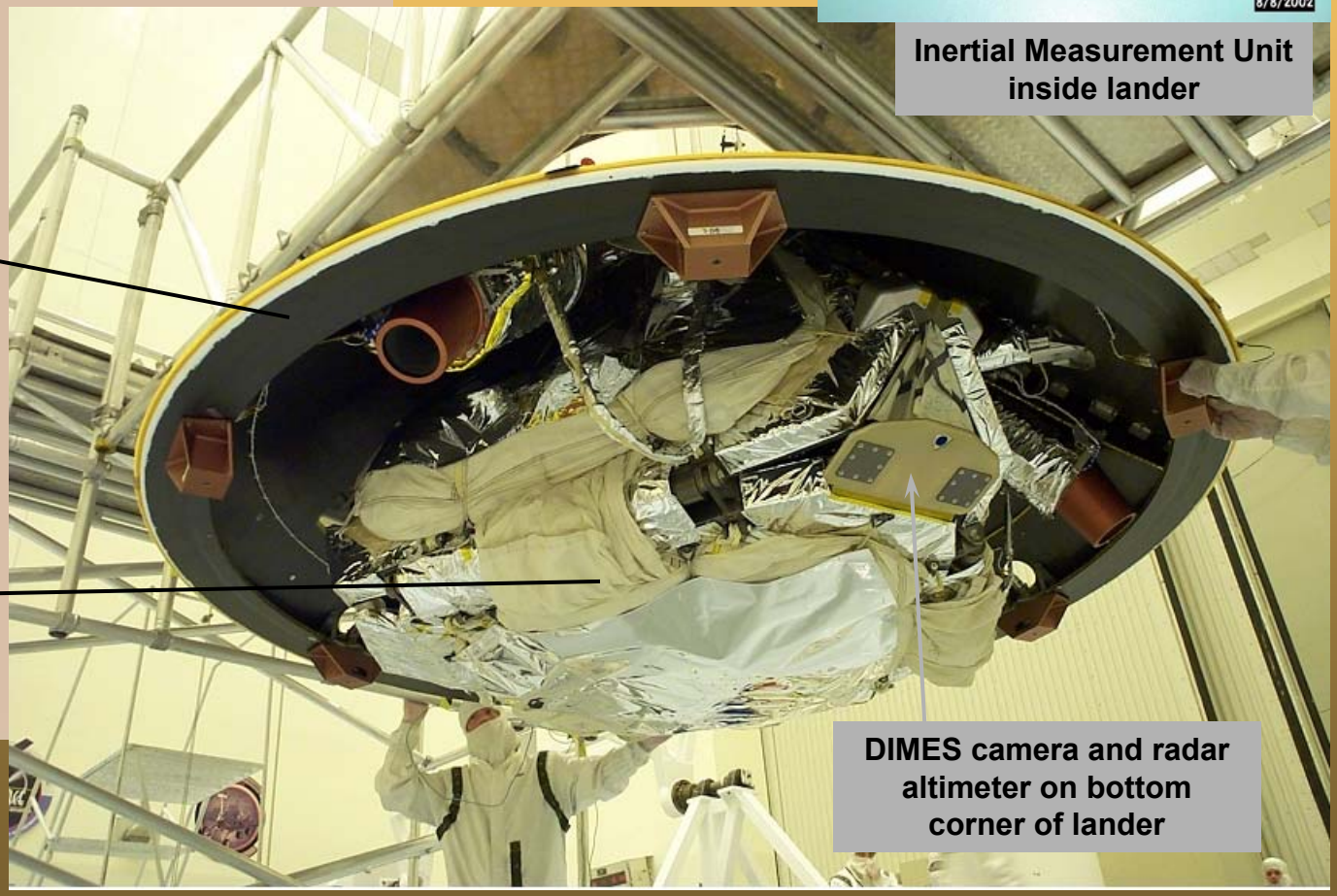
- Bin each image
- Radiometric correction of each image.
- Rectify each image to ground plane using IMU attitude and radar altitude.

Correlate Images

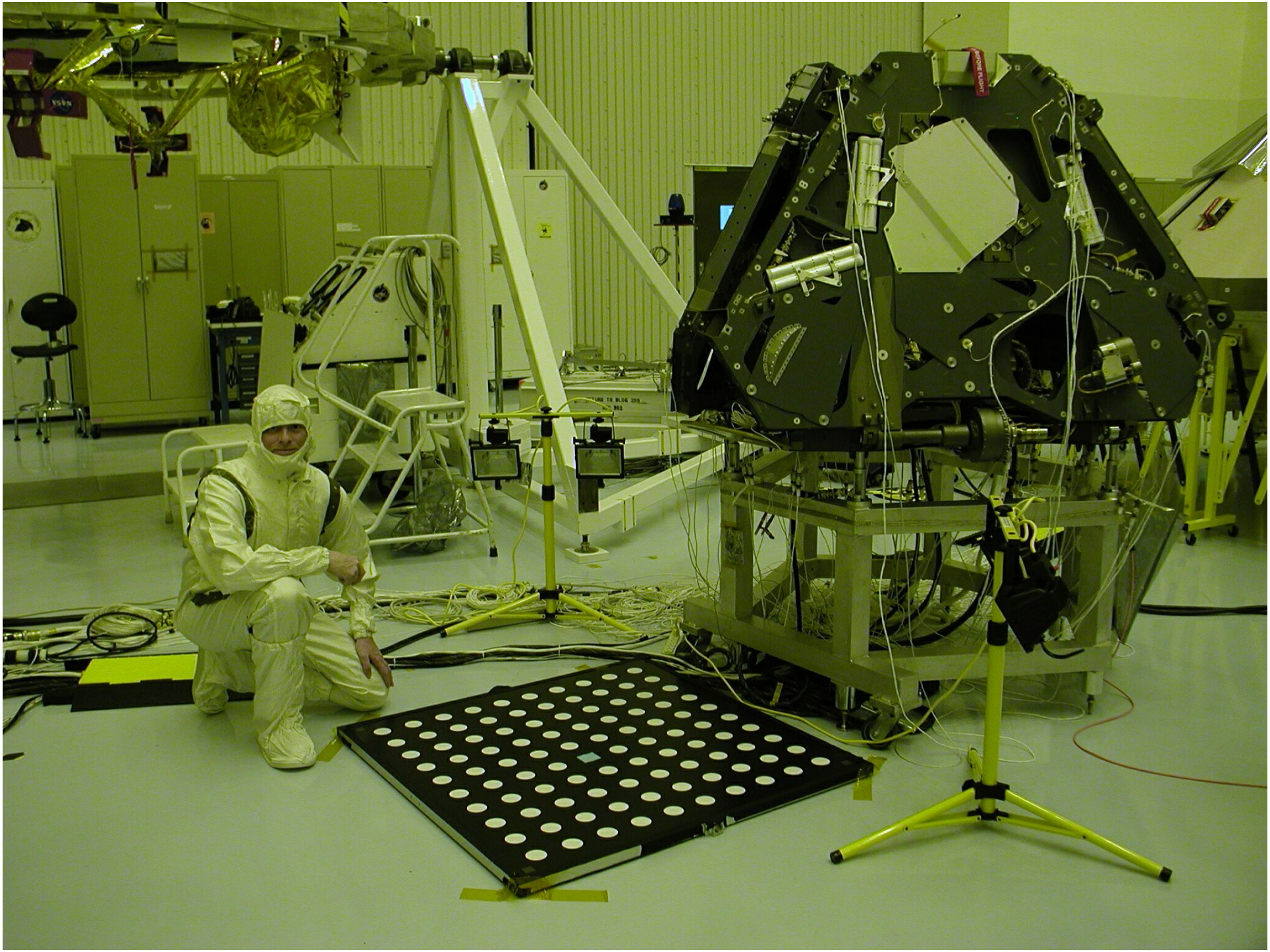
- Apply Interest Operator to first image.
- Select high contrast template in image overlap that avoids zero phase spot.
- Slide template over window in second image and at each pixel compute linear correlation coefficient between template and window DN.
- Find maximum correlation and compute correlation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

DIMES Hardware





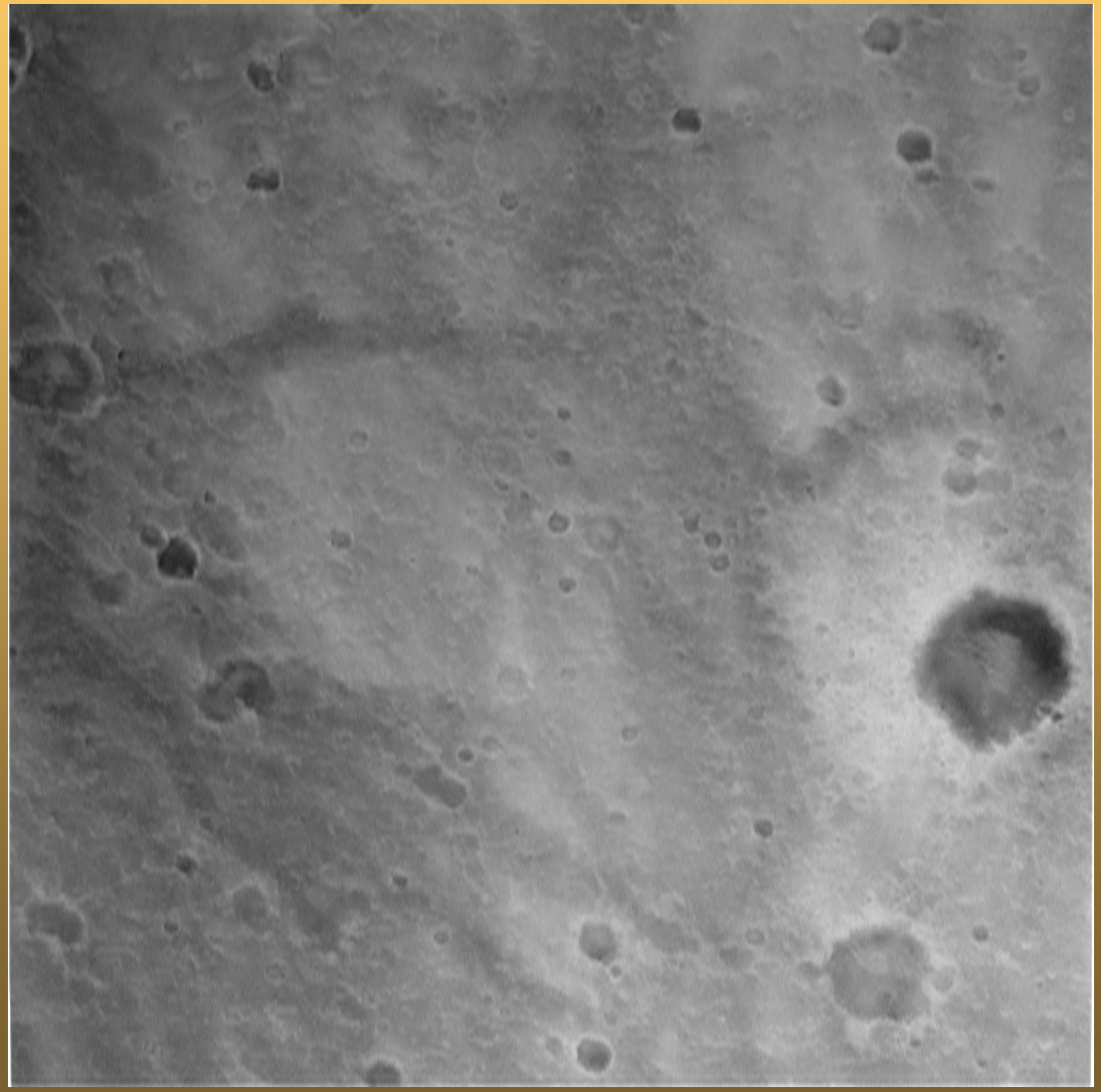
Inertial Measurement Unit inside lander



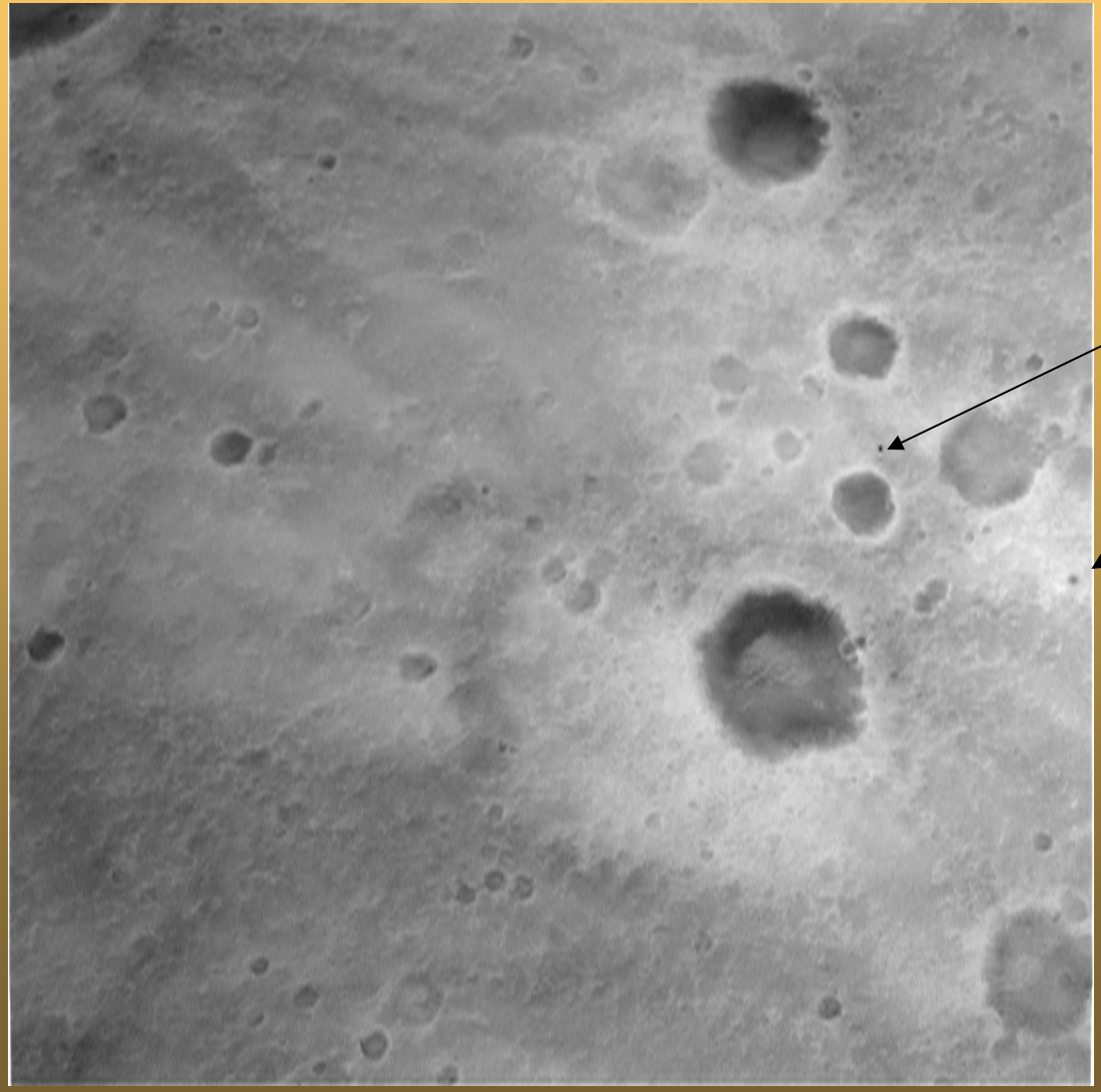
USAF
DELTA

Spirit First Image (1983 m)

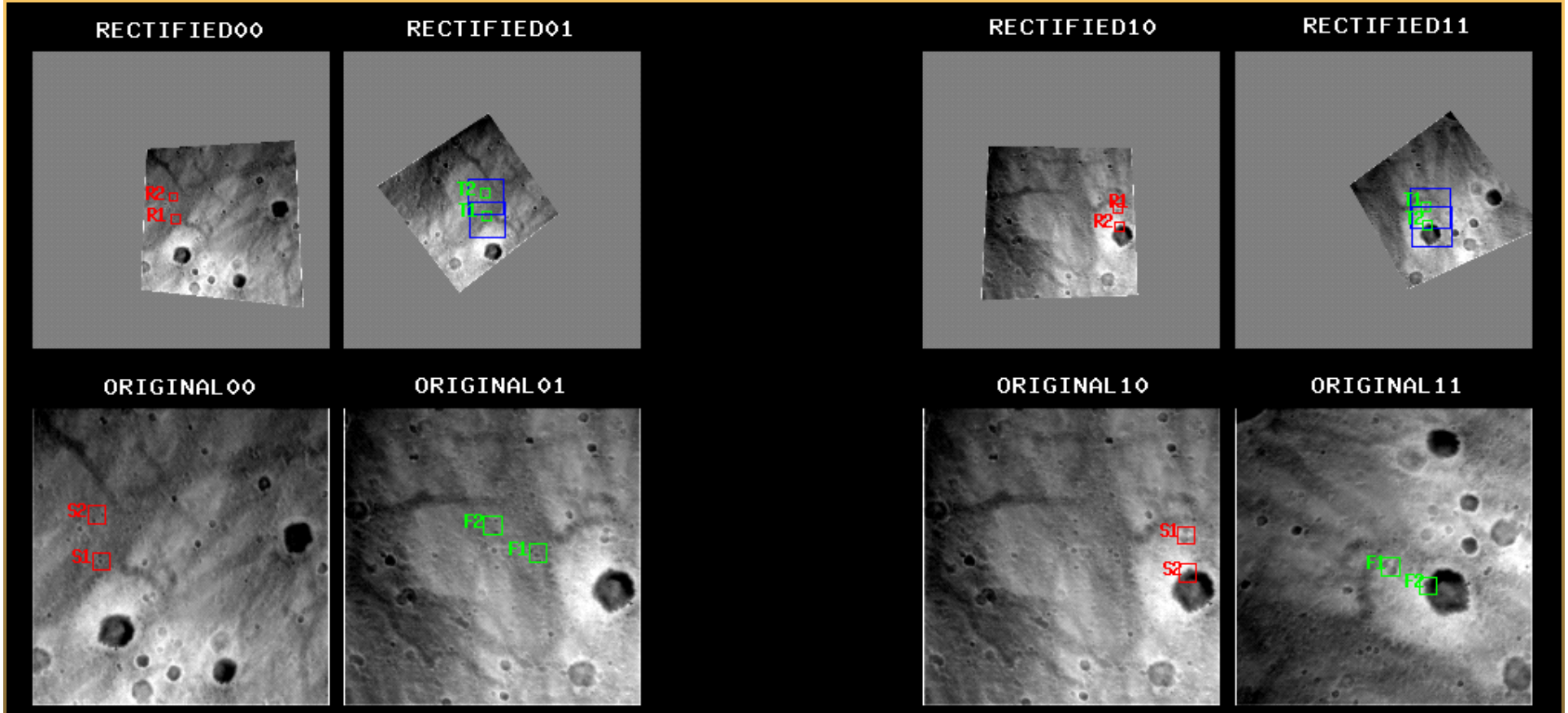
Spirit Second Image (1706 m)



