A Window in the Future of Planetary Surface Navigation

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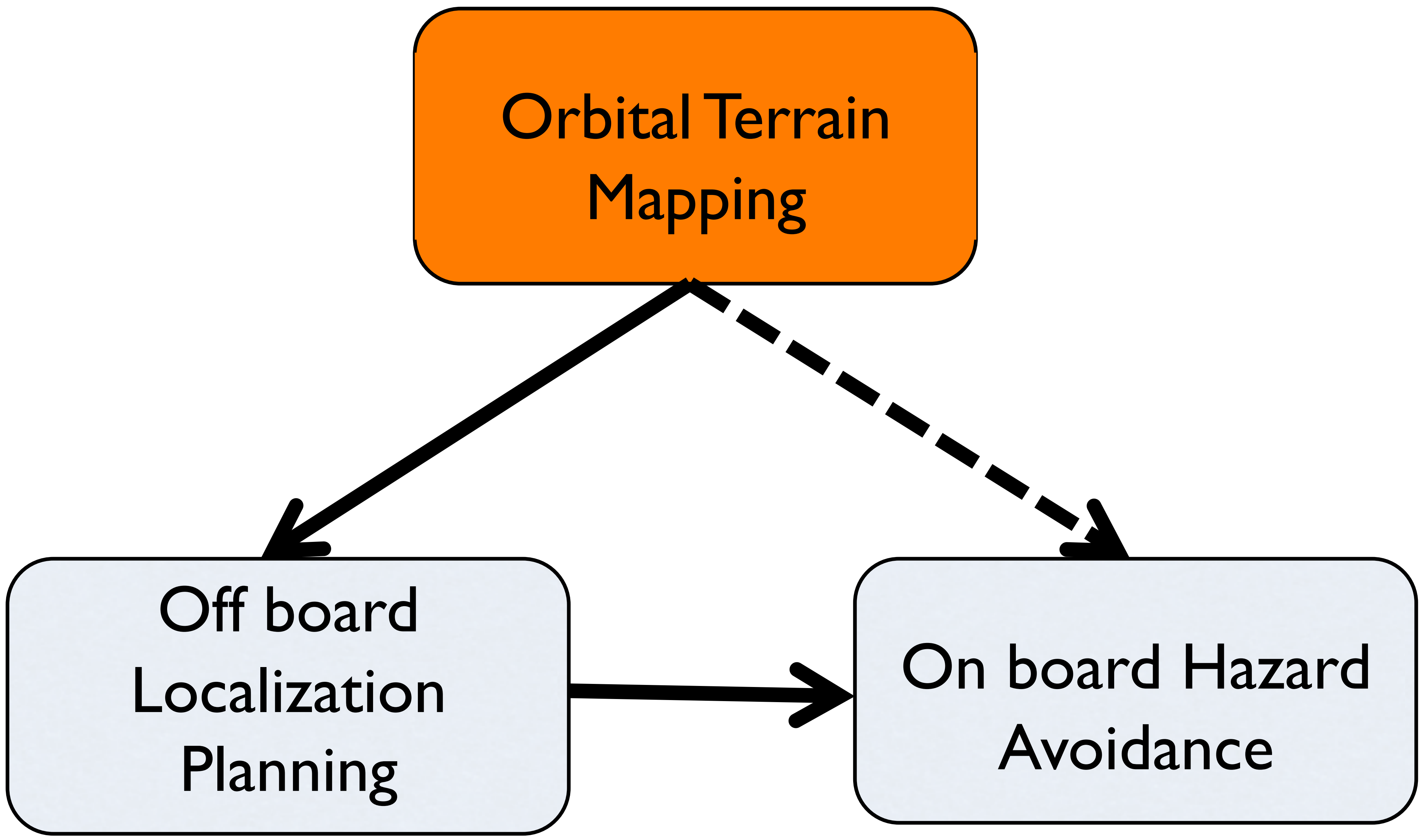
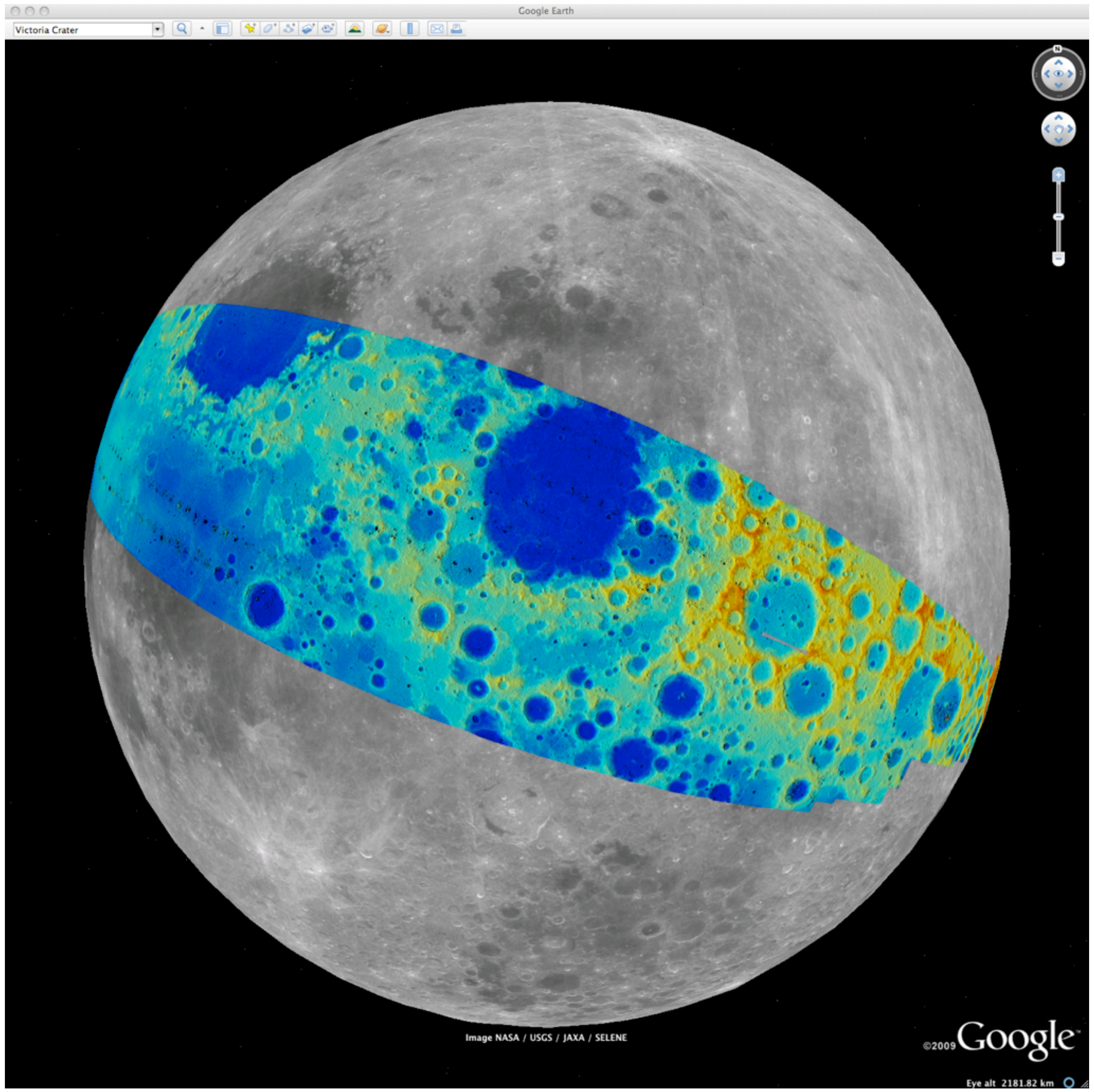
Navigation Challenges

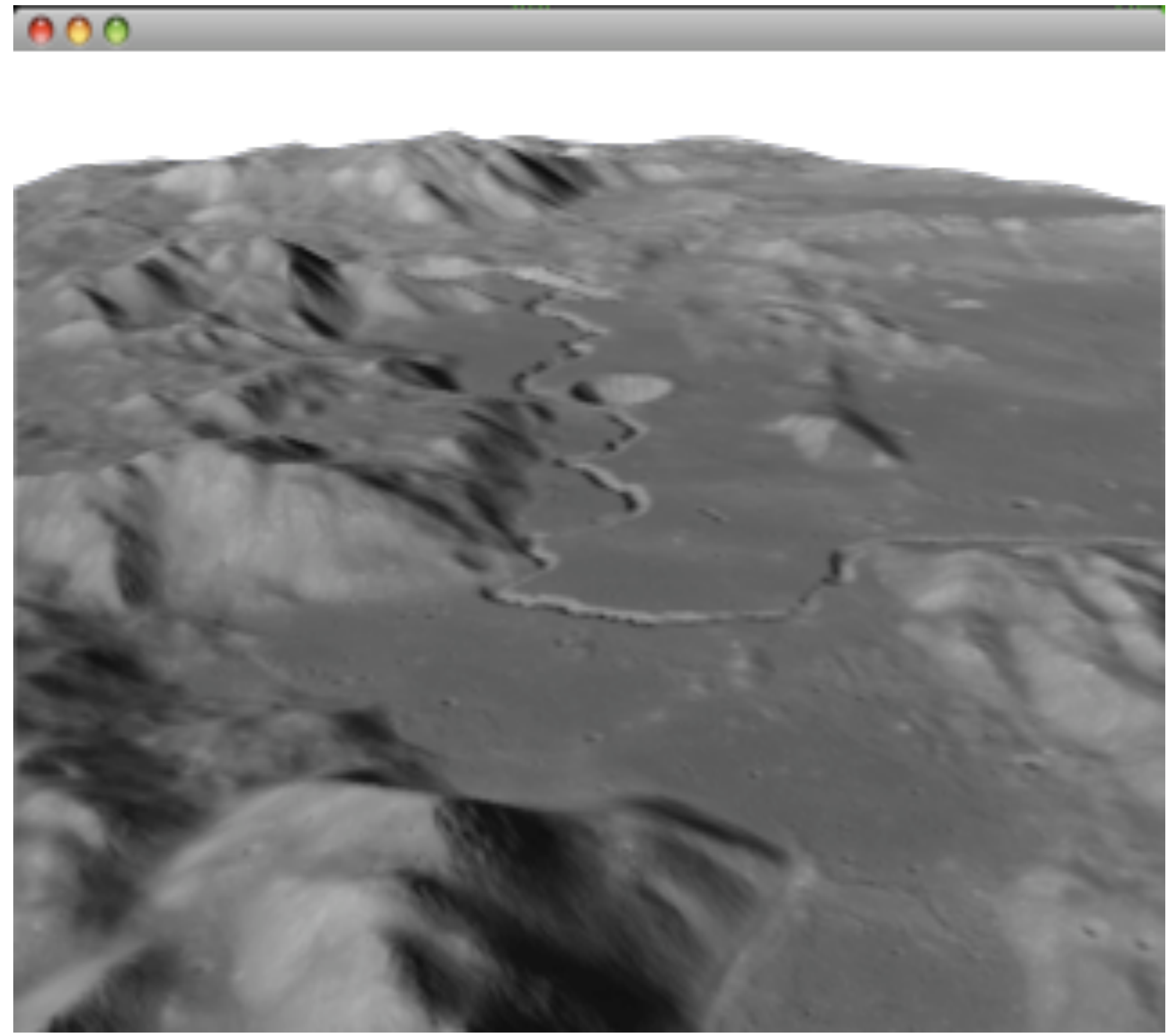
- Lack of surface imagery
- Low gravity
- Terrain uncertainty impacts
    - obstacle avoidance
    - direct communication with Earth
    - illumination conditions
- Lunar Polar reflectance conditions (albedo, reflectance models)
- Rock distribution
- Gaps in regolith and surface characterization
- Lunar temperature conditions
- Low computational complexity available
- Low power systems
- High radiation environment

Planetary Rover Navigation



Stereo Reconstruction from Orbital Imagery

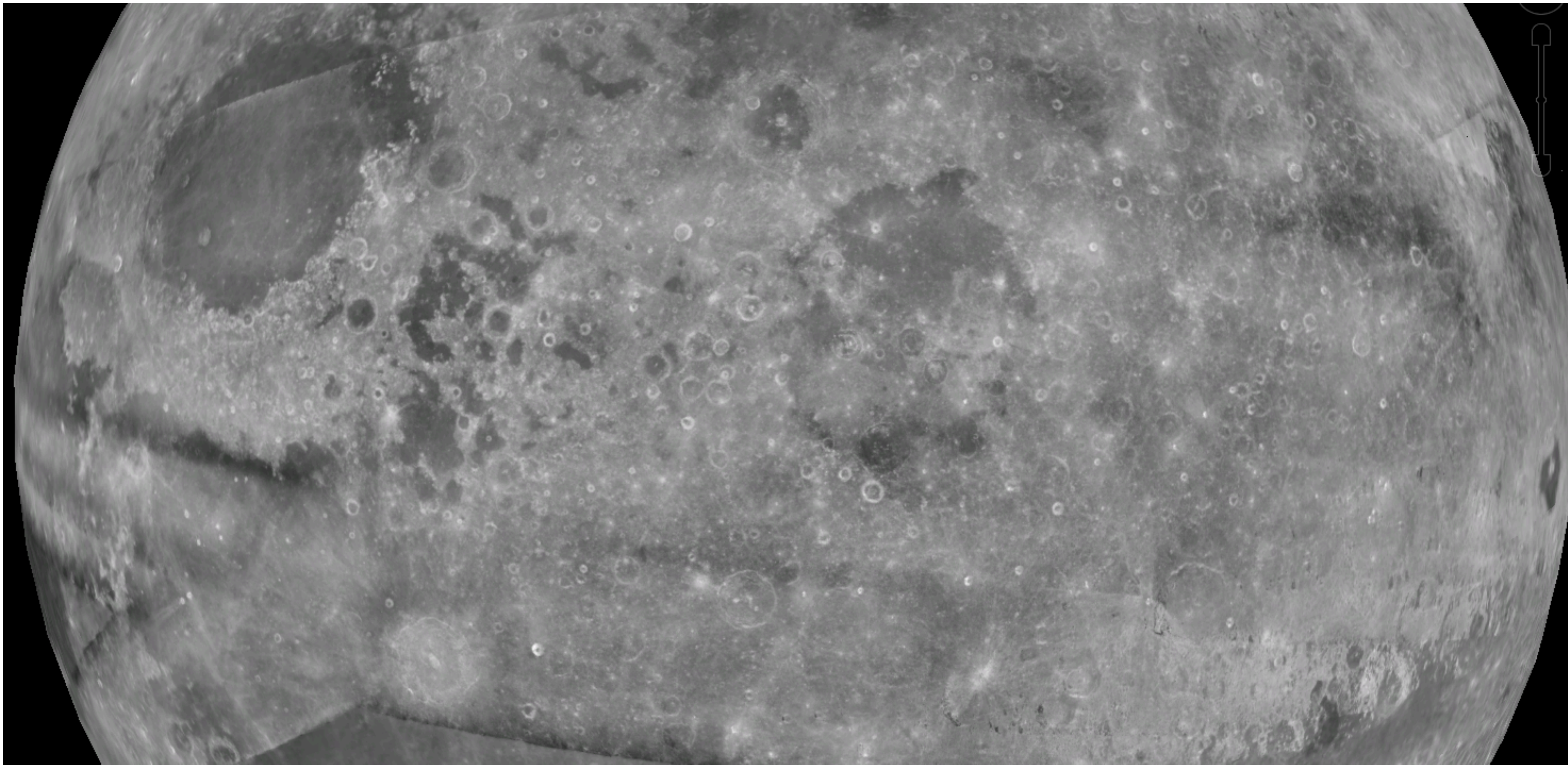




Apollo Zone reconstructed color shade over Clementine imagery in Google Earth (left) and reconstructed oblique view of Apollo landing site (right).

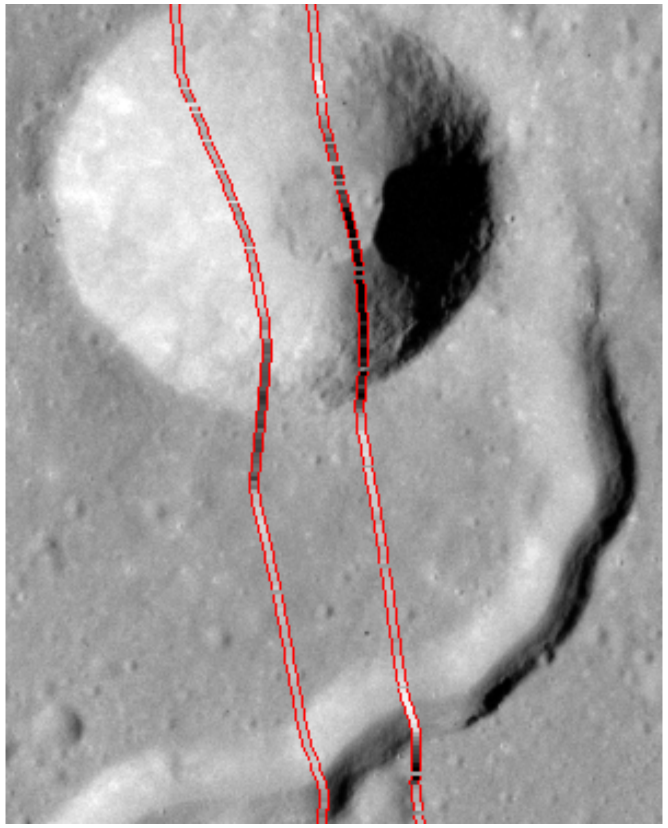
Albedo Reconstruction

http://byss.arc.nasa.gov/oleg/albedo_04_09_2012/albedo_04_09_2012.kml

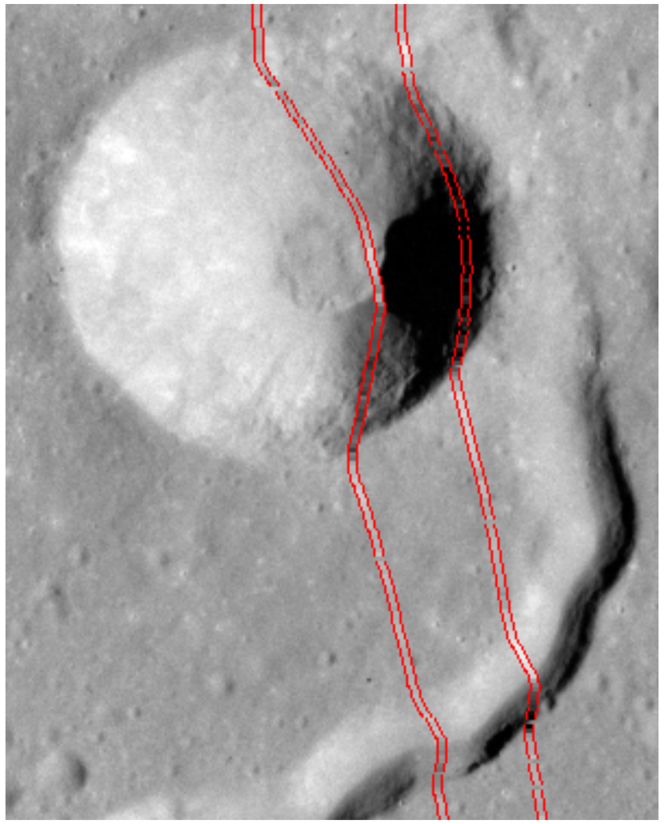


Apollo Zone reconstructed albedo over Clemntine imagery (Google Earth)