Spirit Third Image (1433 m)



Spirit Velocity Result



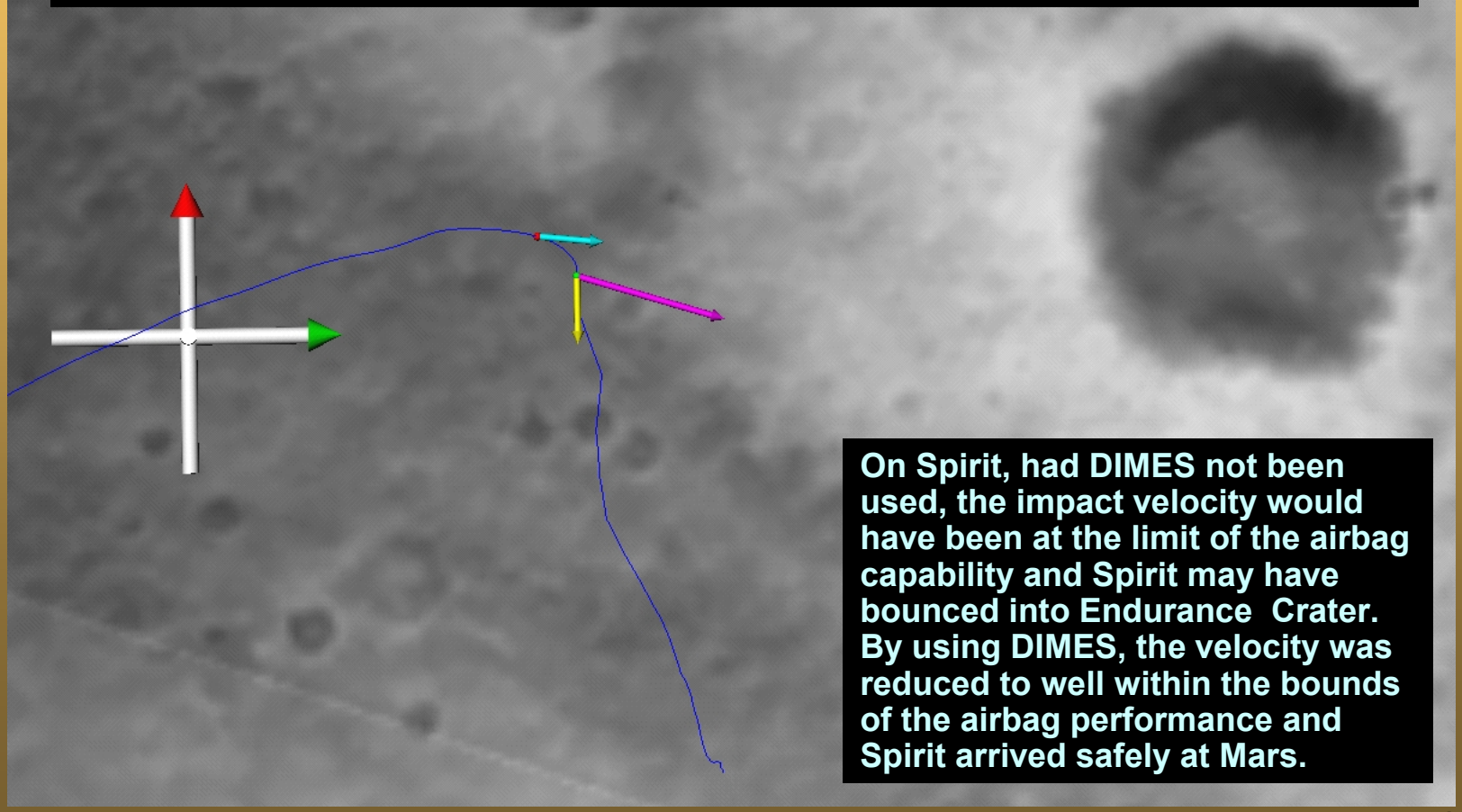
Velocity Correction = 19.1,47.8
DIMES_VALID = 1

feature00: v = 4.2 10.4
feature01: v = 4.1 10.6

feature10: v = 4.1 9.7
feature11: no track

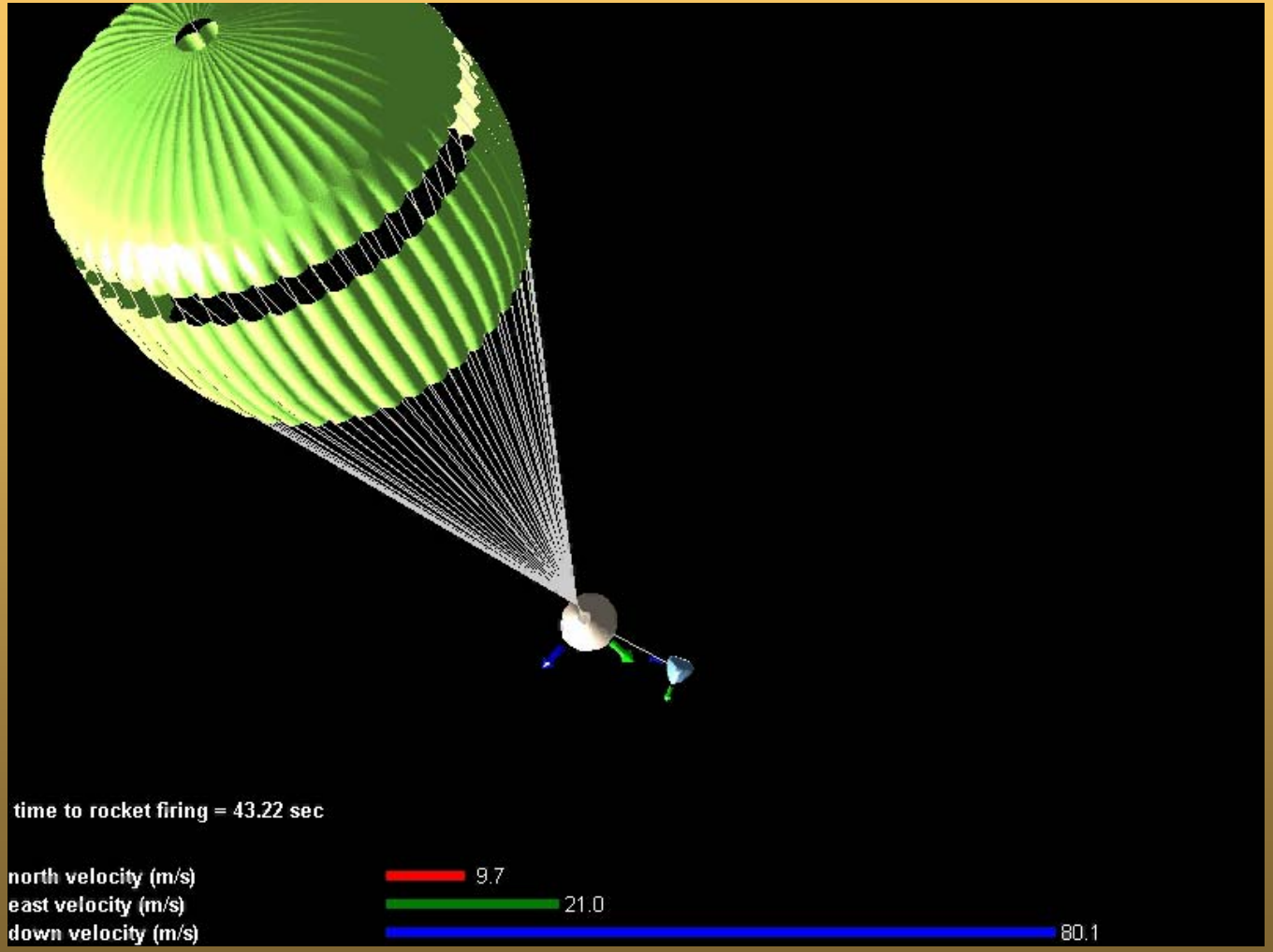
Spirit DIMES/TIRS Vector Diagram

(4.1, 9.7) m/s	steady state computed by DIMES
(-6.8, 22.4) m/s	propagated sum of DIMES and RAD-induced at bridle cut that would have occurred had TIRS not fired
(-11.0, 0) m/s	total at airbag release after RAD and TIRS

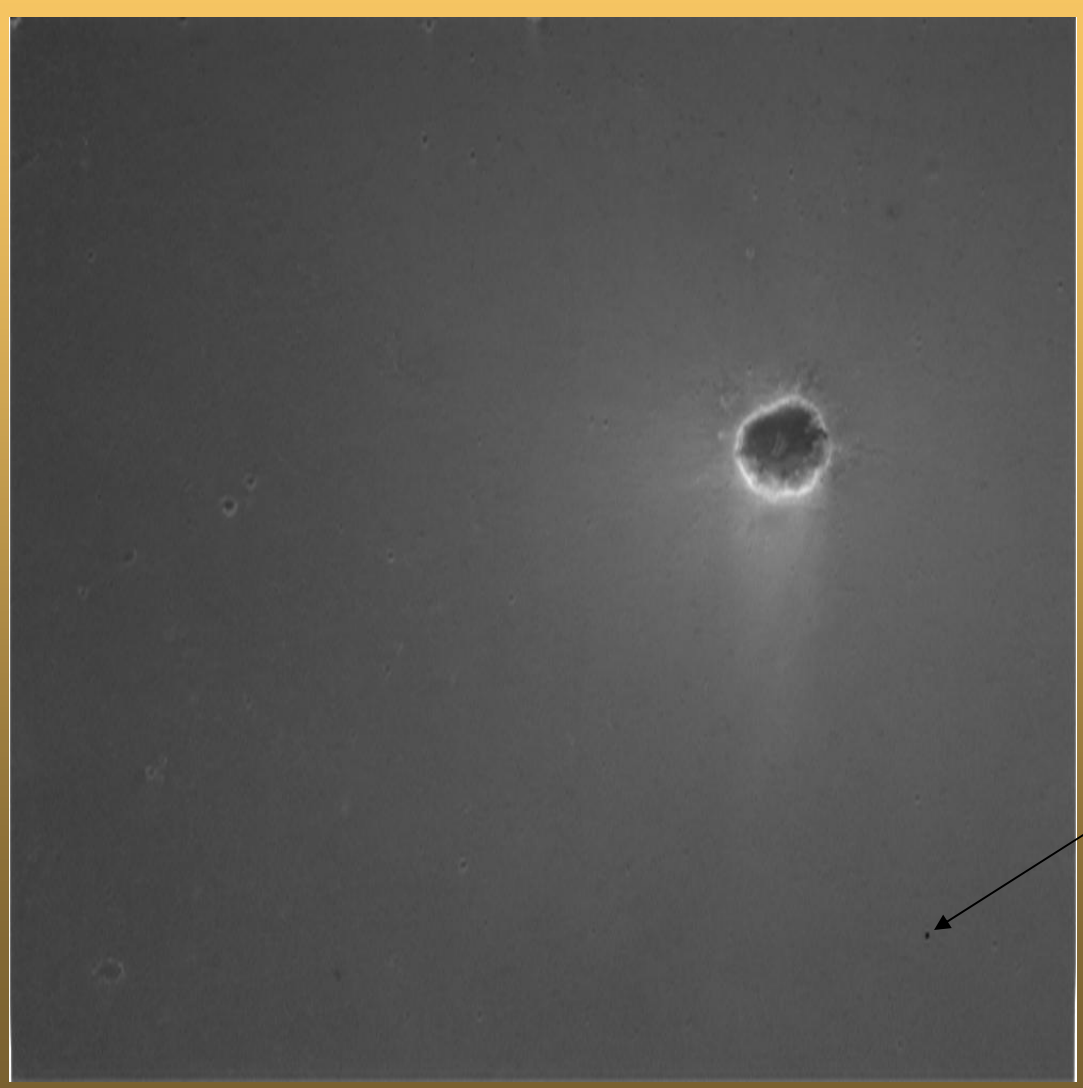


On Spirit, had DIMES not been used, the impact velocity would have been at the limit of the airbag capability and Spirit may have bounced into Endurance Crater. By using DIMES, the velocity was reduced to well within the bounds of the airbag performance and Spirit arrived safely at Mars.

Landing of the Spirit Rover, 3rd, January, 2004

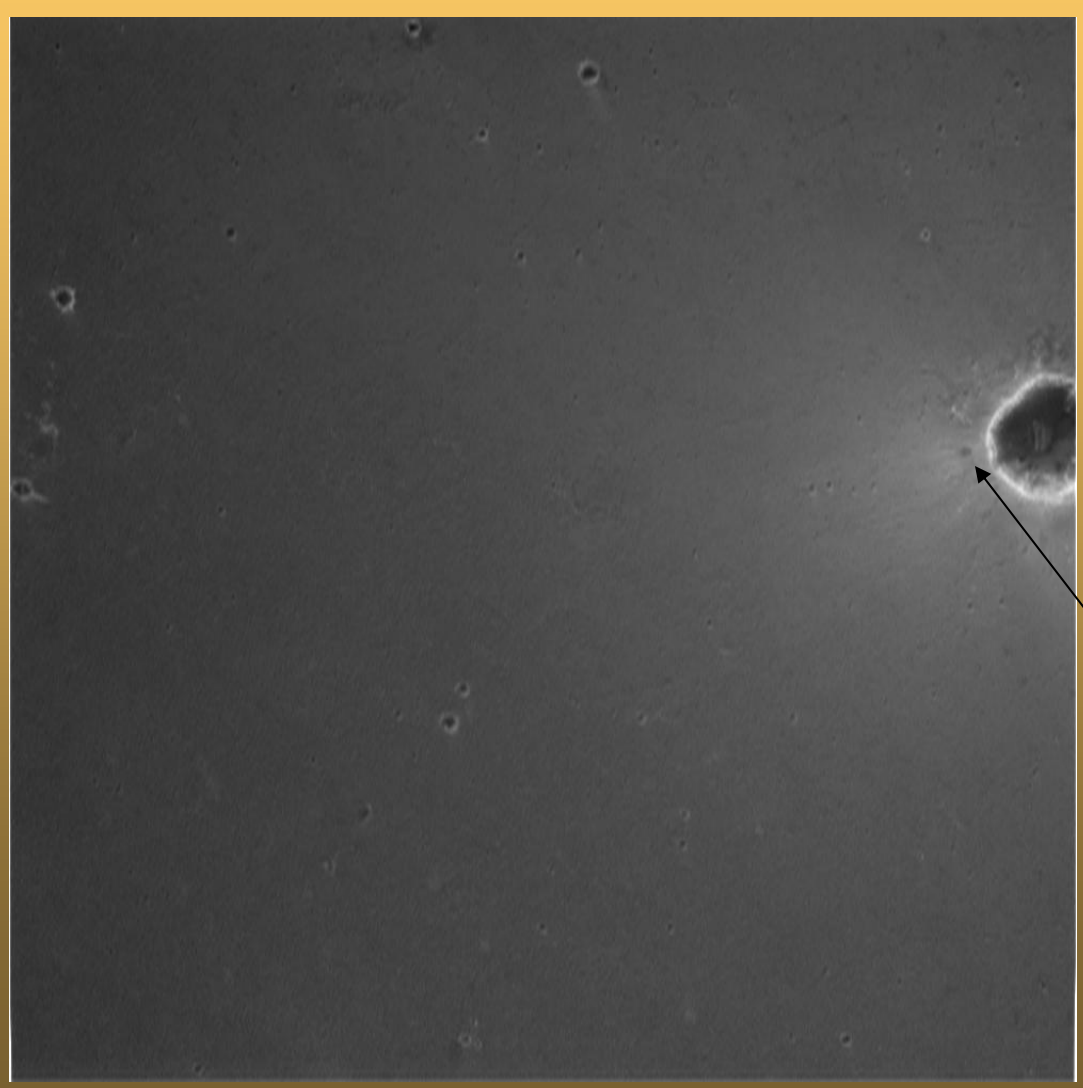


First Opportunity Image (1986 m)



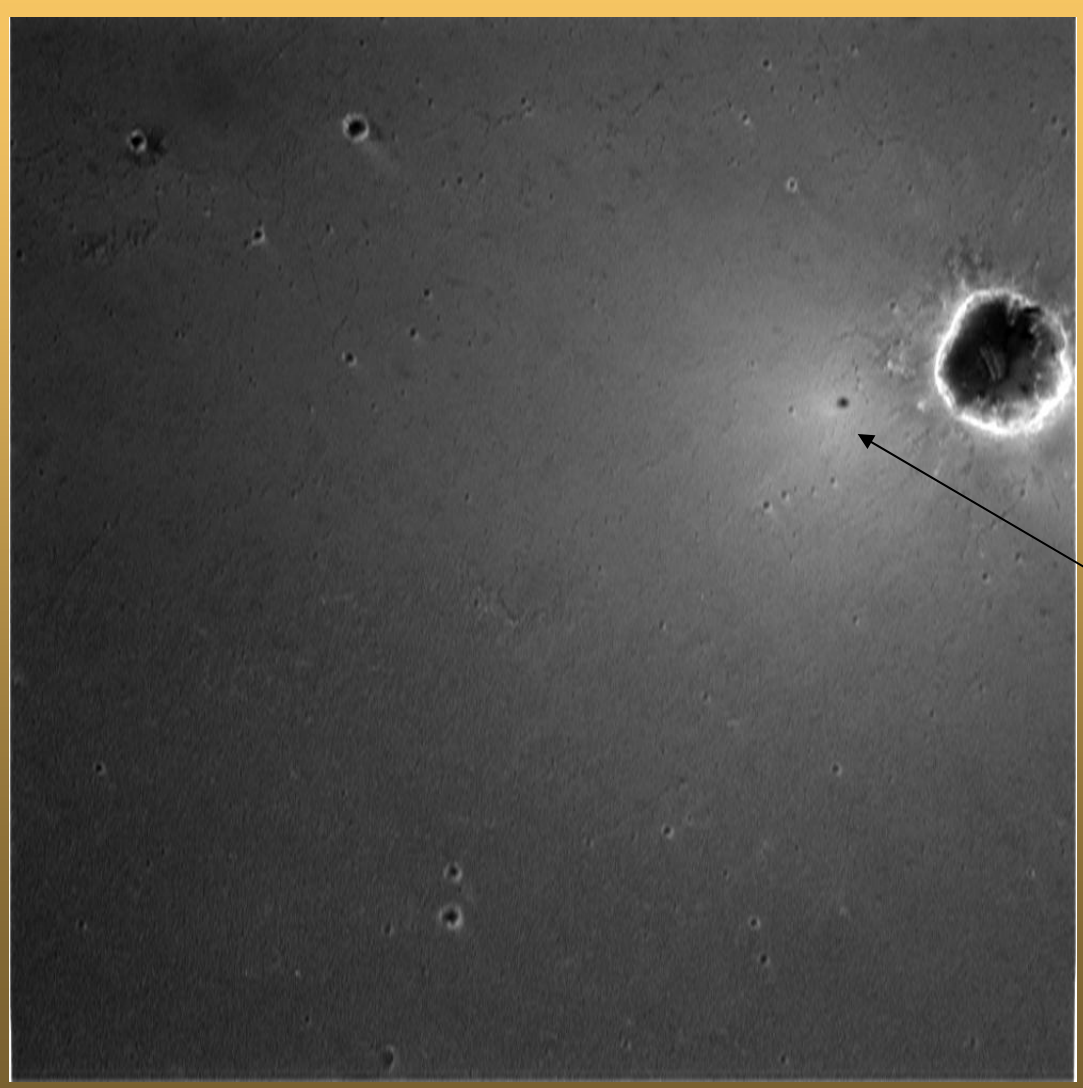
heatshield at
1257 m altitude

Second Opportunity Image (1690 m)



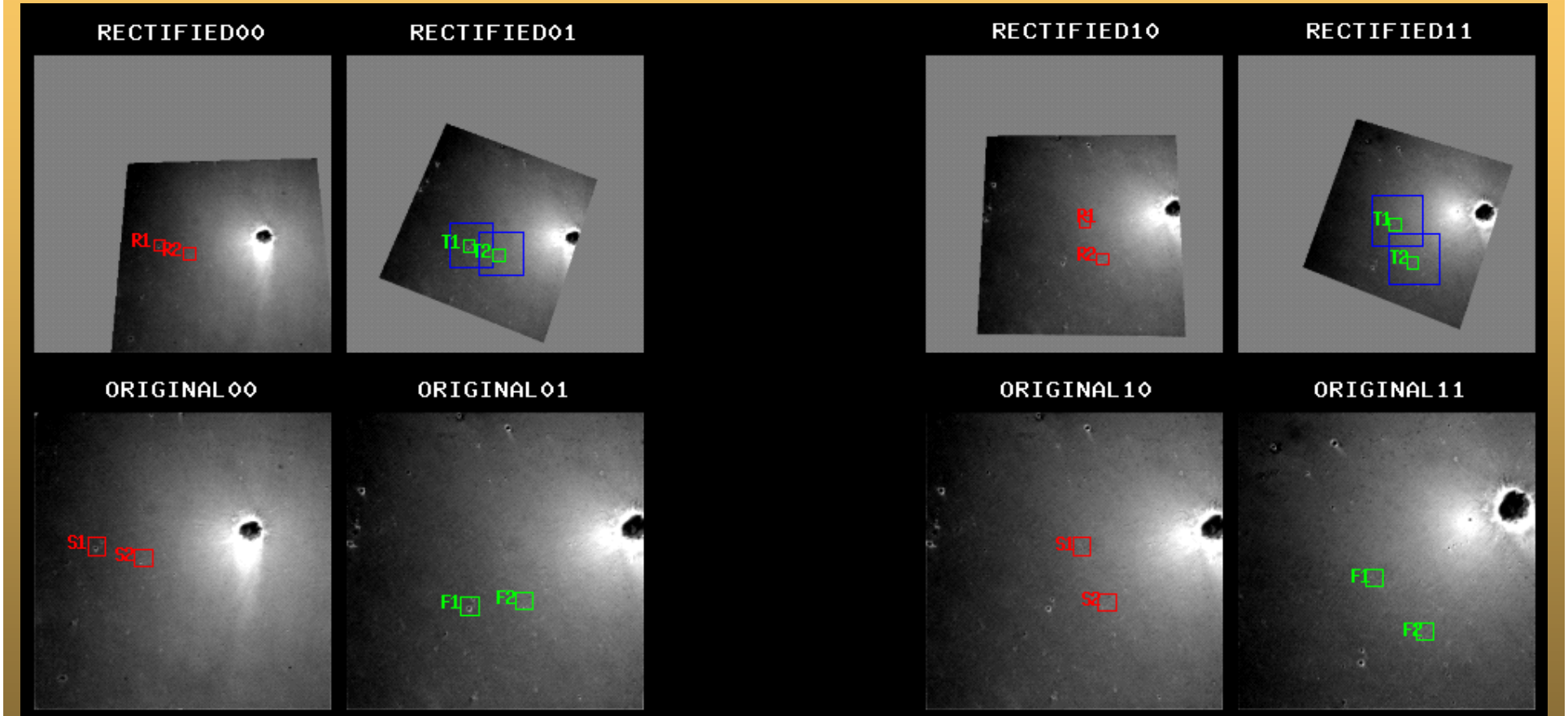
parachute shadow and opposition effect

Third Opportunity Image (1404 m)



parachute shadow and opposition effect

Opportunity Velocity Result



Velocity Correction = 7.3,49.4
DIMES_VALID = 1

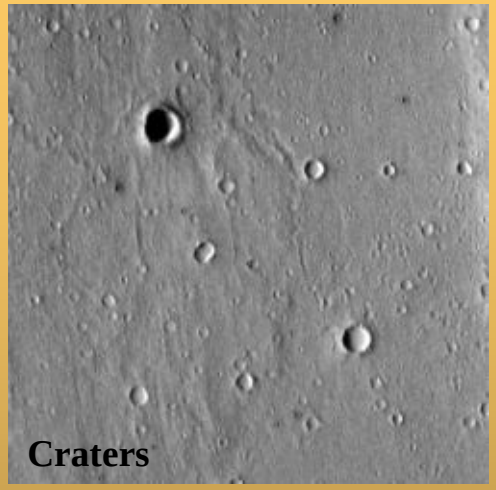
feature00: v = 6.3 1.2
feature01: v = 6.1 1.1

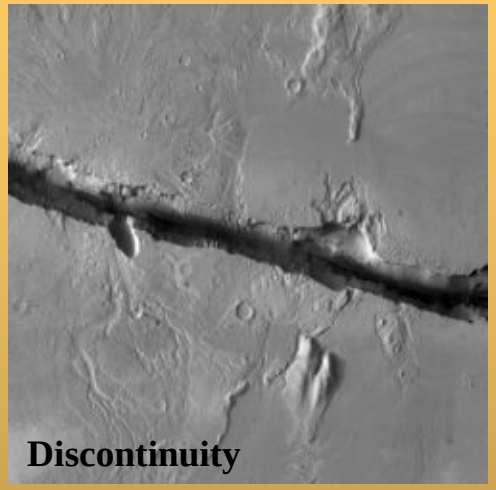
feature10: v = 8.0 -0.3
feature11: no track

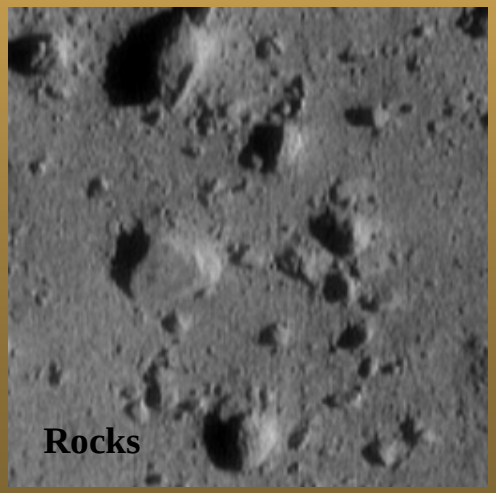
Hazard Detection and Avoidance

Shadow and Stereo Rock Detection

Spacecraft Landing Hazards





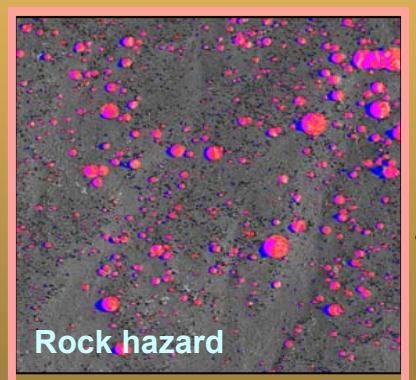


Passive Imaged Hazard Detection Scenario and Technical Approach

Hazard Map from Orbit Image

TRN (Parachute deployment to ~1000 m AGL)

- Landmarks matching and feature tracking tie s/c to local hazard map, which contains large scale hazard such as crater, slopes and discontinuities
- Safe landing region (~100-200m) selection



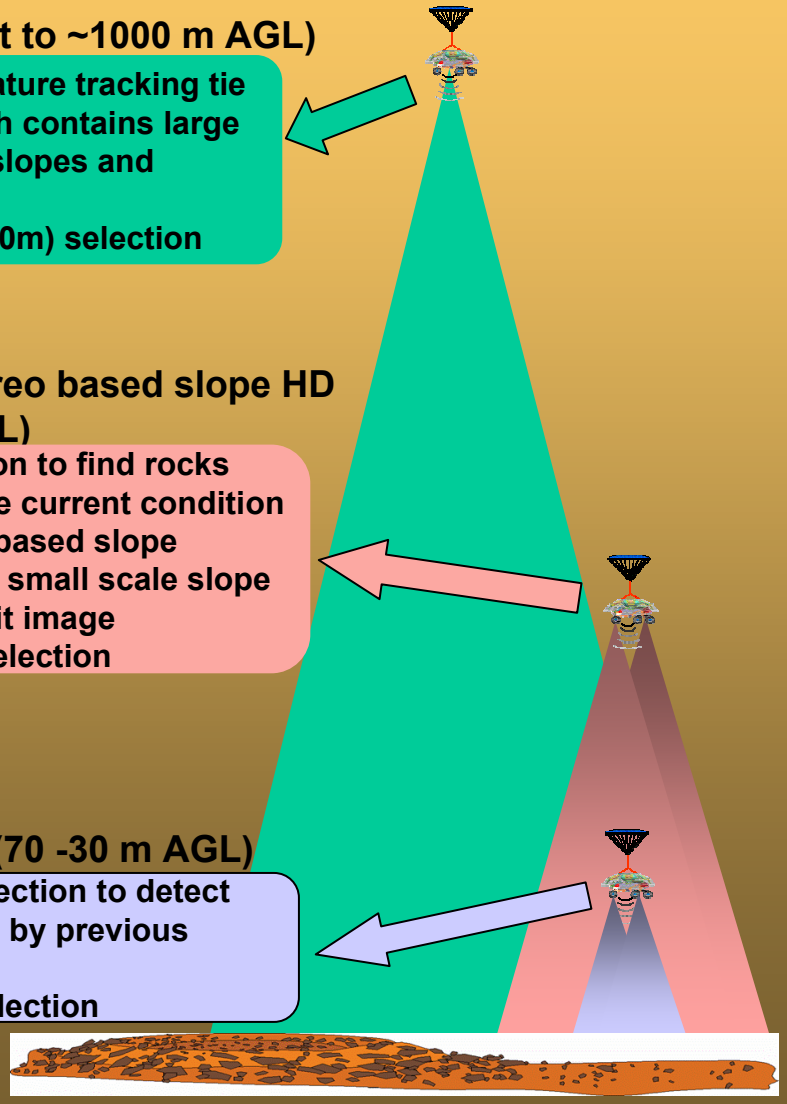
Shadow Based rock HD & stereo based slope HD (1000-70m AGL)

- Shadow based hazard detection to find rocks which cast shadows under the current condition
- Stereo based of homography based slope estimations to determine local small scale slope which are not visible from orbit image
- Safe landing area (~10-20m) selection

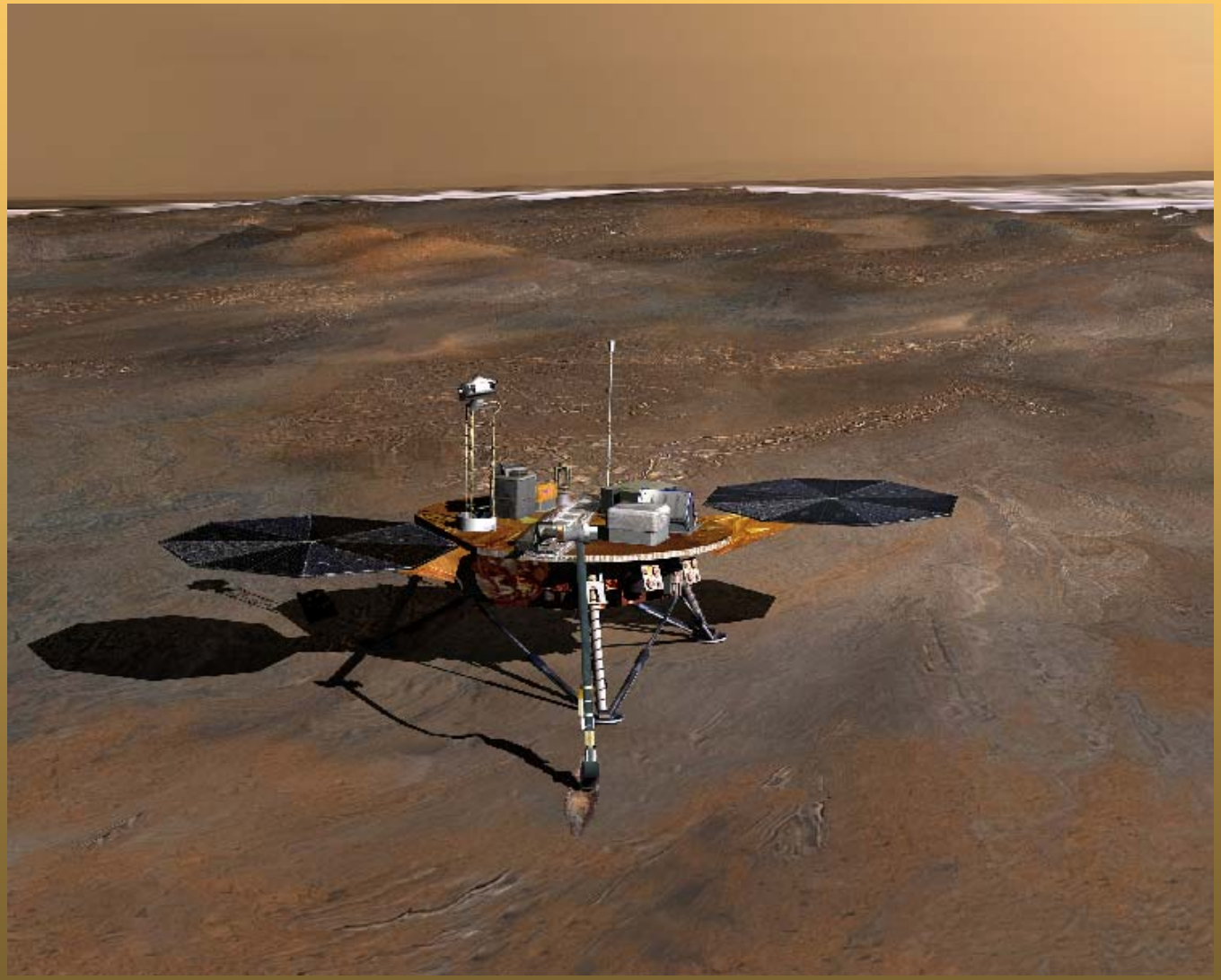
Surface Elevation

Stereo Based Rock HD (70 -30 m AGL)