LOLA to Image Coregistration

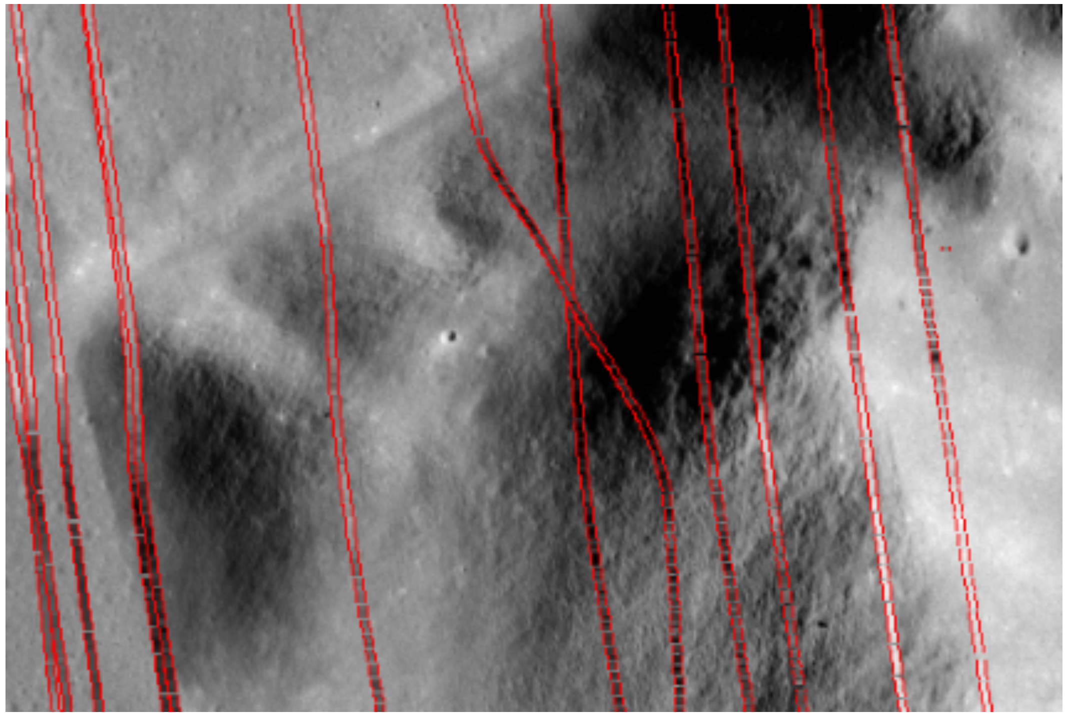


Original

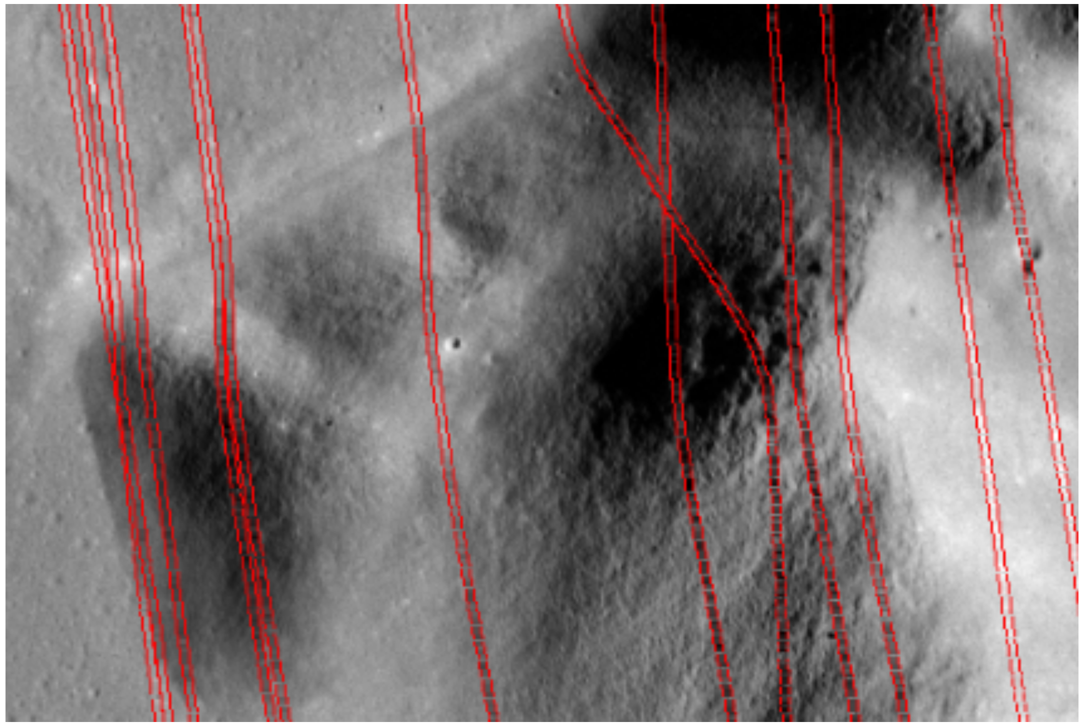


Adjusted

Alignment of LOLA altimetry data to Apollo Imagery using the Lunar Lambertian reflectance model.