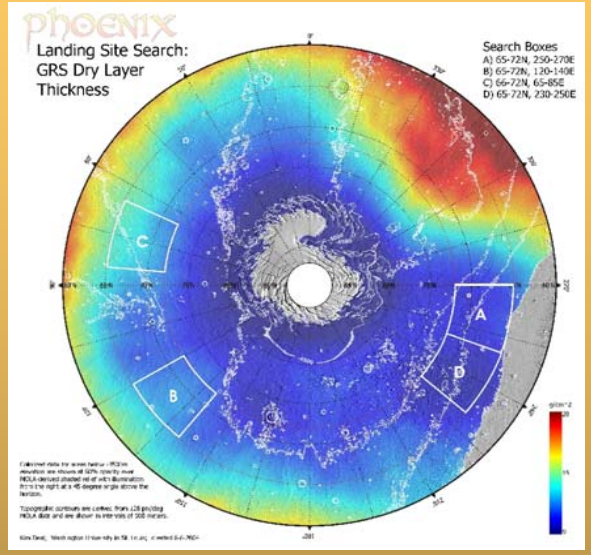
- Stereo based rock hazard detection to detect rocks, which might be missed by previous detection
- Safe landing site (~ 1-10m) selection



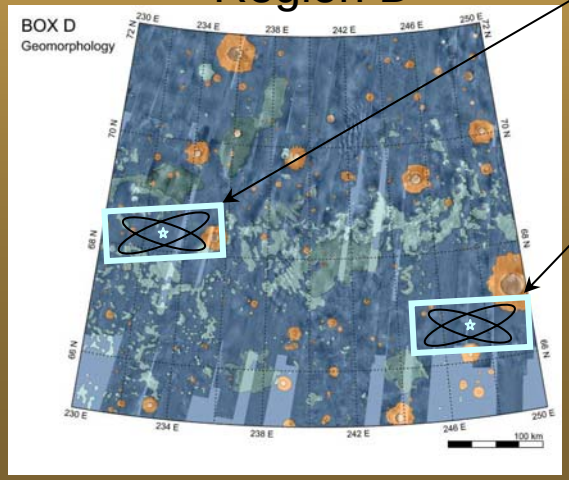
Phoenix Mission



Very Rocky Mars



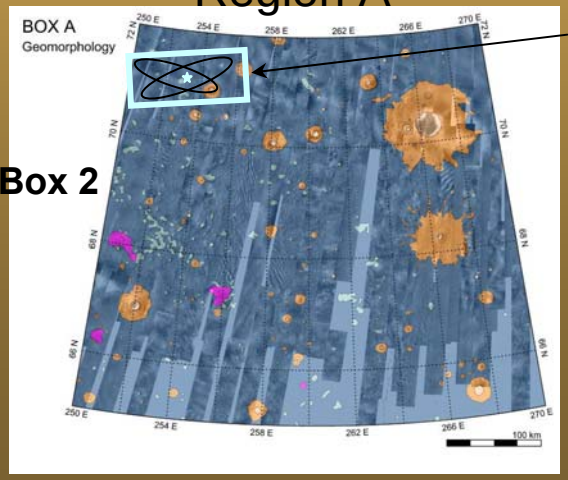
Region D



Box 1

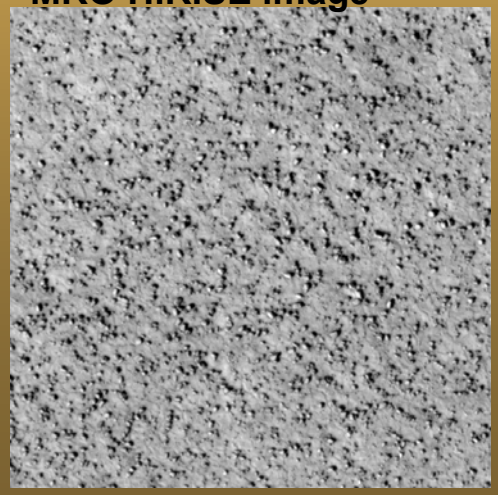
Box 2

Region A



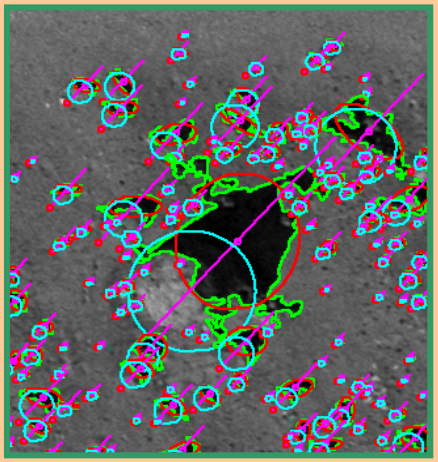
Box 3

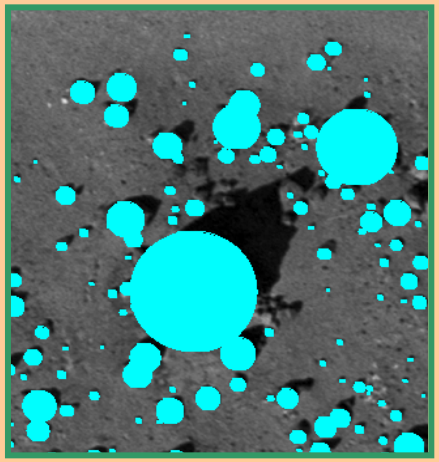
MRO HiRISE image

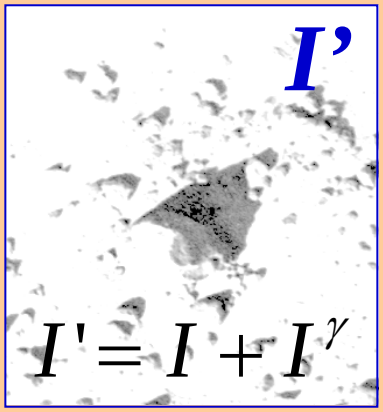


Shadow-based Rock Detection and Its Performance Model

1. Greylevel Image → **2. Shadow Segmentation** → **3. Shadow Analysis** → **4. Rock Modeling**







Green: shadow outline

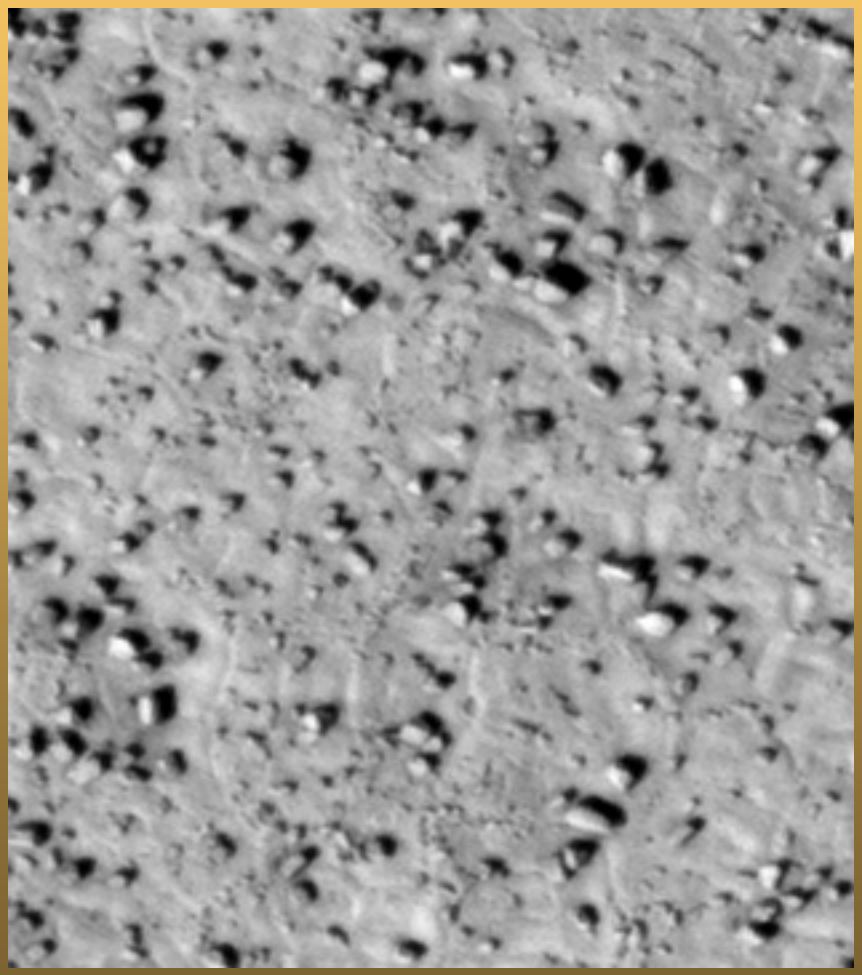
Red: ellipse fit to shadow

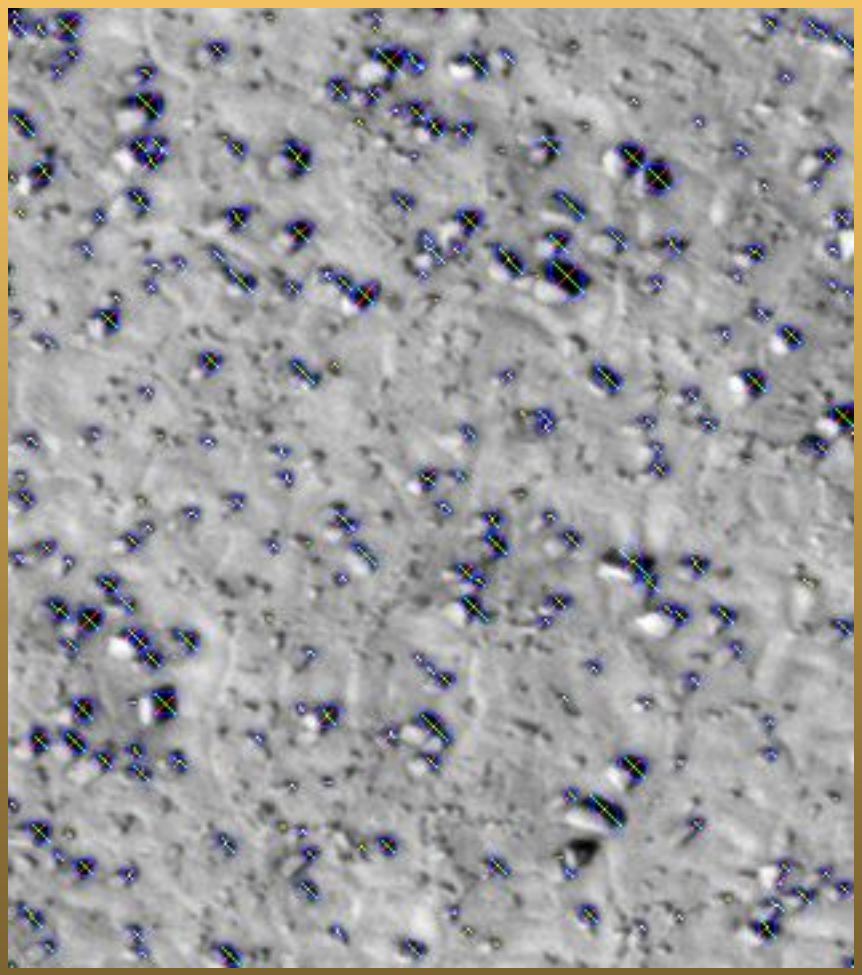
Magenta: sun direction

Cyan: estimated rock

New Shadow length/width Estimates

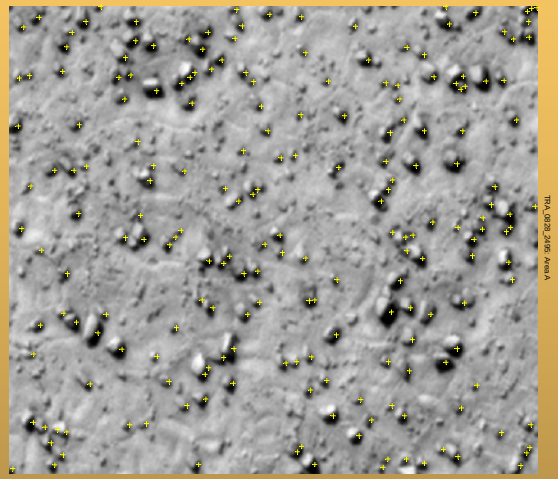
Example from TRA_000828_2495 – Area A (317x360 pixels) ~98x116 m^2

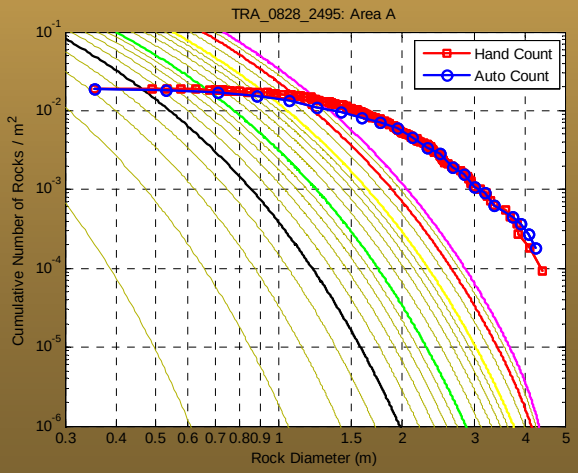




Auto Count Vs Hand Count

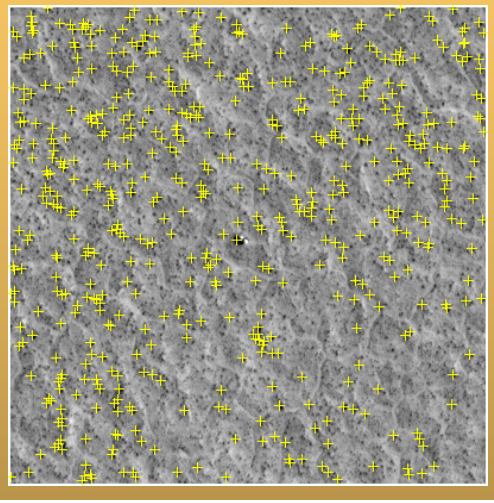
TRA_0828_2495:Area A

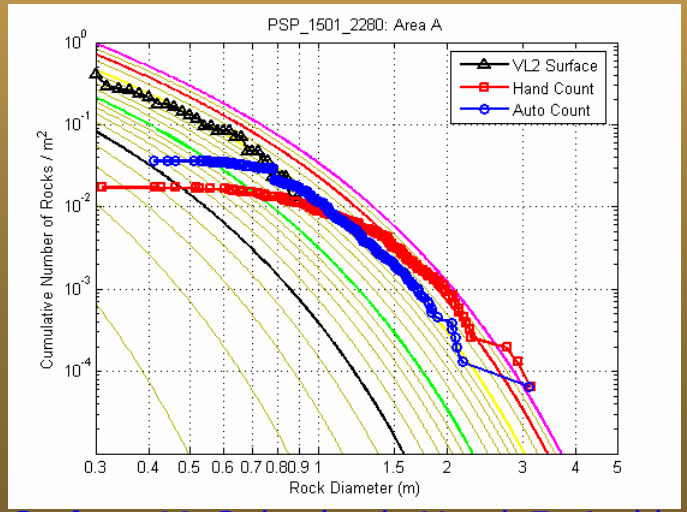




Auto: 204 rocks; Hand: 208 rocks

Viking Lander 2 Site

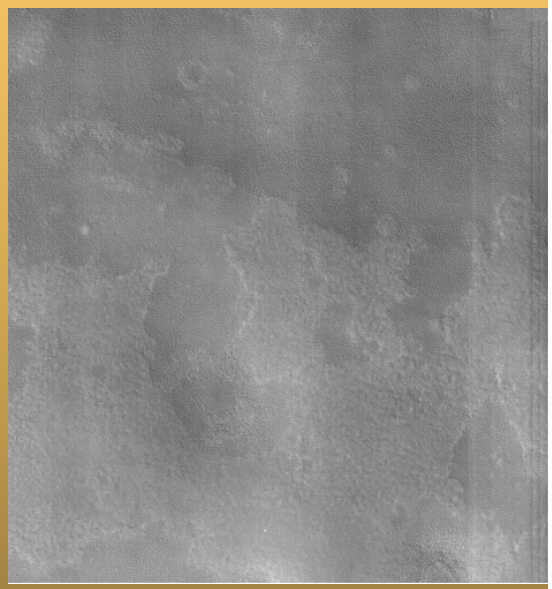




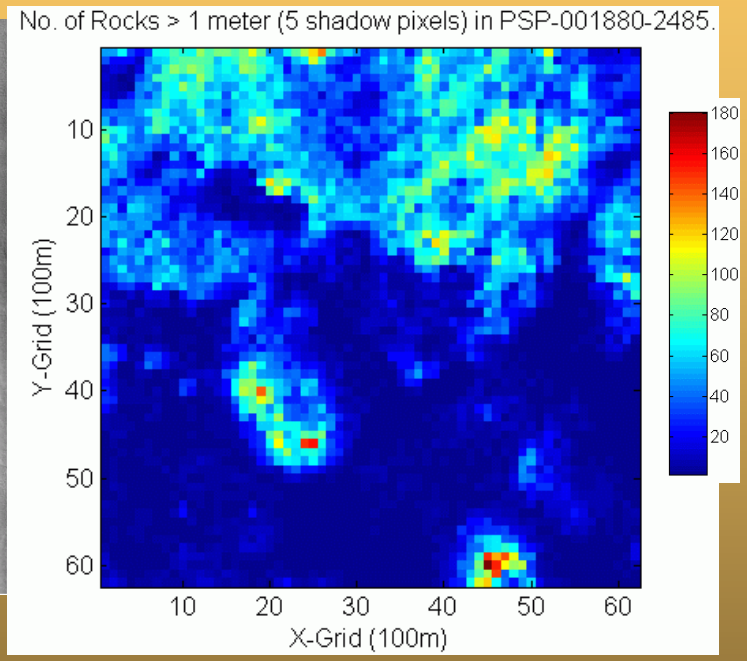
Surface: M. Golombeck; Hand: R. Arvidson