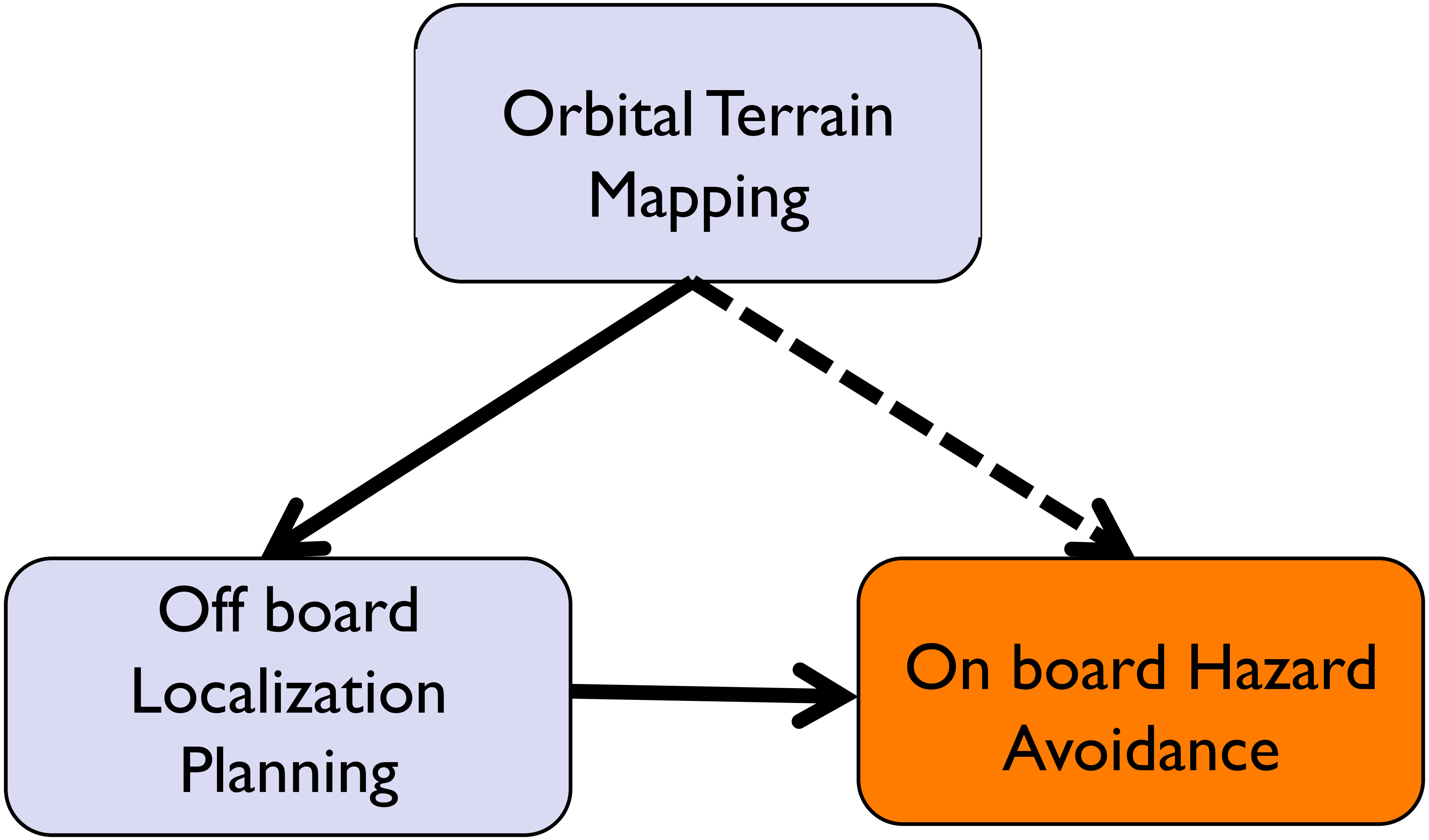


Original



Adjusted

Planetary Rover Navigation

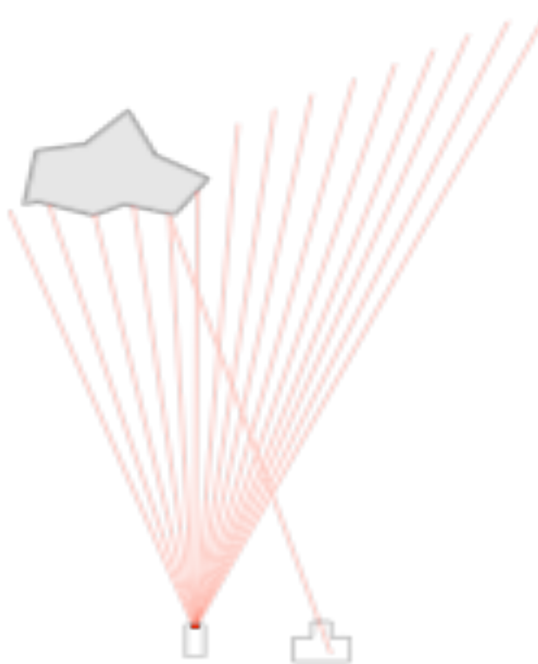


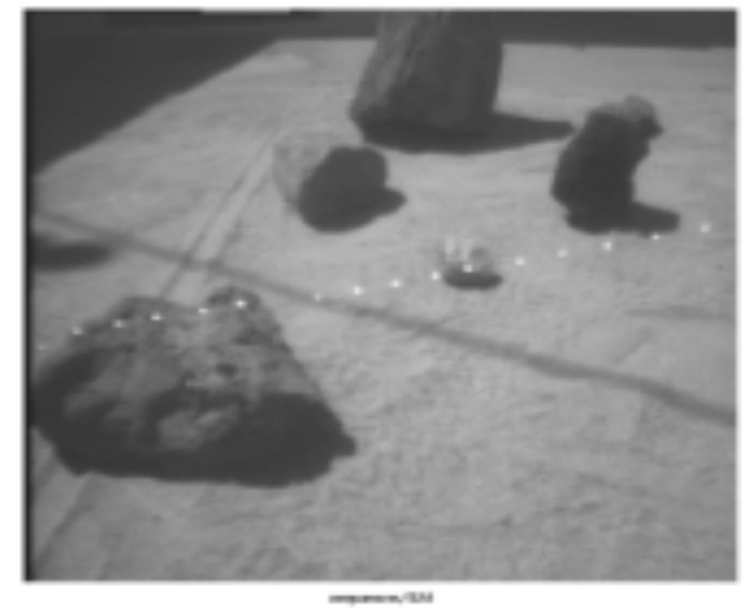
Structured Light: Onboard Hazard Detection

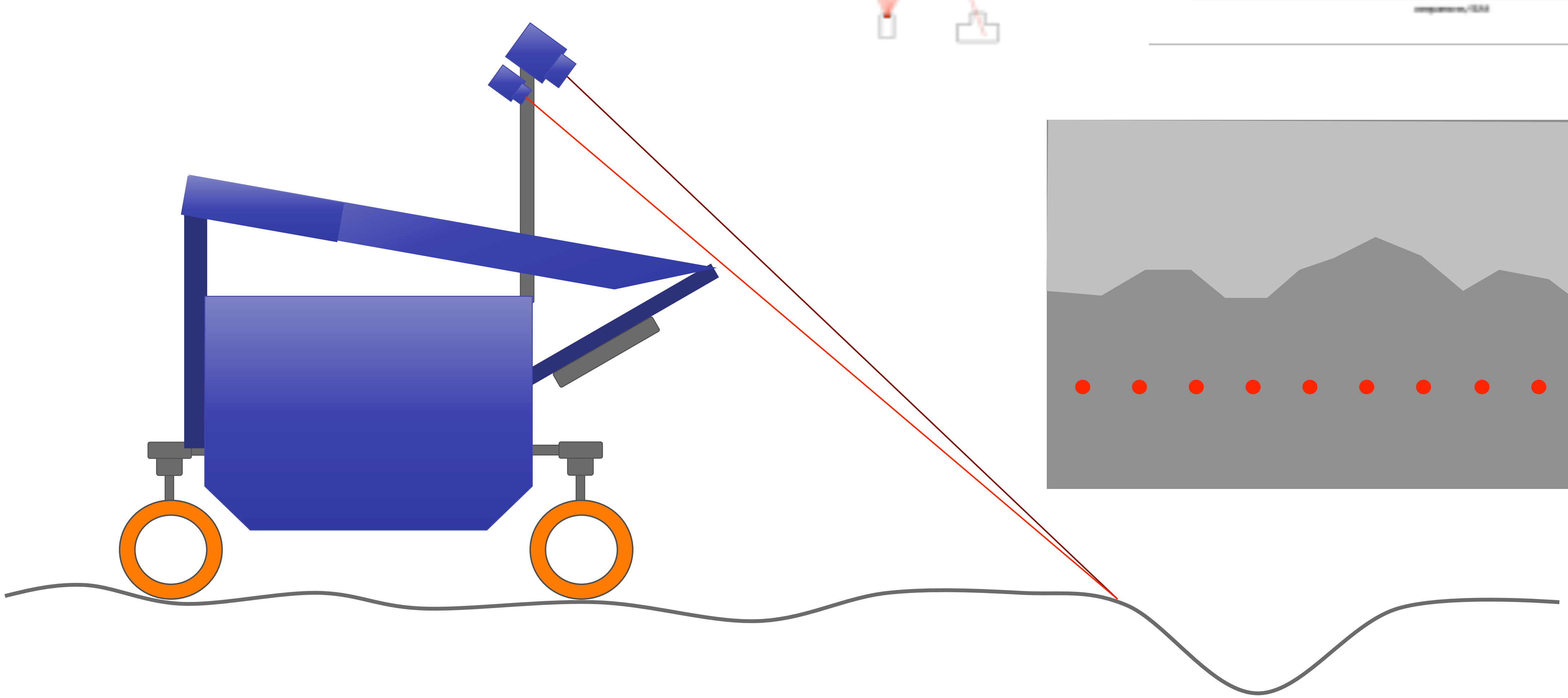
“Virtual Bumper”