Auto Rock Detection can Process very Large Image

Full HiRISE Image



Auto rock segmentation

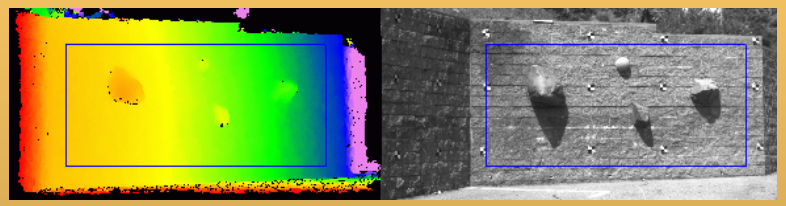


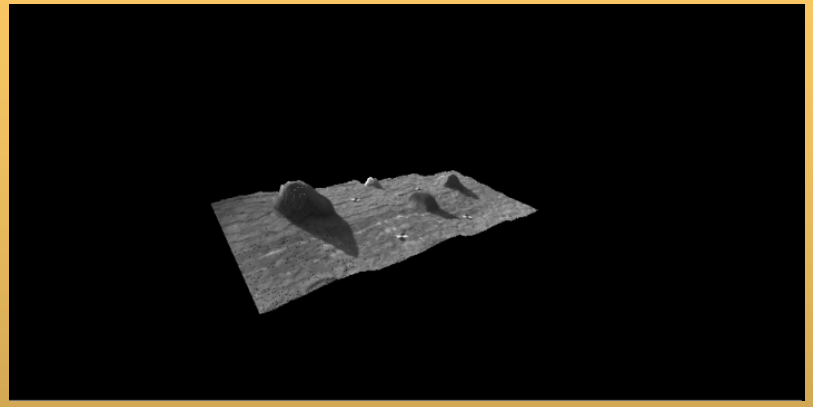
Manual rock segmentation

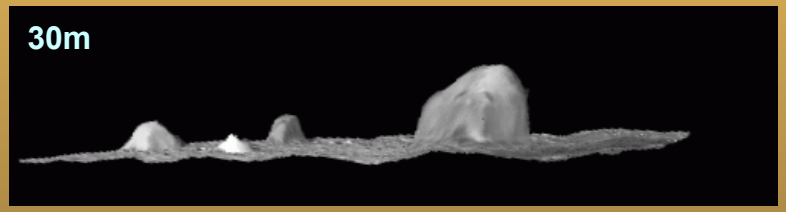
Image: 20048x20000 pixels; ~6.2x2.3 Km^2 Time: ~4 minutes

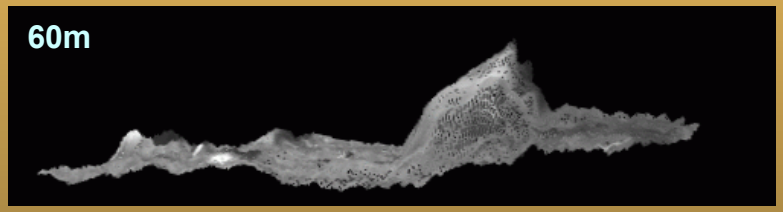
Rock counts from full size HiRISE image at 100x100m2 grid resolution

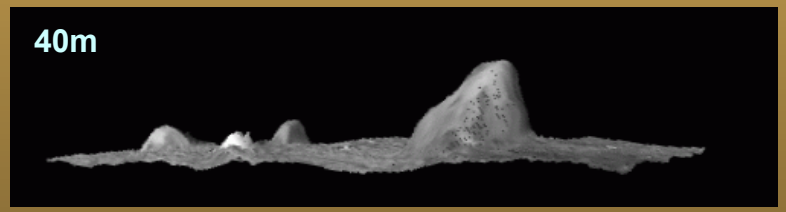
Stereo Based Rock Detection

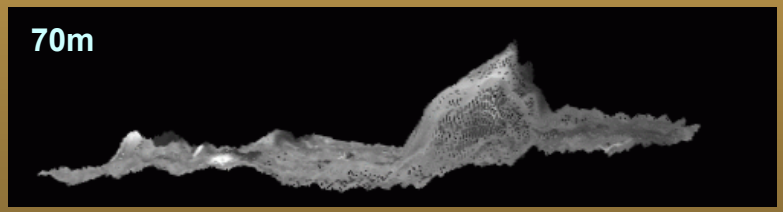


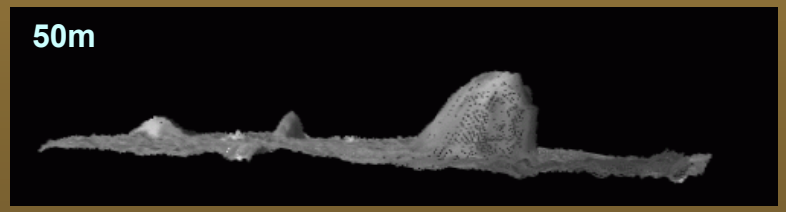


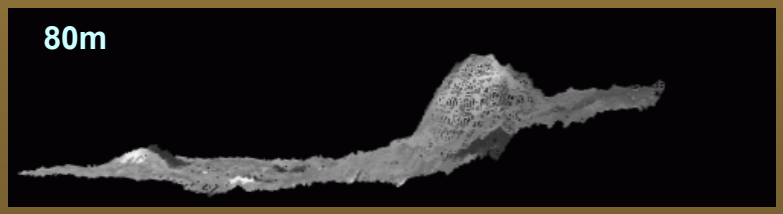




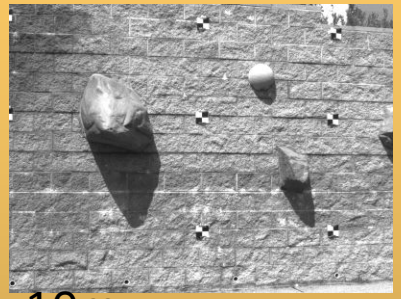








Rock Wall Images


10m

20m

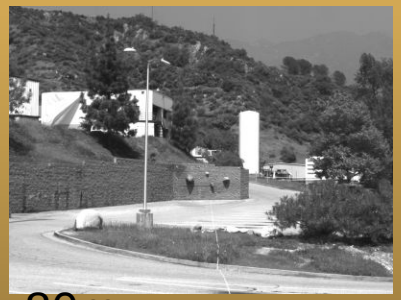
30 m

40m

50m

60m

70m

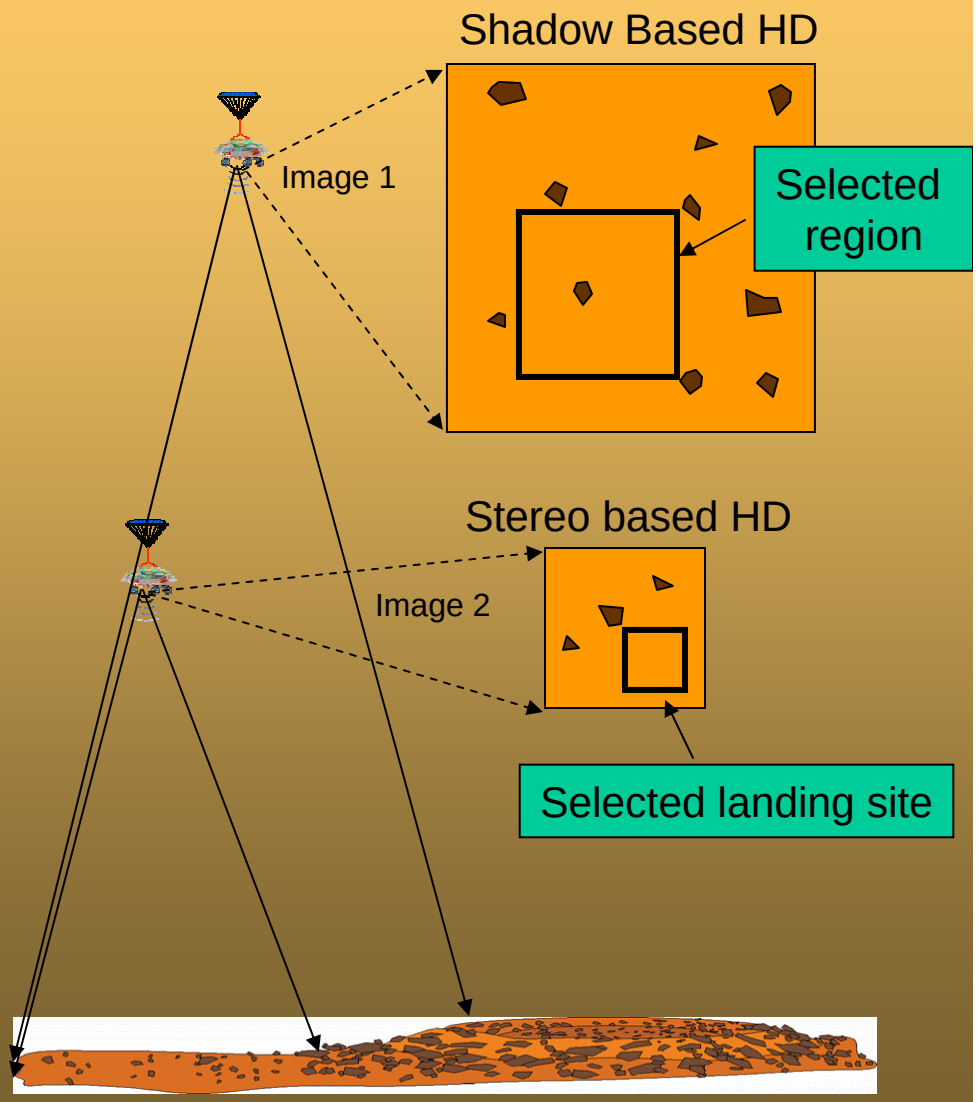

80m

90m

100m

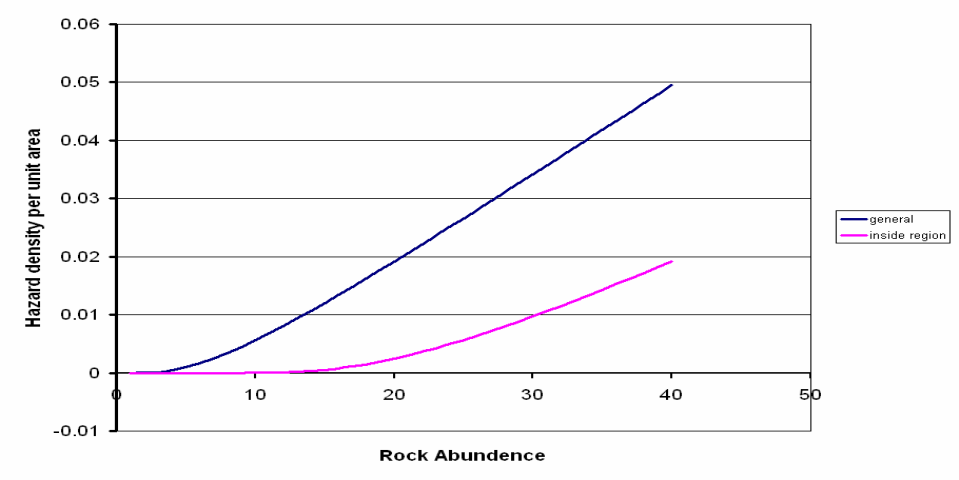
Shadow + Stereo Hazard Detection Fusion Model

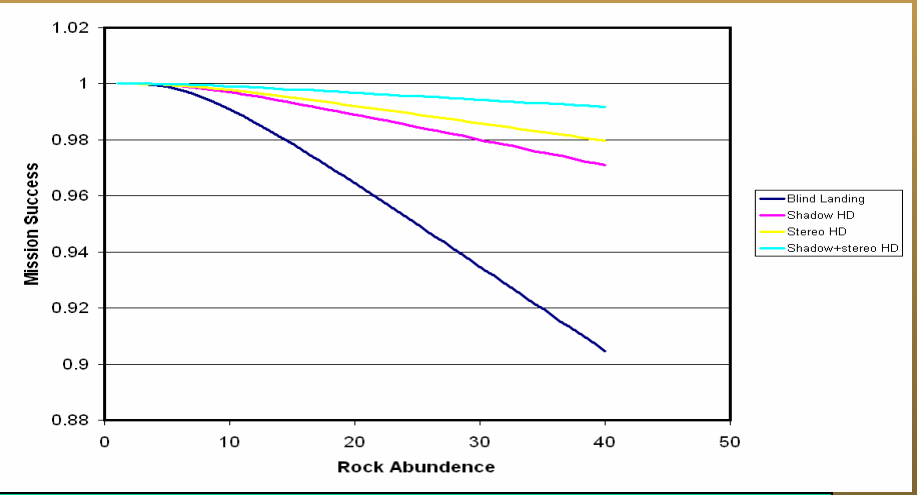
- Strategy:
  - At higher altitude, a shadow based hazard detection is executed and a hazard map is created
  - A region, which is the same size of the final image coverage and with fewest number of rocks, is selected
  - Maneuver the s/c toward to the selected region
  - At lower altitude (~ 40 m) the stereo based hazard detection will be executed and landing site is then selected
  - Land on the selected landing site



Shadow + Stereo HD Safe Landing Probability Model

- Arbitrary Instantiated Parameters:
  - The first image is taken at 100 meters AGL and its image coverage is 21 by 21 meter^2
  - The second image is taken at 40 meters AGL and its image coverage is 8 by 8 meter^2
  - The shadow based hazard detection error is 30% of detected rock height
  - Mechanical hazard size 1.2 and algorithm hazard threshold for shadow based hazard detection is t_{sd}= 1.0m
- A 8 by 8 meter^2 region is selected in the detected rock hazard map. The hazard density in the region and overall imaged area is shown at right





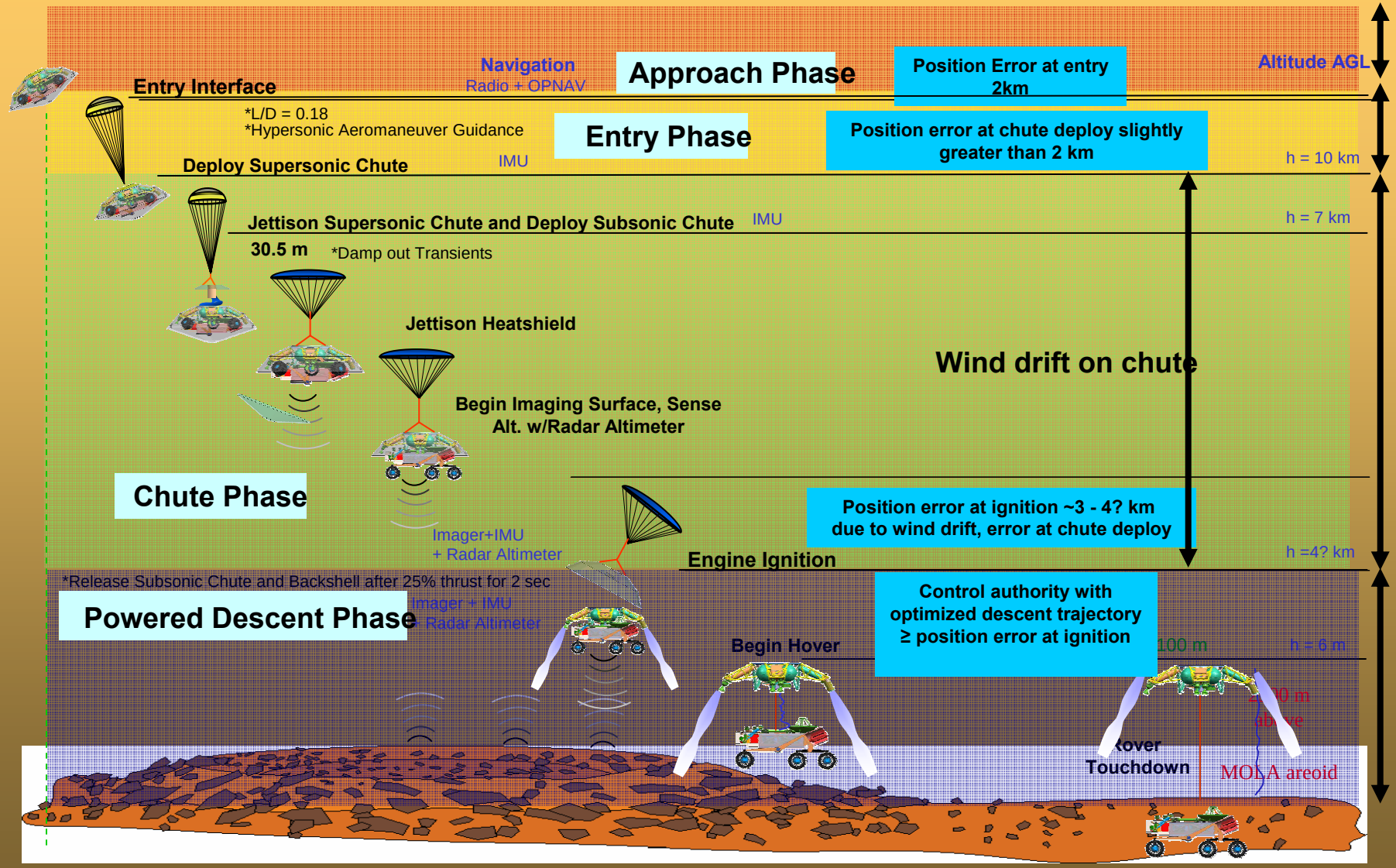
By combining the shadow HD and stereo HD will ensure the safe landing probability better than 99% for any rocky terrain