Uses projected dots

Triangulation



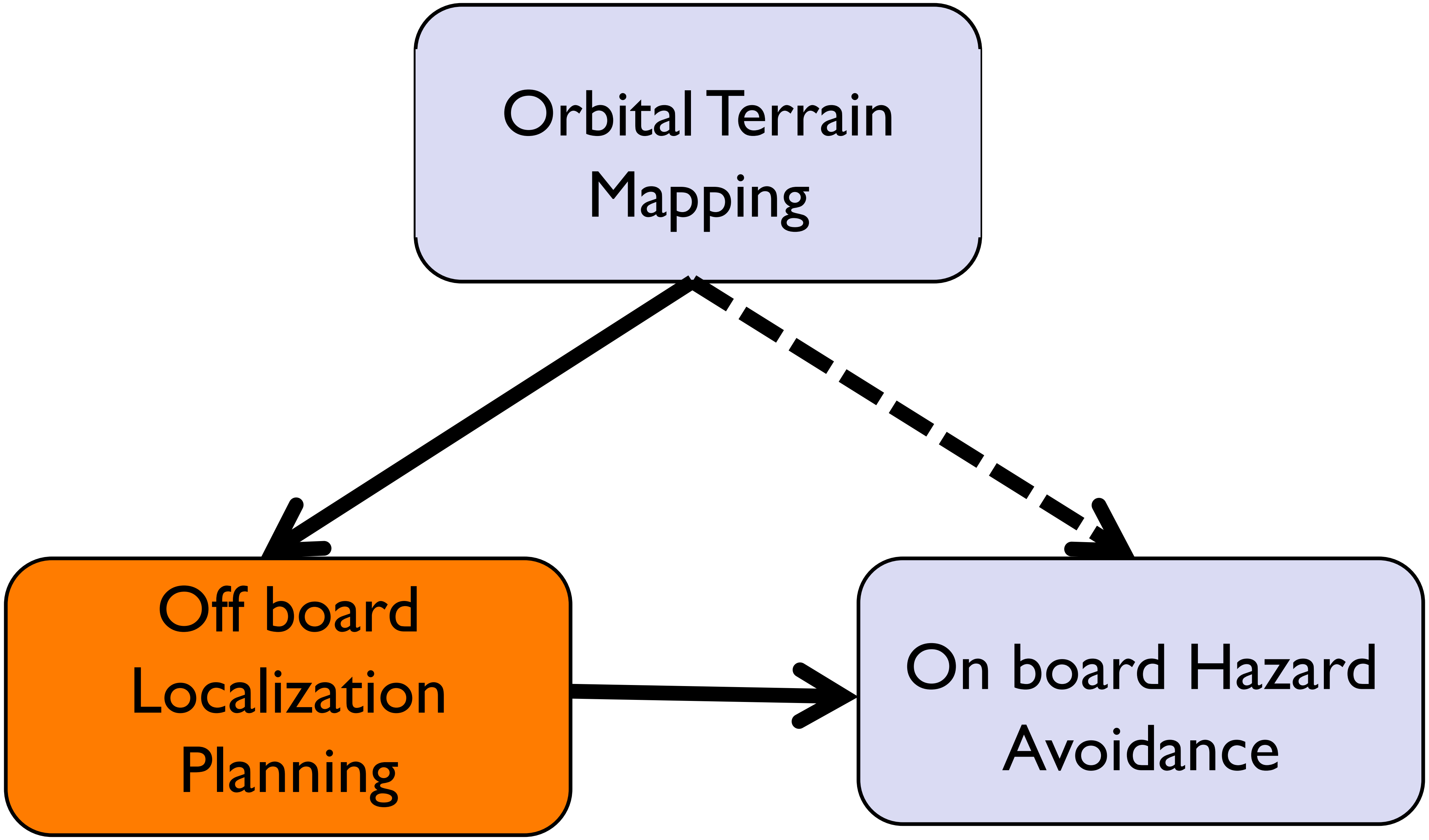




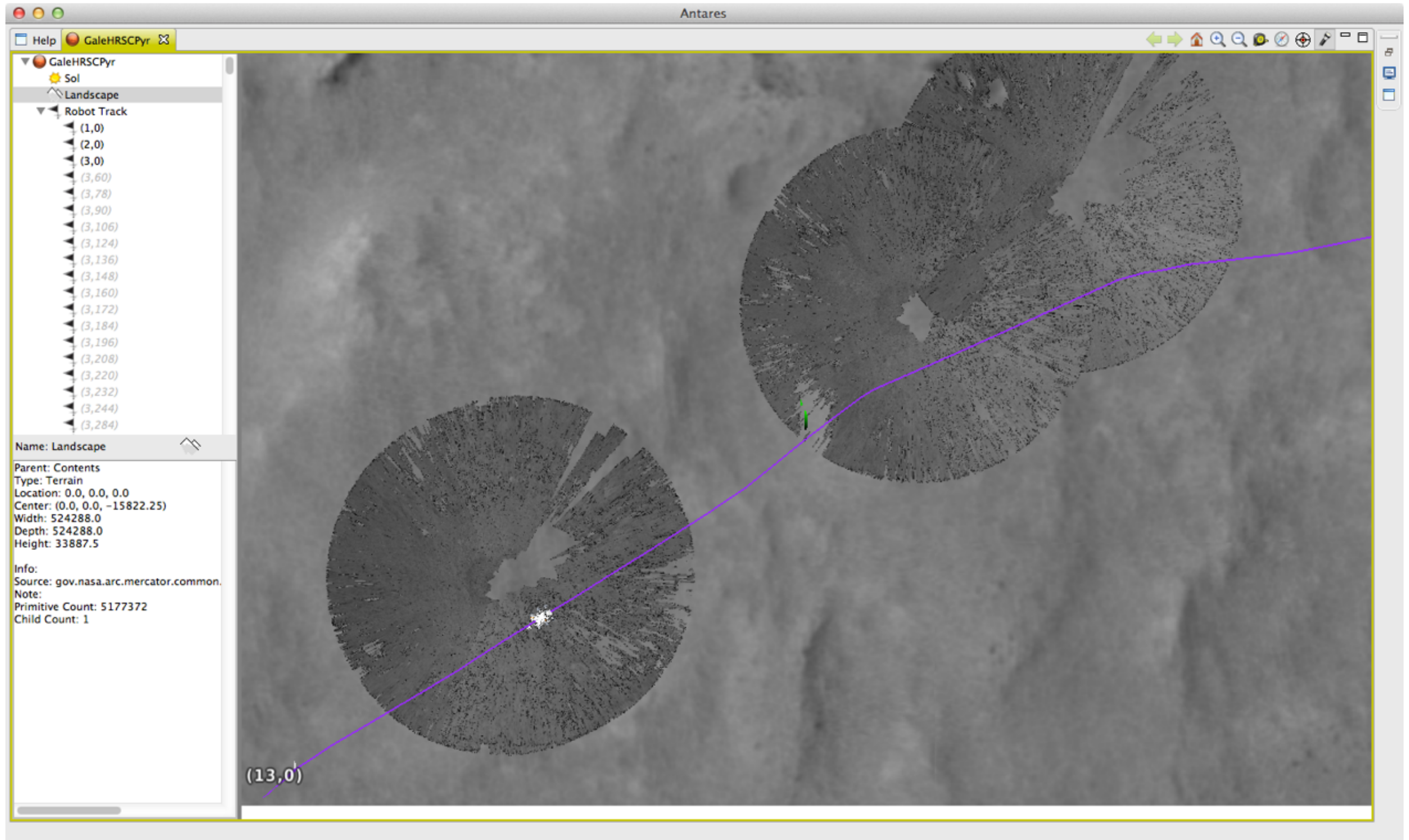
Structure Light Day Time with Color Filter