Landmark Based Spacecraft Pinpoint Landing

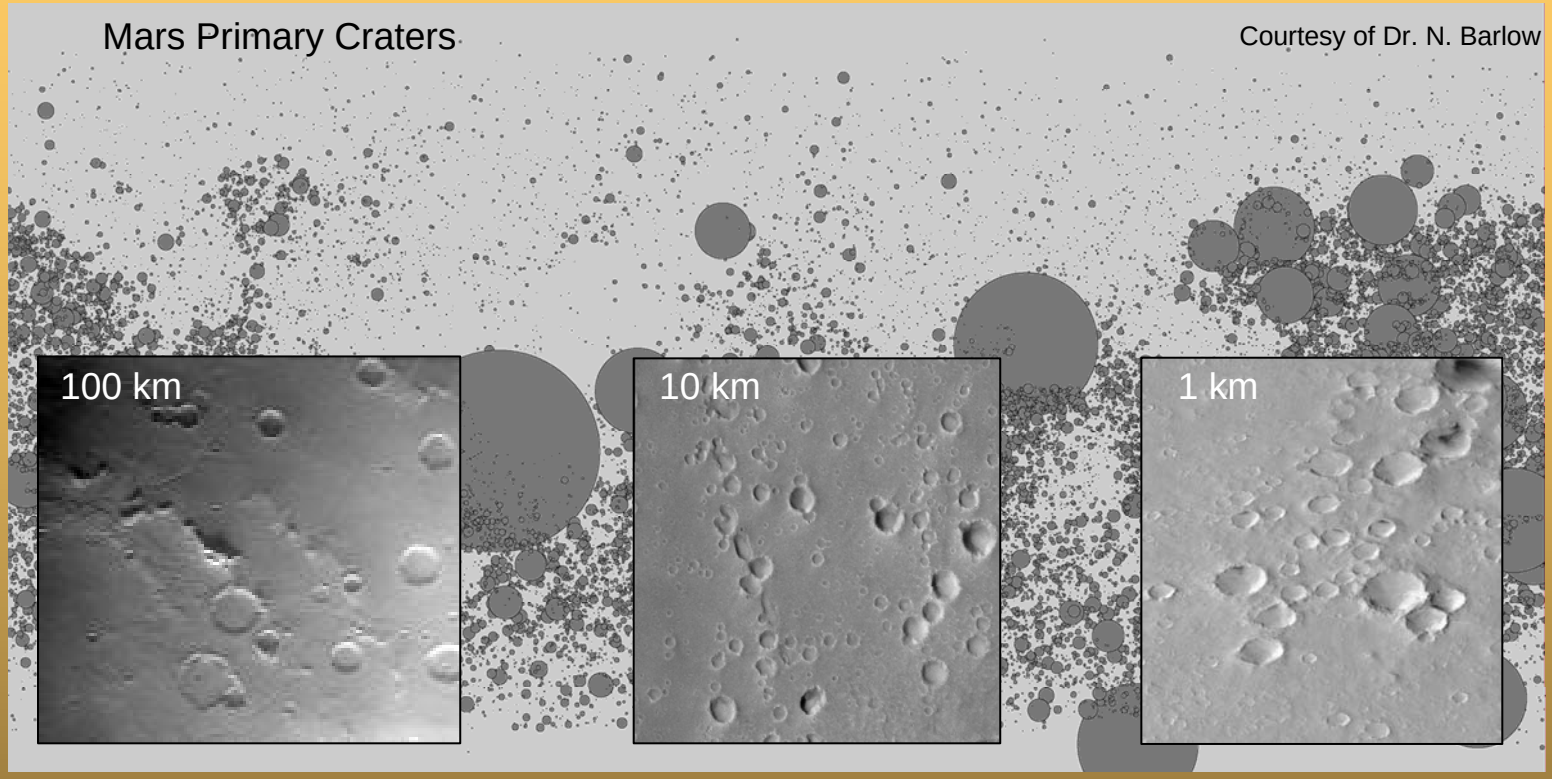
Terrain Relative Navigation

Pinpoint Landing: ≤ 100m from Target

(cartoon using MSL Skycrane configuration)



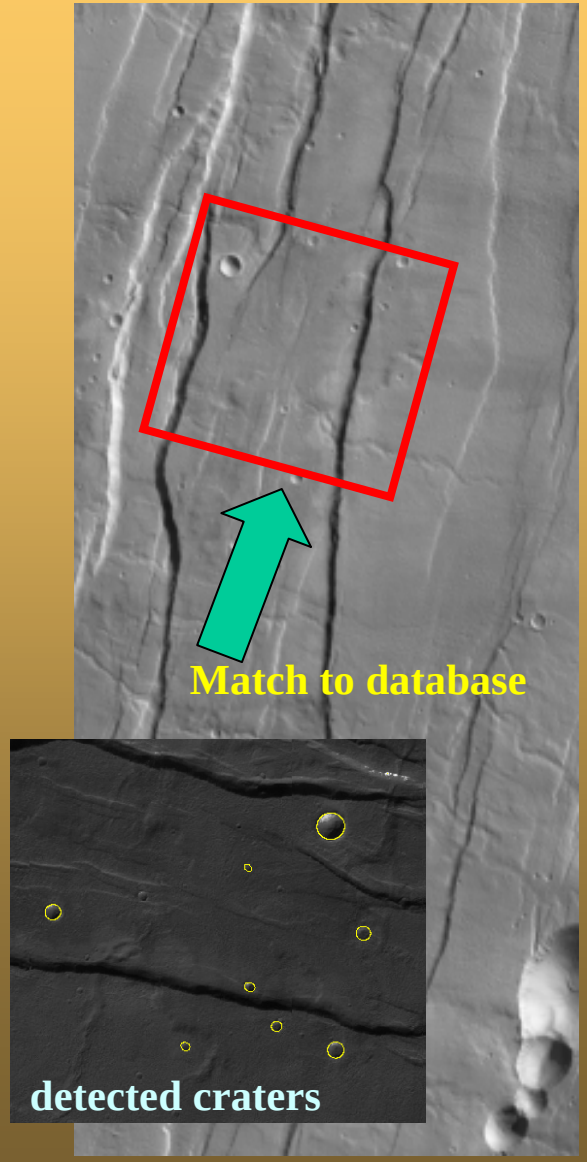
Why Craters are Ideal Landmarks



Mars's surface has a large amount of craters, which are ideal landmarks
. According to literatures on Martian cratering, 60 % of Martian surface is heavily cratered.
• The ideal (craters) landmarks for pinpoint landing will be between 1000 to 50 meters in diagonal
• The ideal altitude for position estimation should greater than 2 km above the ground

PPL Terrain Recognition (Crater) Algorithm

- **Objective:** Develop a system able to determine a Lander's position relative to the center body in real time during descent
- **Methods:** Extract craters from descent image and match them to an existing crater database to determine spacecraft pose.
- **Sensor:** Passive camera, IMU, Altimeter
- **Range:** up to 100 KM
- **Expected Results:** ~10 meters accuracy in position determination
- **Targeted Performance:** ~2 seconds for detecting craters; ~1 second for matching and position estimation on 200 MIPS processor
- **Targeted Missions**: 2nd and 3rd generation entry, descent and landing



Crater Landmark Detection Algorithm

Edge Detection

↓

Edge Selection

↓

Edge Grouping

↓

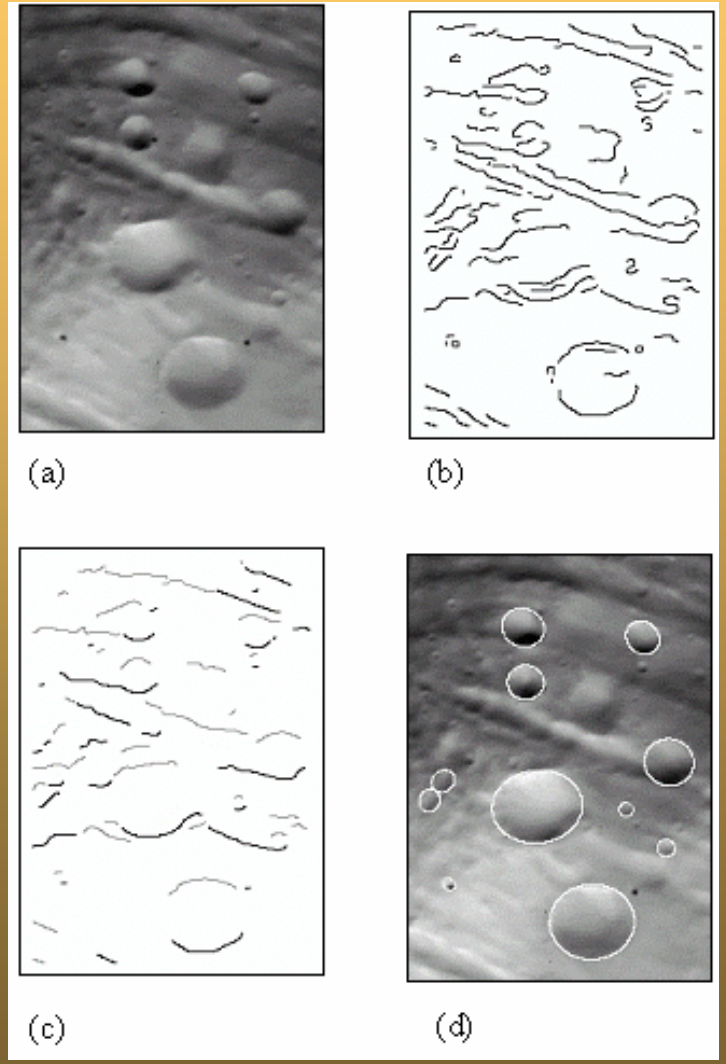
Crater Fitting

↓

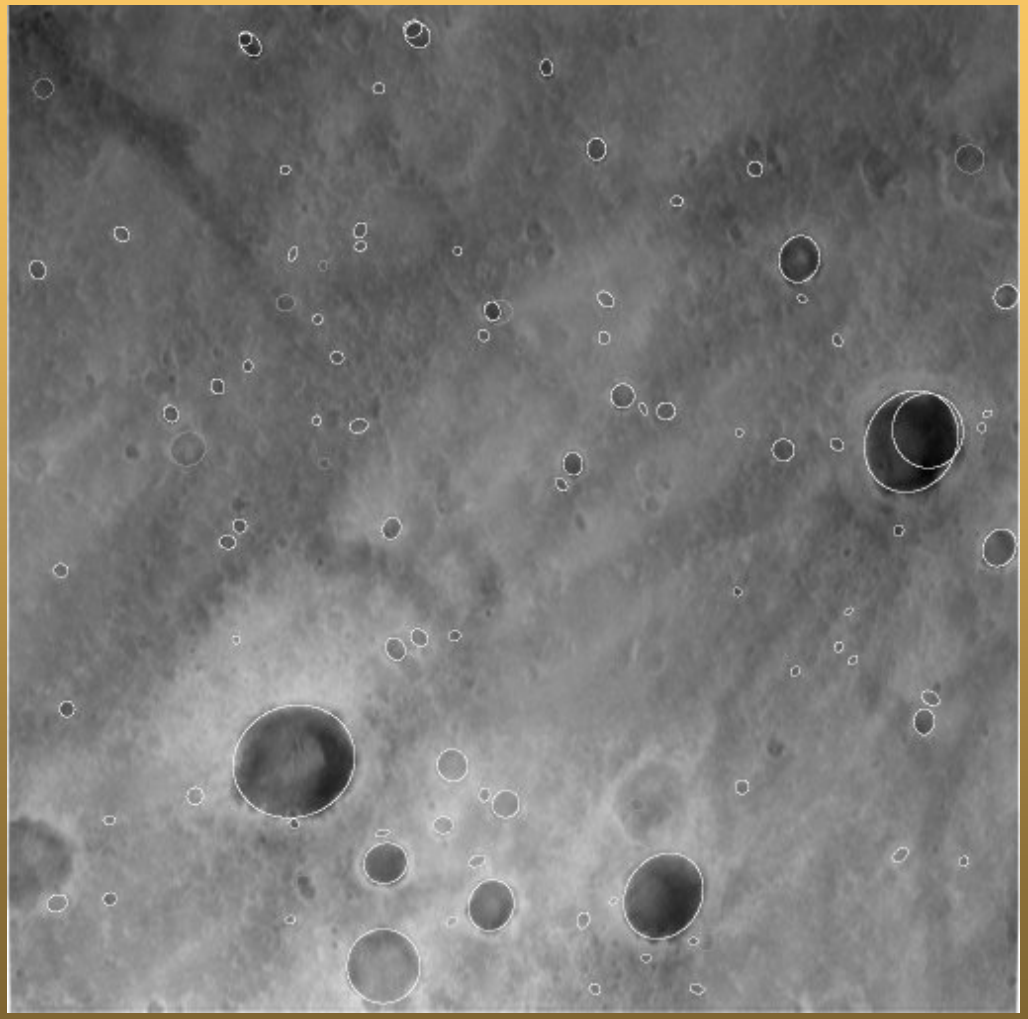
Precision Fitting

↓

Confidence Evaluation



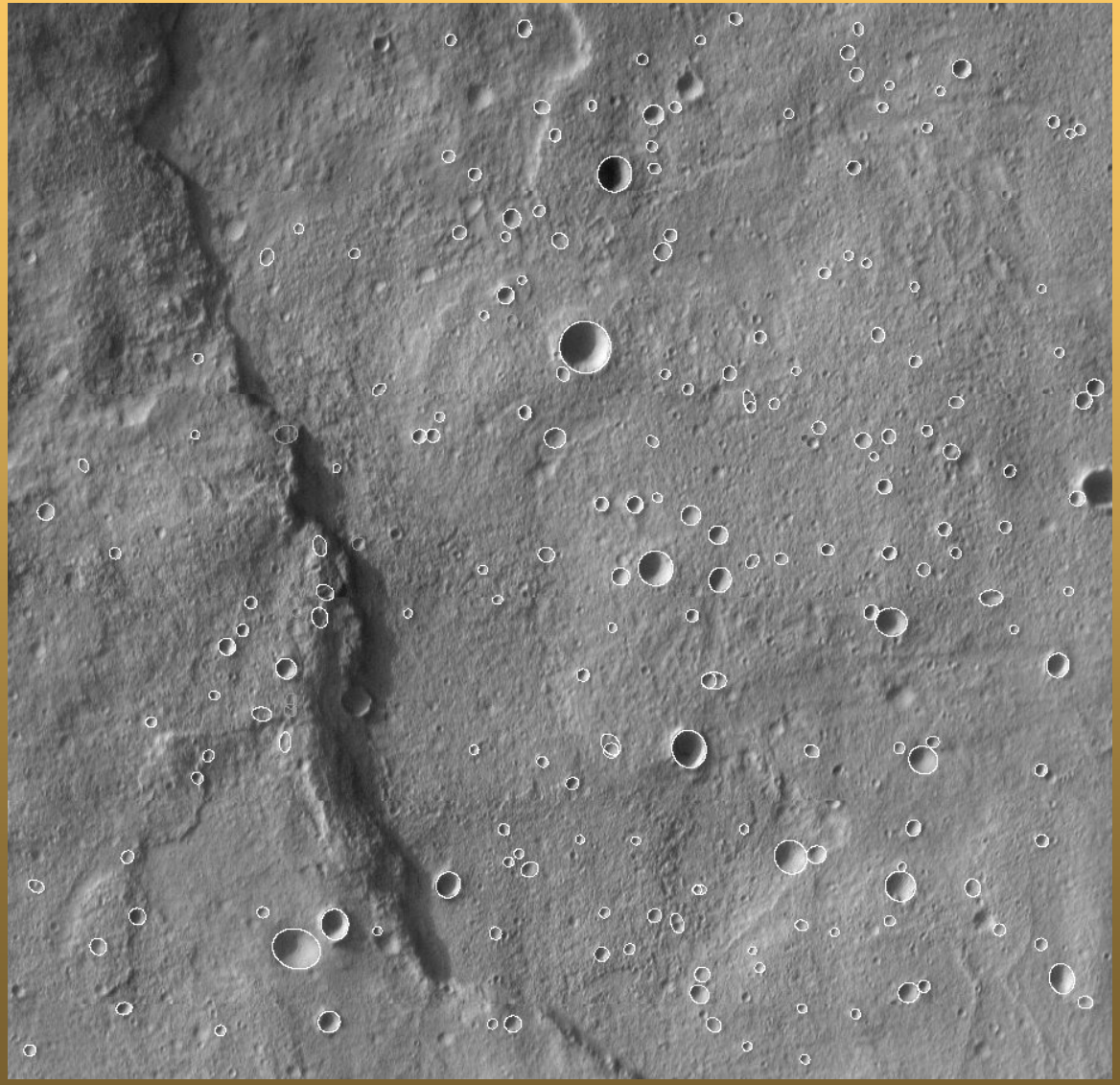
Detected Craters in MER-A Descent Image 1



Detected: 103
Missed: 2
False Detection: 0

Crater Detection Examples

The Crater Detection Algorithm Performance



Total 14 images were tested.

Detection Rate: > 94%

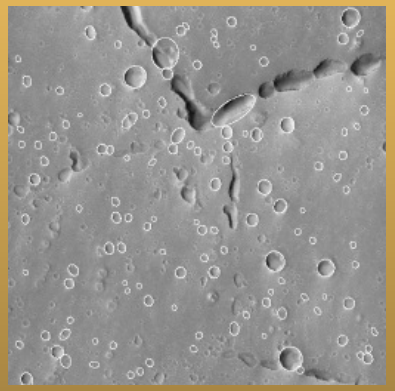
False Alarm Rate: < 7%

Crater Matching Algorithm

Objective: To match craters detected in a descent image to a crater database in real-time.

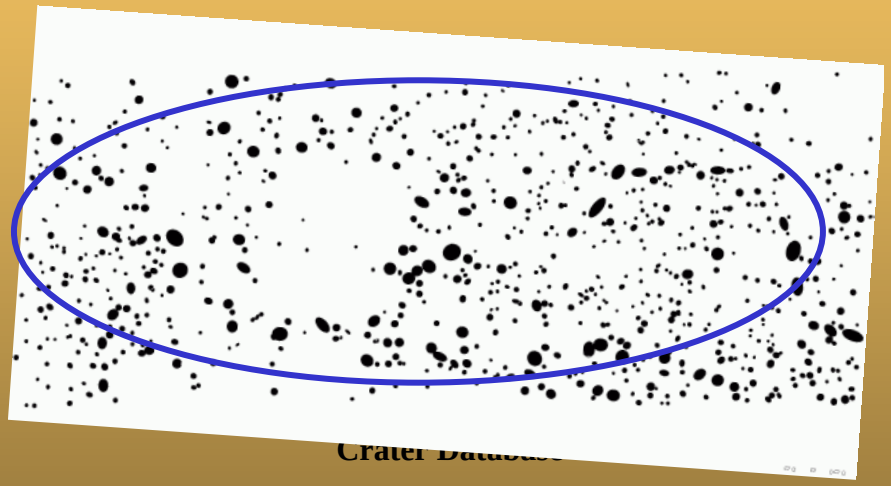
Problems:

- Large initial spacecraft position uncertainty
- Uncertainty of onboard spacecraft state (attitude and altitude) measurements
- The difference between inertial and local map coordinate system
- The onboard computing power and time constraints.



Detected Craters

Crater Matching



Solution:

- **Use conic invariants as constraint**
- **Use Hash table for fast crater search**
- **Use affine and homography transform for context based crater matches**
- **Use crater's geometry (size, shape, orientation, etc).**

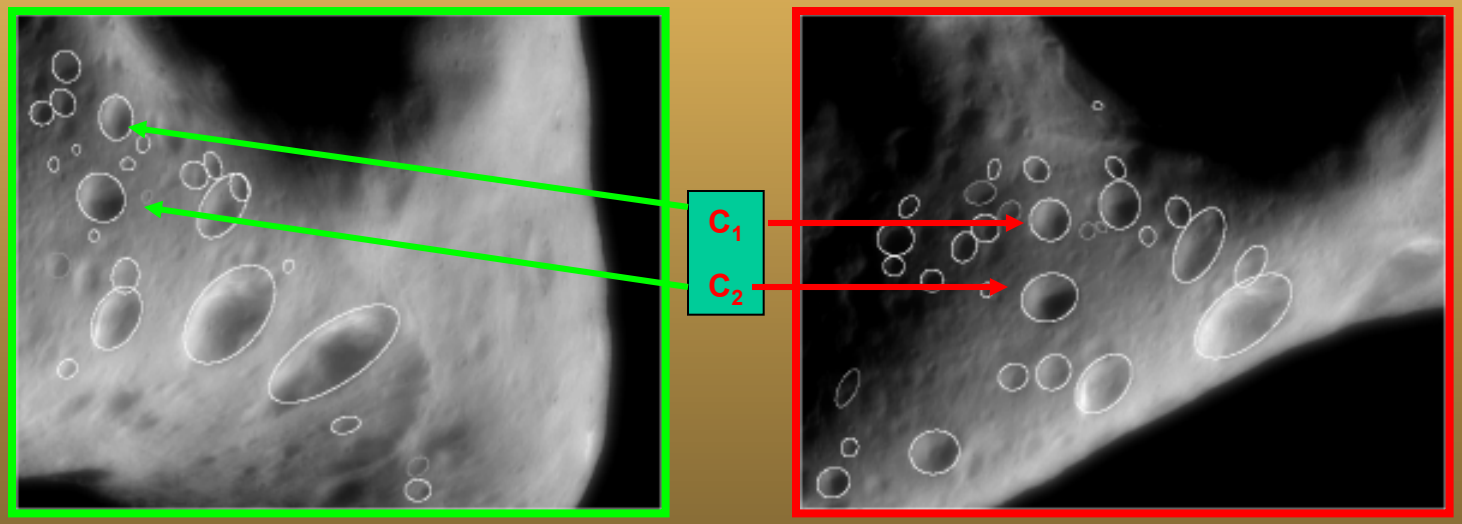
Result: **A very fast (real-time) algorithm for high altitude and large bodies**

Conic Invariance Match

A plane conic can be written as $x^t c x = 0$. Given two coplanar conics with matrices of coefficients c_1 and c_2, we have

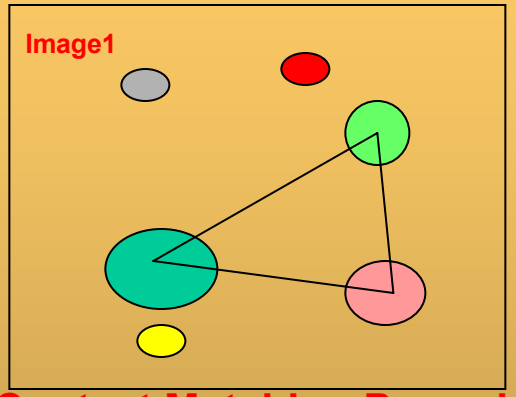
$$I_{c1c2} = Trace(c_1^{-1} c_2)$$
$$I_{c2c1} = Trace(c_2^{-1} c_1)$$

They are invariants under linear transformation*.

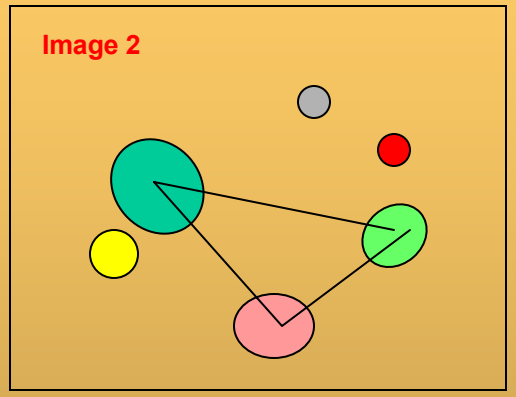


*The object from a distance that is an order of magnitude or more greater than the maximum object range along the direction of view.

Context Matching

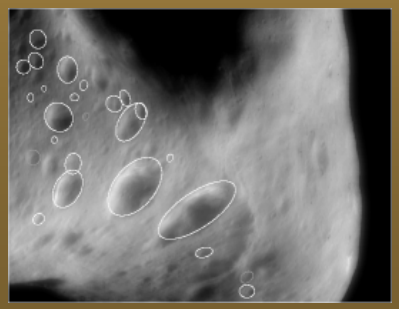


$$X_2 = \frac{a_1 X_1 + a_2 Y_1 + a_3}{a_7 X_1 + a_8 Y_1 + 1} \quad Y_2 = \frac{a_4 X_1 + a_5 Y_1 + a_6}{a_7 X_1 + a_8 Y_1 + 1}$$



Context Matching Procedure

1. Randomly select three craters in image1 and form their epipolar lines between image 1 and image2;
2. For any craters in image 2 that are close to these epipolar lines, form a linear transform between image 1 and image 2;
3. Transform all craters from image 1 to image 2 using the linear transform;
4. Find their counterparts in image 2 using the location, size, and shape of these craters.
5. If more than 5 craters are found, it stop. otherwise go to step1.

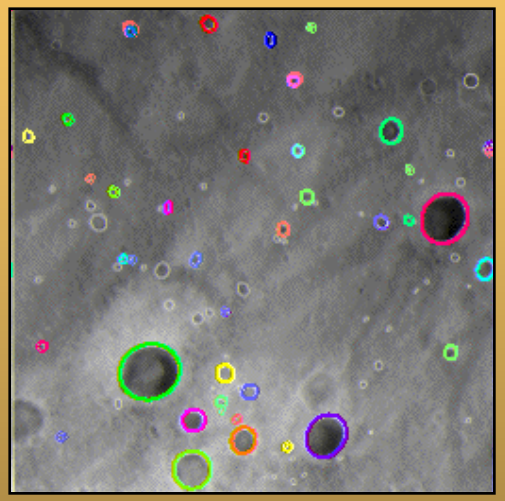


Uniqueness of matching is > 99.9% for 5 and more crater constellations.

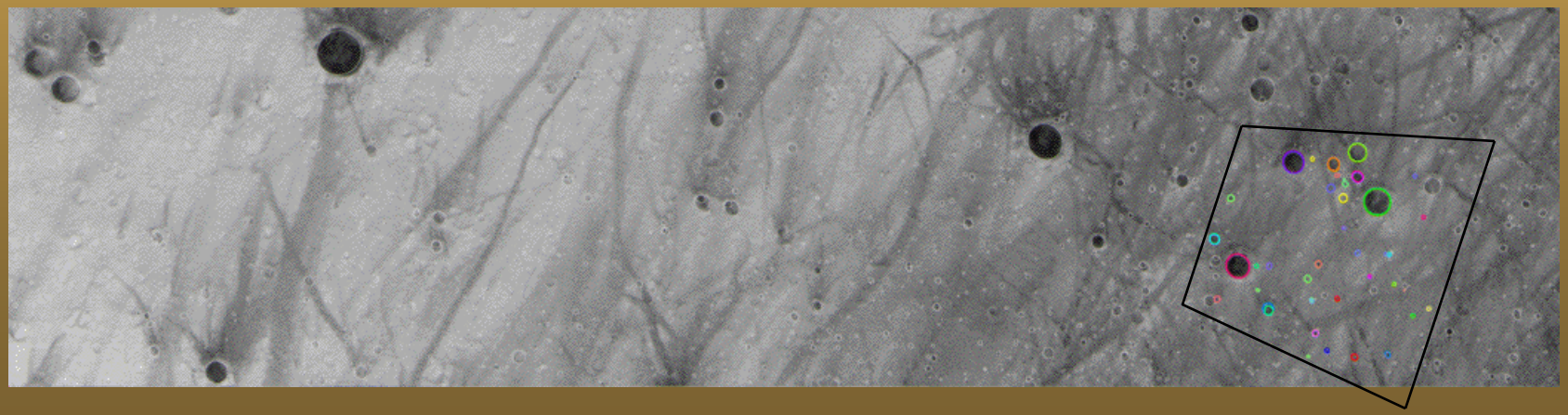
Matched Craters in MER-A Descent Image 1

- MER-A Descent Image
- MOC-NA image is “Map” of Landing Site
- Match craters detected in descent image to craters in map
  - crater color indicates a match
  - gray craters are detected but not matched

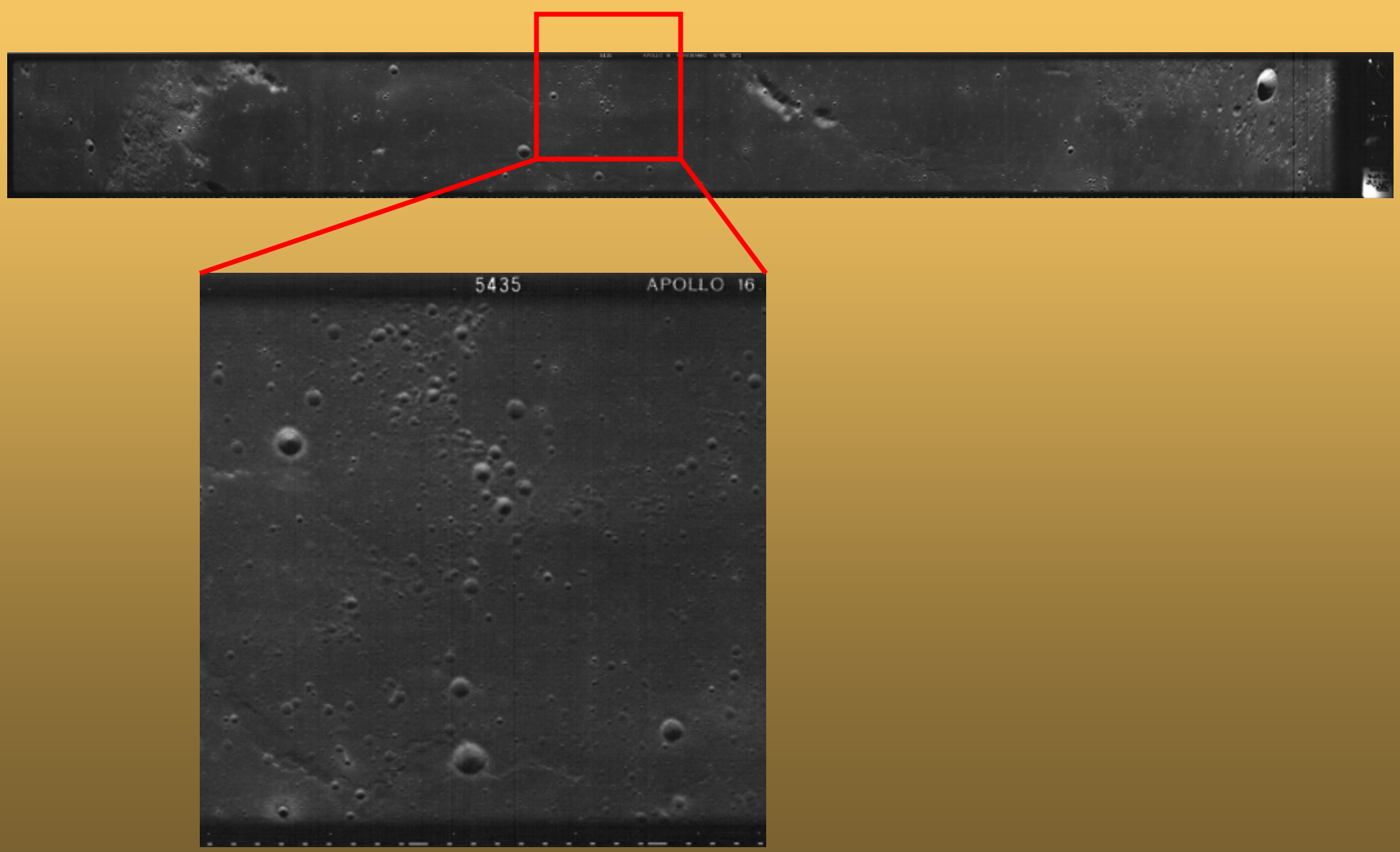
Descent Image



MOC Image



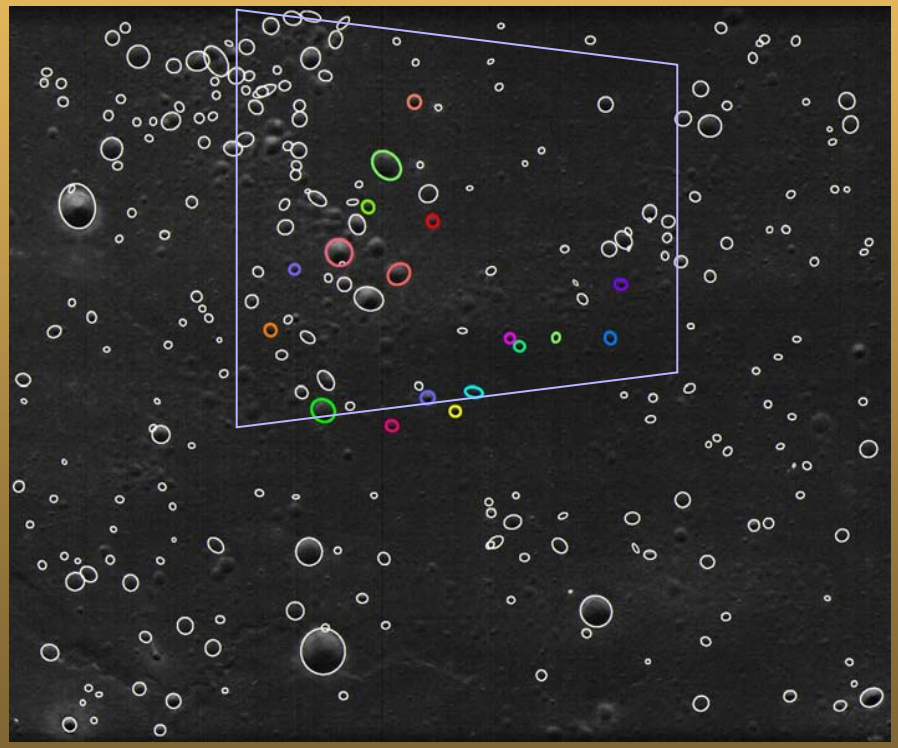
Apollo 16: Panoramic Camera

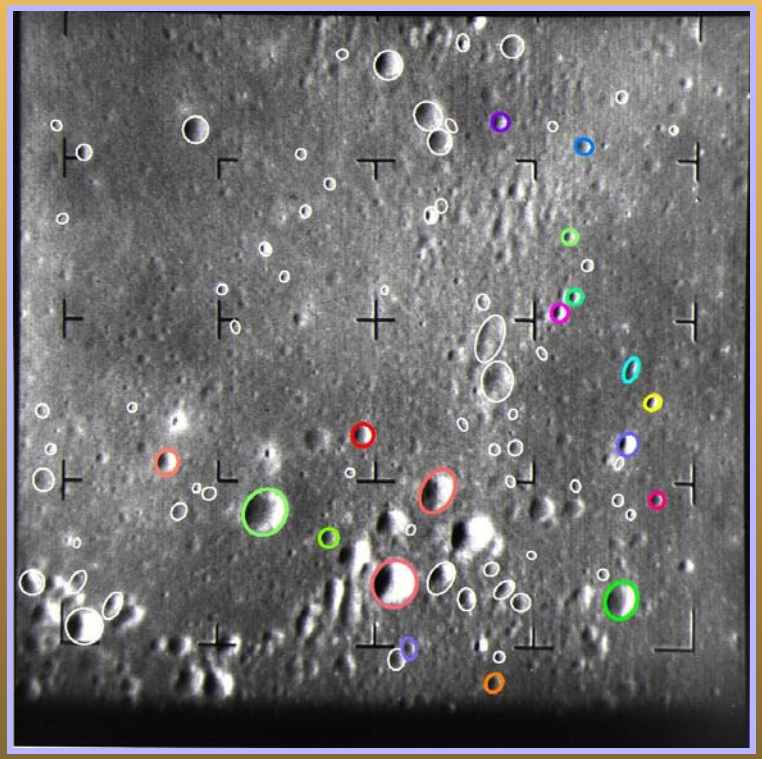


Range VII image

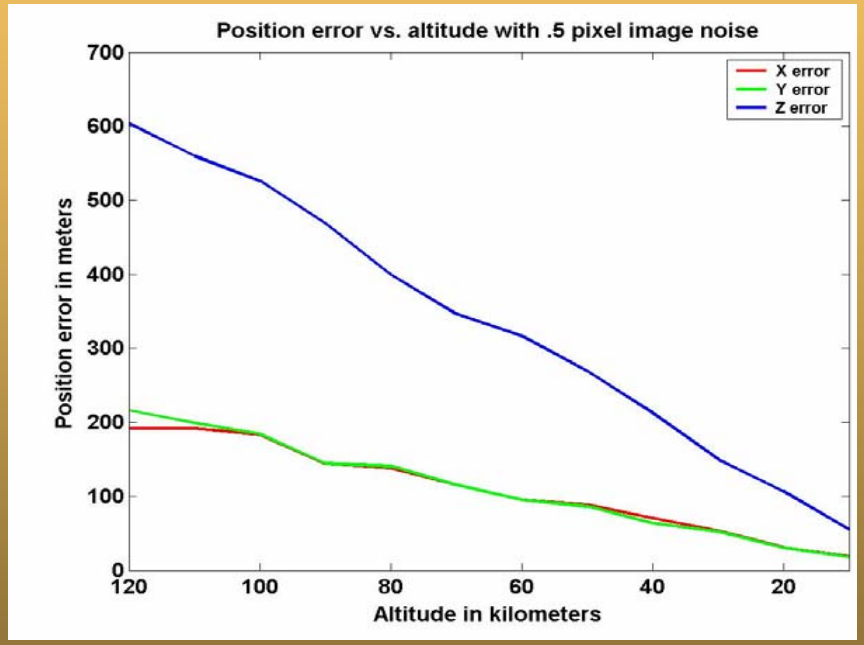
Matched Craters in Map and Descent Images