Structure Light at Night Time

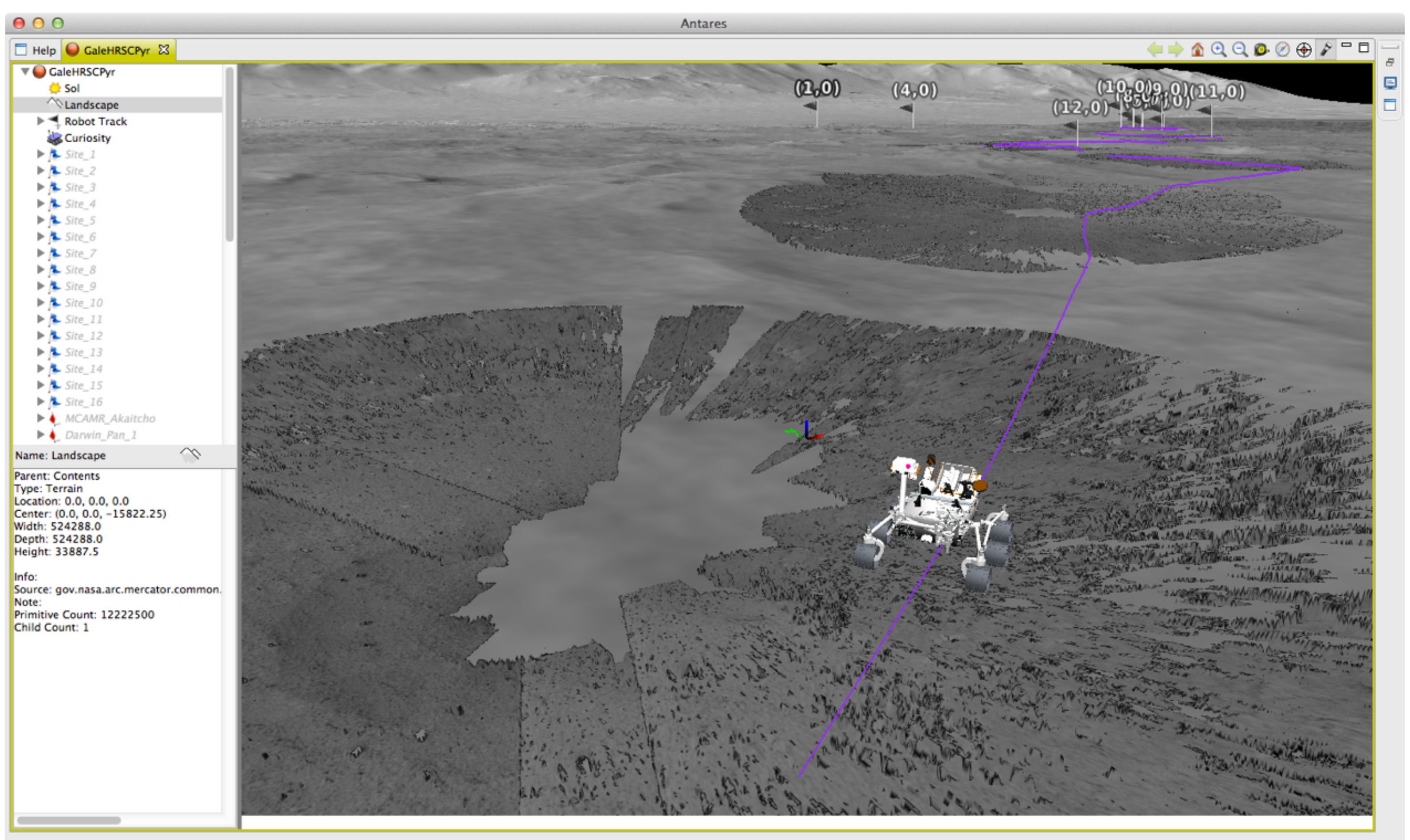
Planetary Rover Navigation



Mars Science Lab



Top view of MSL rover panoramas over Gale Crater HiRISE terrain



Oblique view of MSL rover panoramas over Gale Crater HiRISE terrain

Impact on automatic localization for planetary rover missions

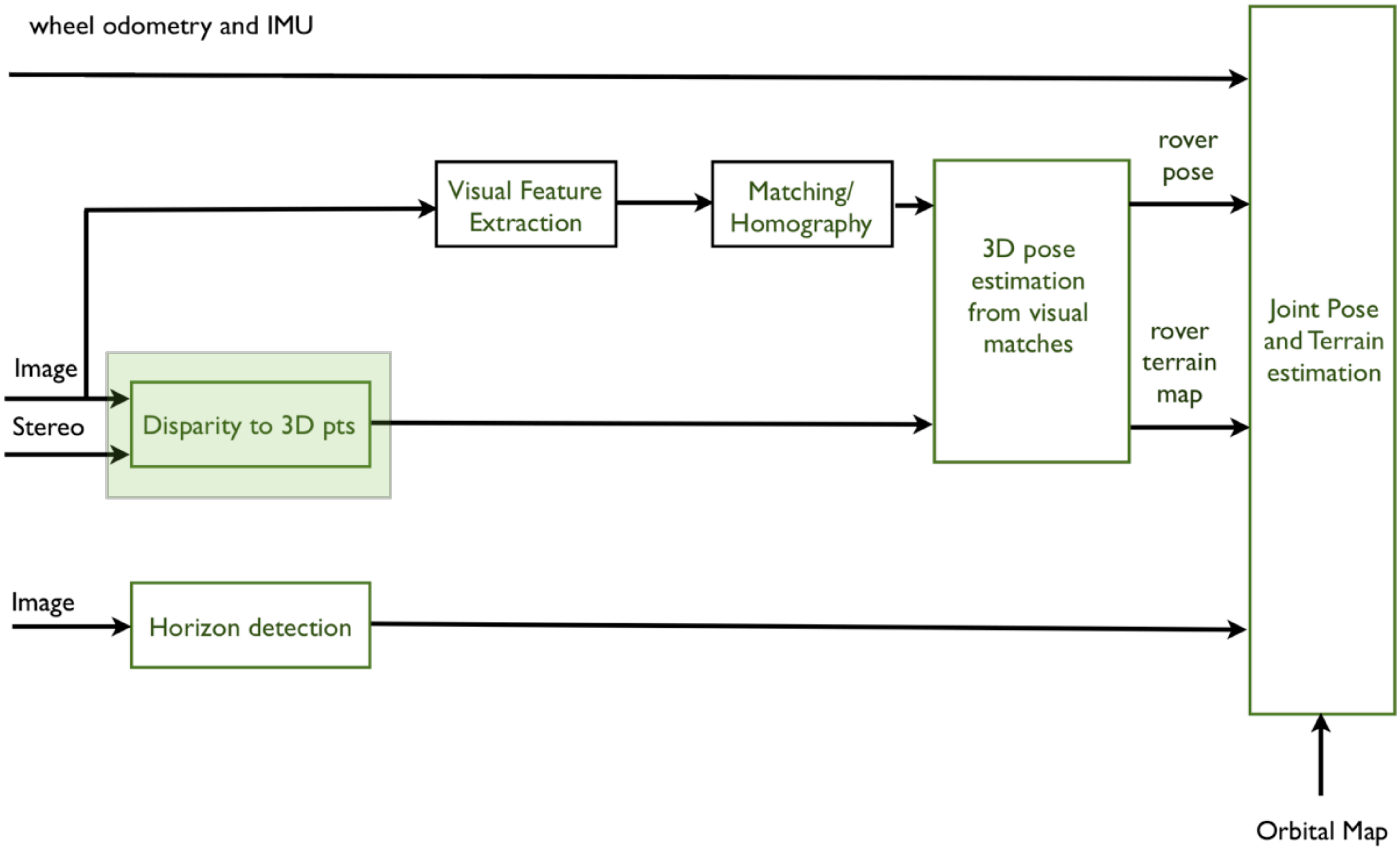
MSL mission localization through odometry is shown in purple lines in both top (top) and oblique (bottom) views.

The final partially automatic localization is shown by the rover panorama positions over the Gale crater HiRISE terrain.

The offset between odometry and final rover localization is generally of about 10-20m.

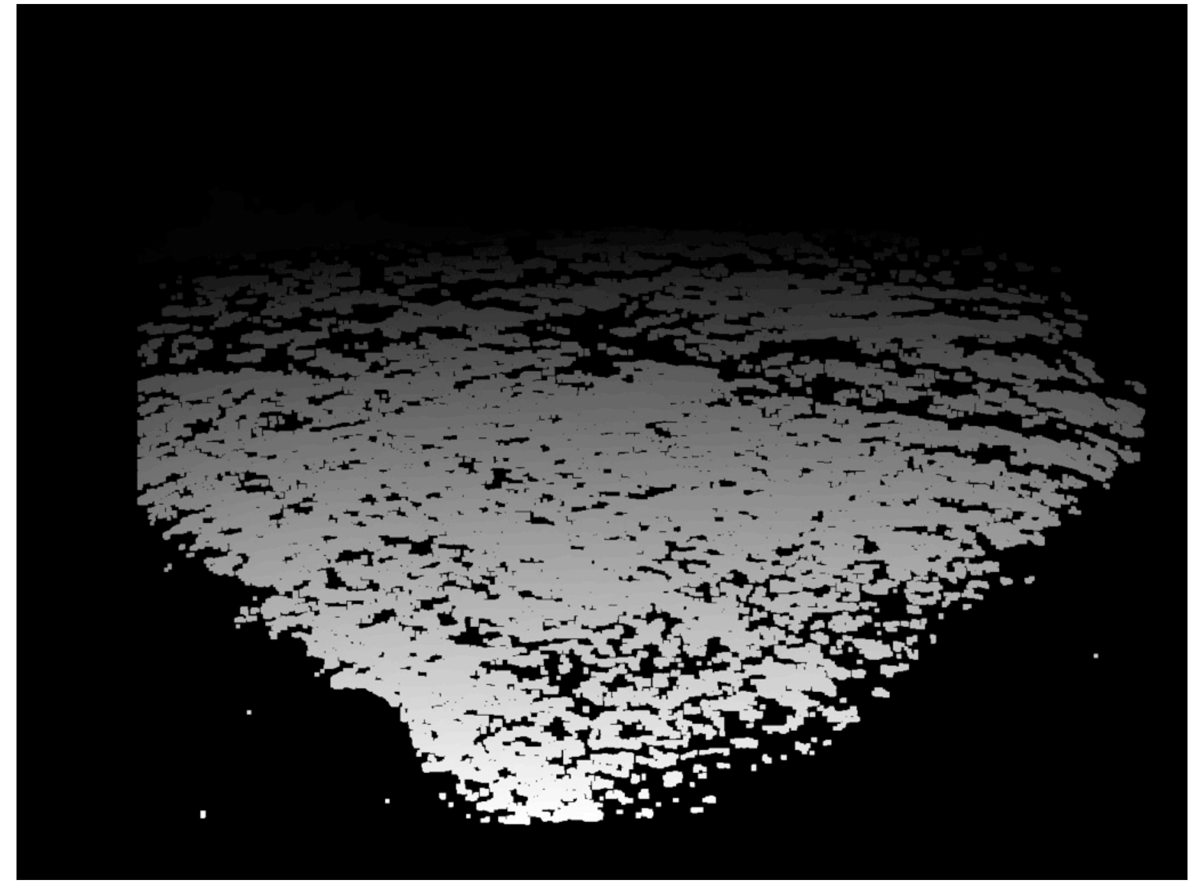
Fully or partially automatic localization using the system prototyped here will allow MSL and future missions for rapid turn around localization and support long traverse autonomous navigation.