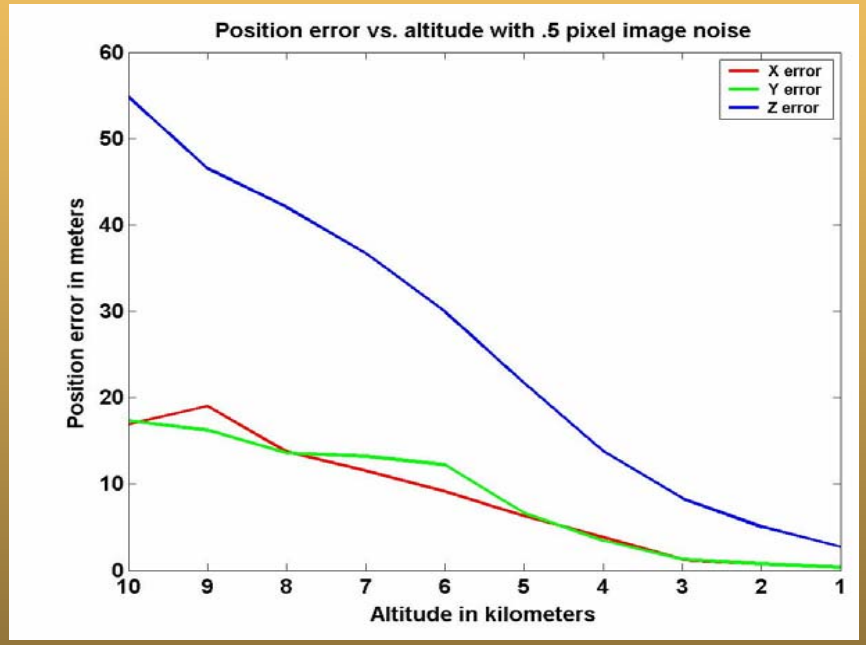
- Colored ellipses denote positive match between craters in both images
- White ellipses denote craters detected in one image but not matched in other image
- Enough craters matched to allow position and attitude estimation to be performed





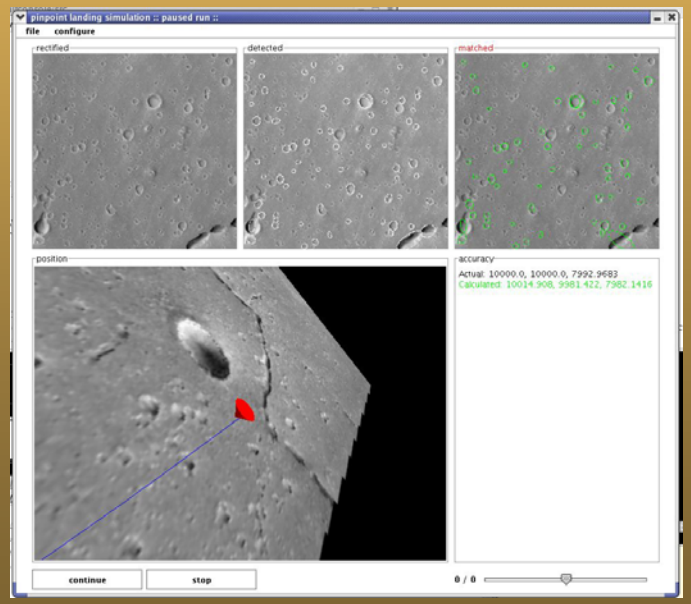
Position Estimation Accuracy Analysis

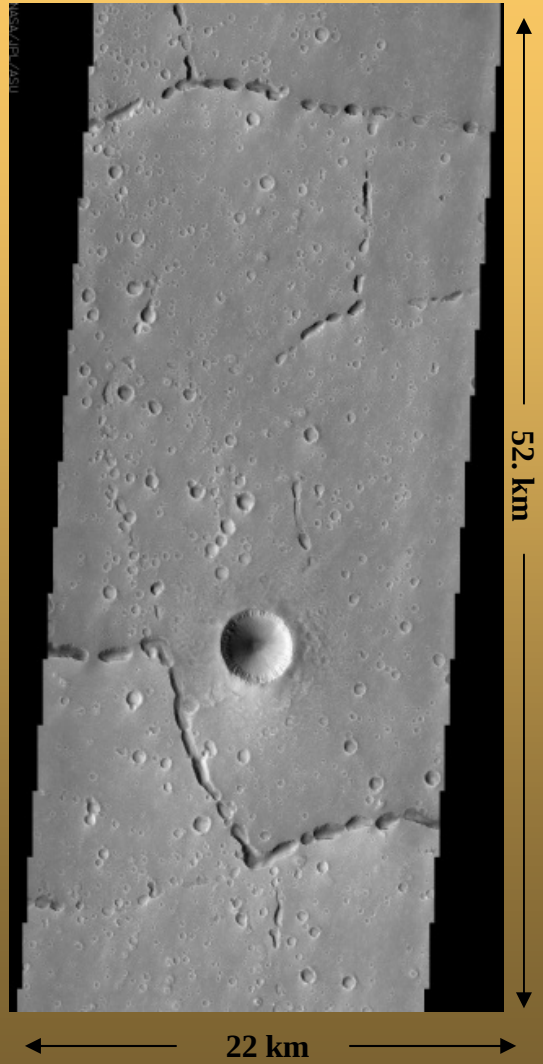




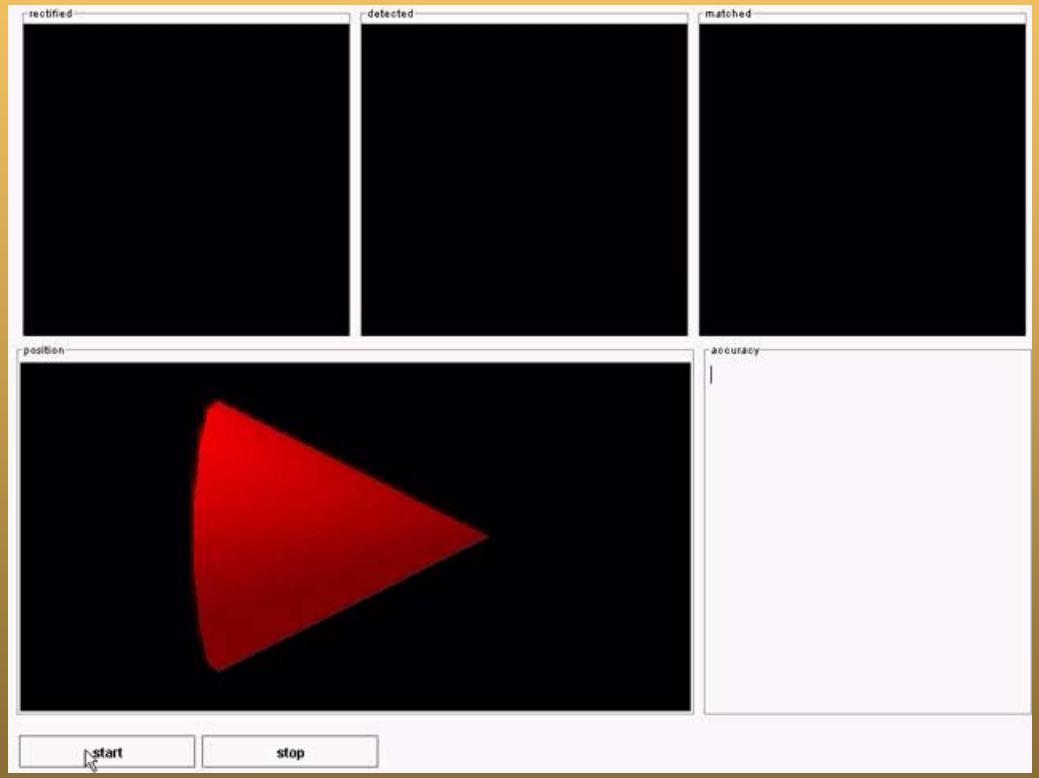
Terrain Relative Navigation Simulation

- The landing area base map is 22 x 52 km^2
- A randomized MSL like trajectory is used (generated by DSENDS)
- The descent image is generated by warping a THEMIS image (18 m pixels)
- The crater matching and pose estimation do not use any state measurements
- The recovered pose is compared with the pose from true trajectory.

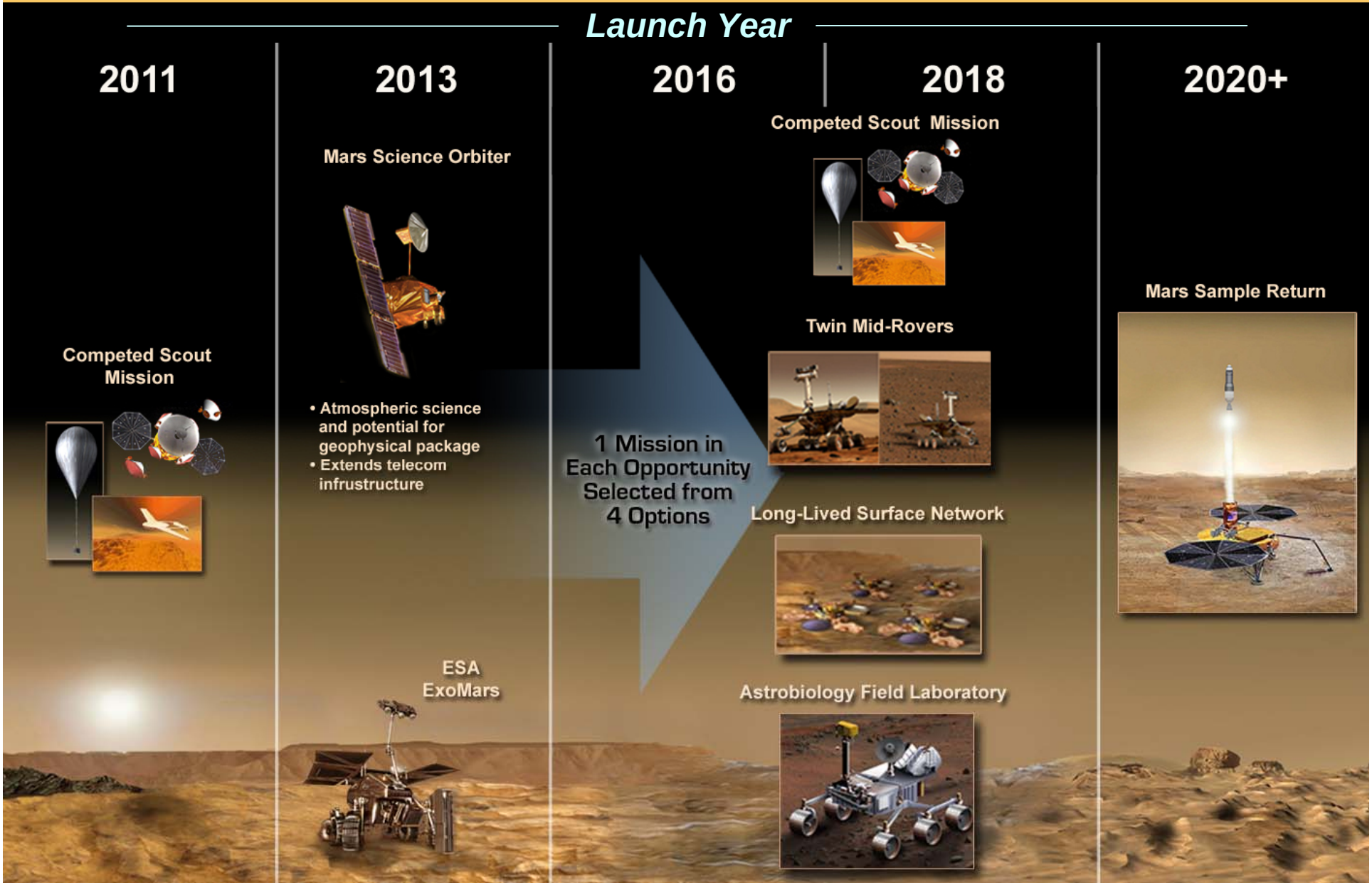




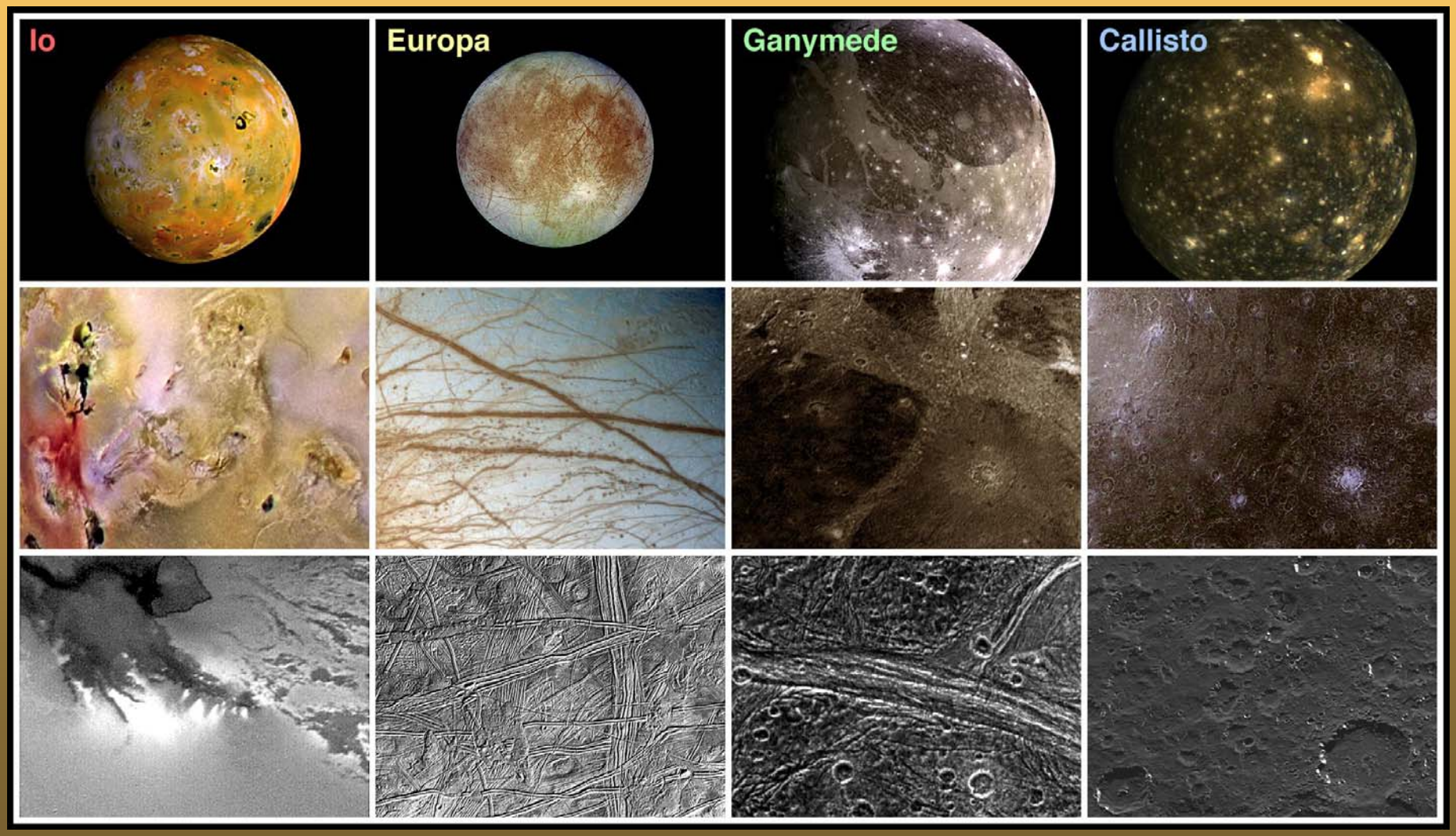
PPL Terrain Relative Navigation Simulation



Mars Program Architecture: Next Decade



Jupiter Icy Moons Landmark Identification for Orbit Determination



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Pinpoint Landing

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DIMES

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