Off board Localization System



Stereo Processing

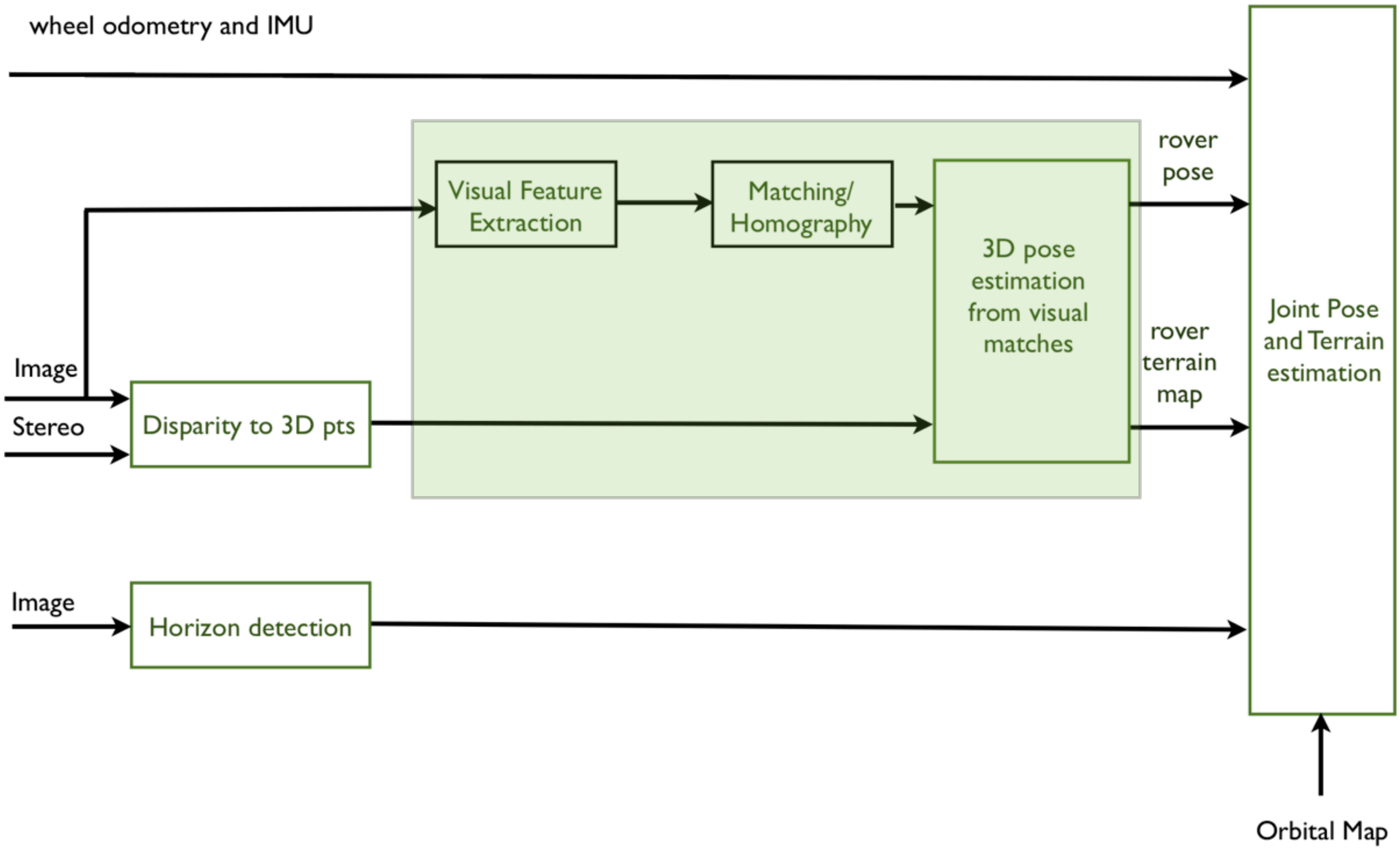
Rectified left image



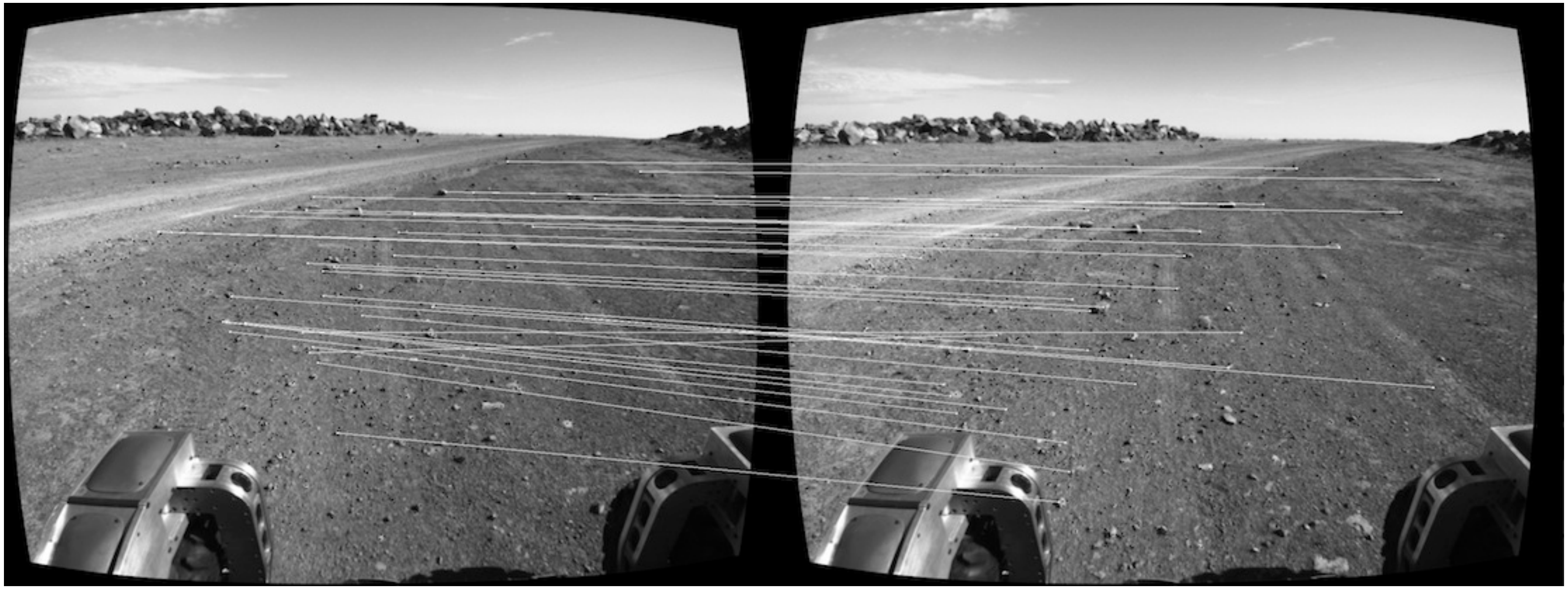
Disparity map

calibration package using OpenCV
block matching based disparity computation OpenCV
outlier rejection using morphological filtering
run time 6 fps
terrain reconstruction at 40m, 30cm baseline, 1388x1088 image size

Off board Localization System



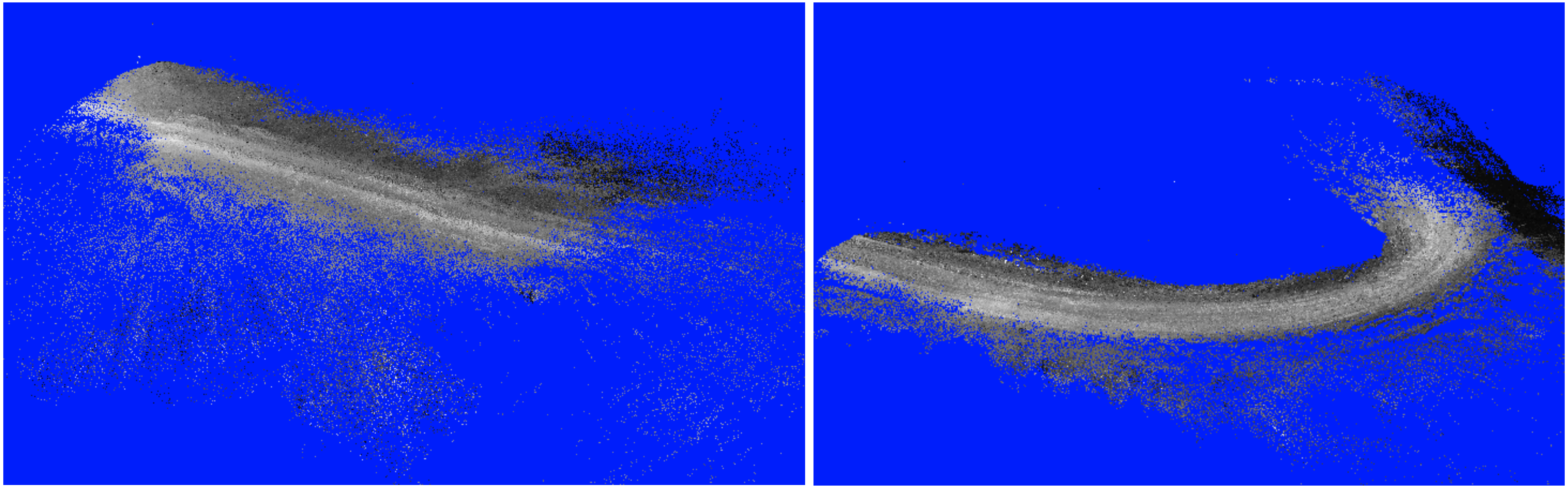
Stereo Visual Odometry



BRISK Visual Feature Matching.

SURF Visual Feature Matching.

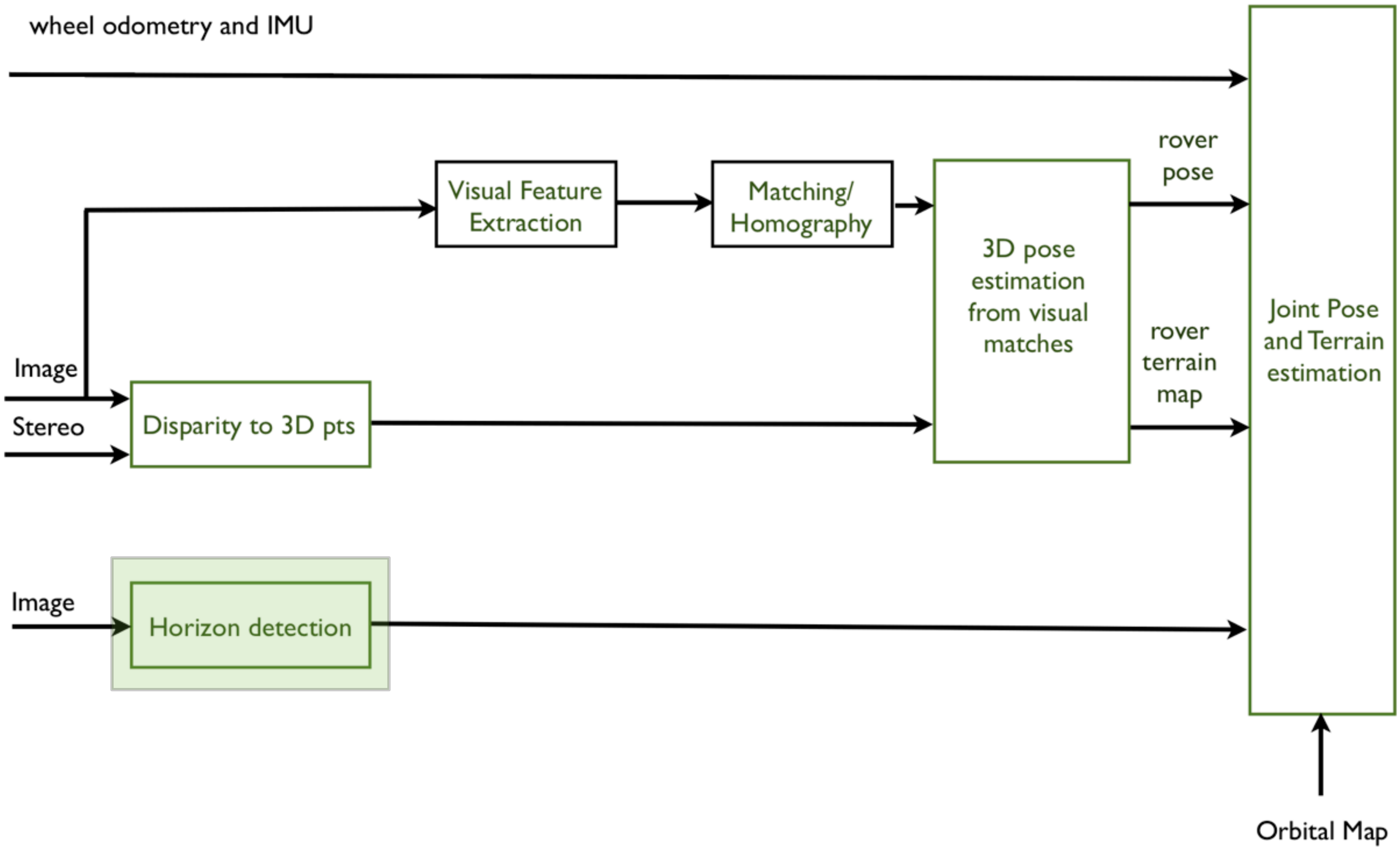
Stereo Visual Odometry



Mapping results of the stereo visual odometry system.

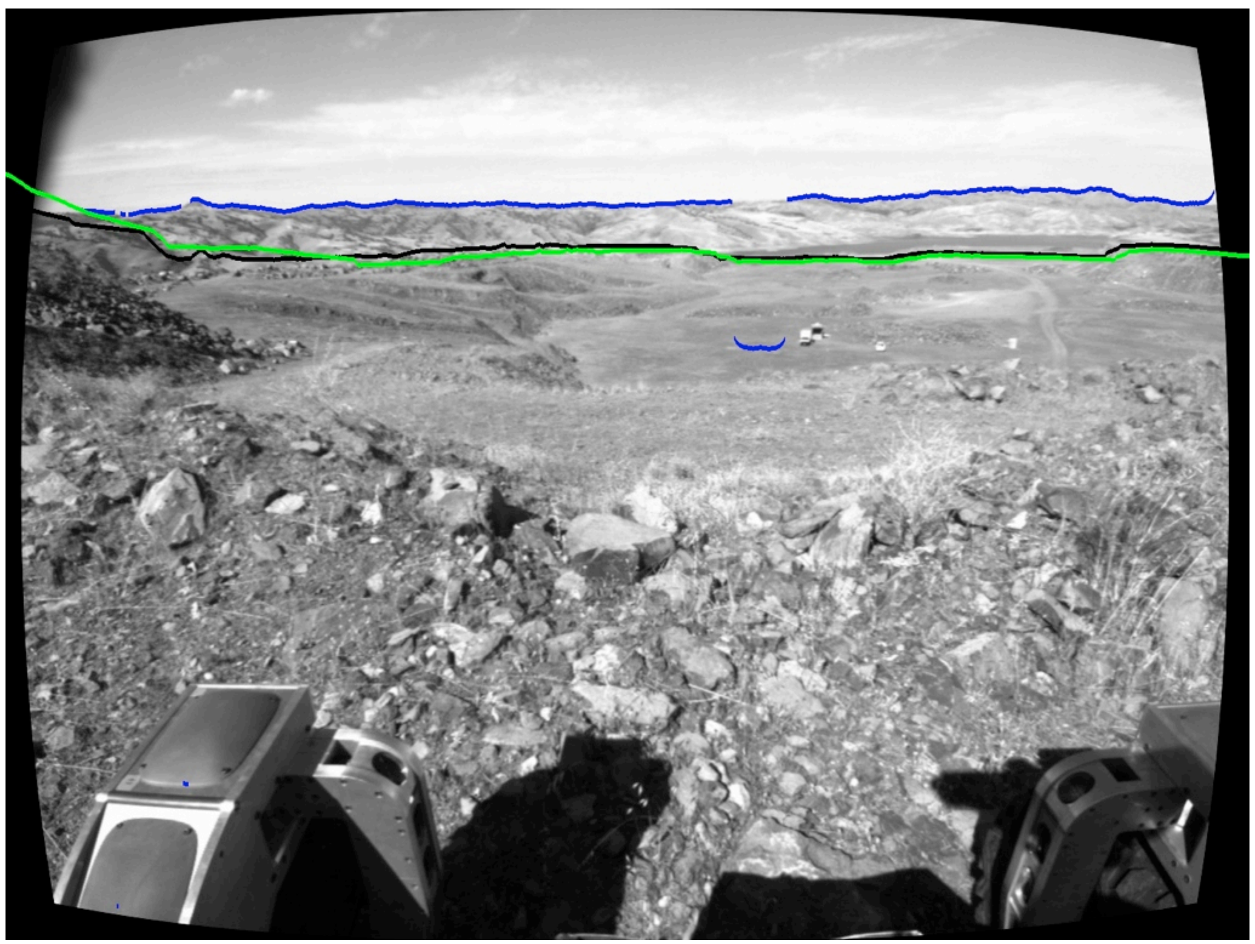
Uses stereo reconstructed terrain.
Visual feature extraction SIFT, SURF, **BRISK**,ORB.
Descriptor matching using FLANN, homography based outlier detection (RANSAC).
Pairwise 3D pose estimation using stereo results.
3D outlier rejection
Running time: 8 fps (BRISK)

Off board Localization System

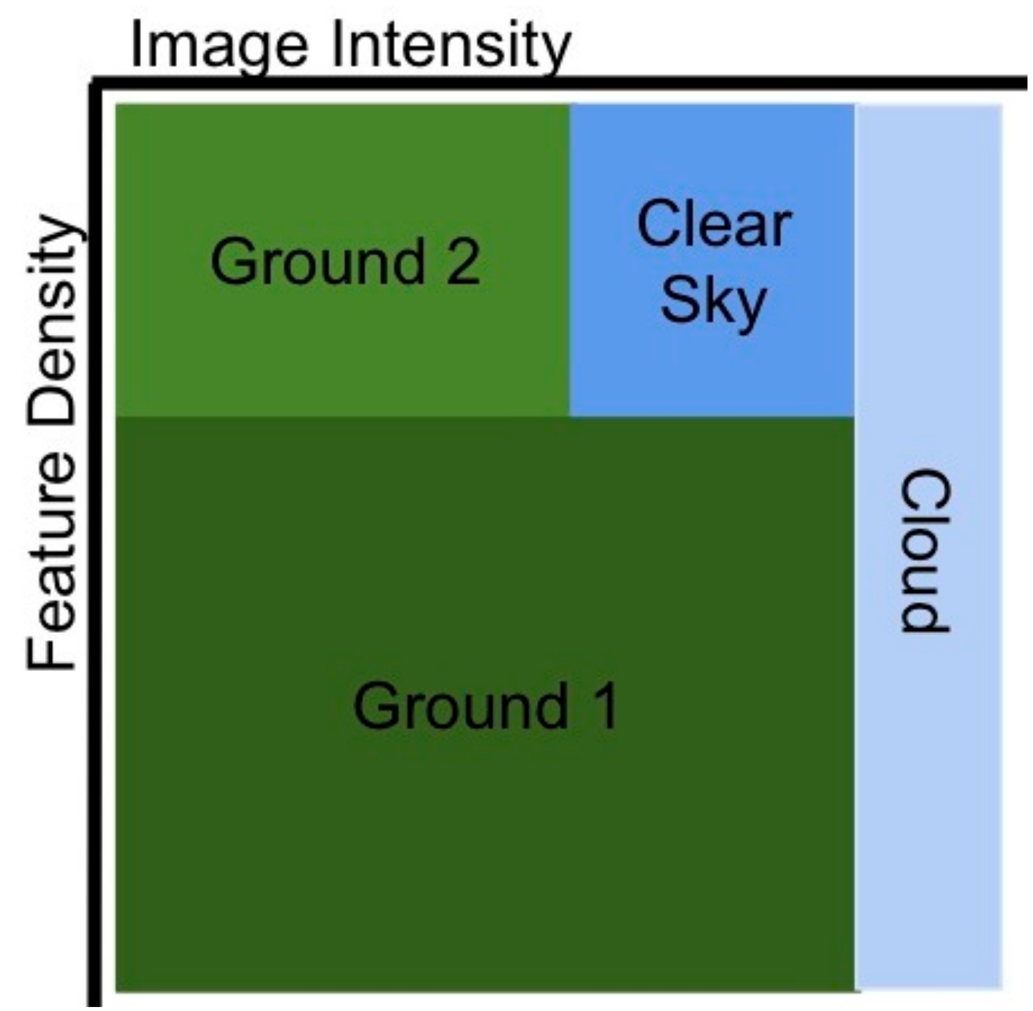


Horizon Detection

Real time horizon detection.
Method for gray scale imagery to be used in various planetary environments.
No training set imagery is used.

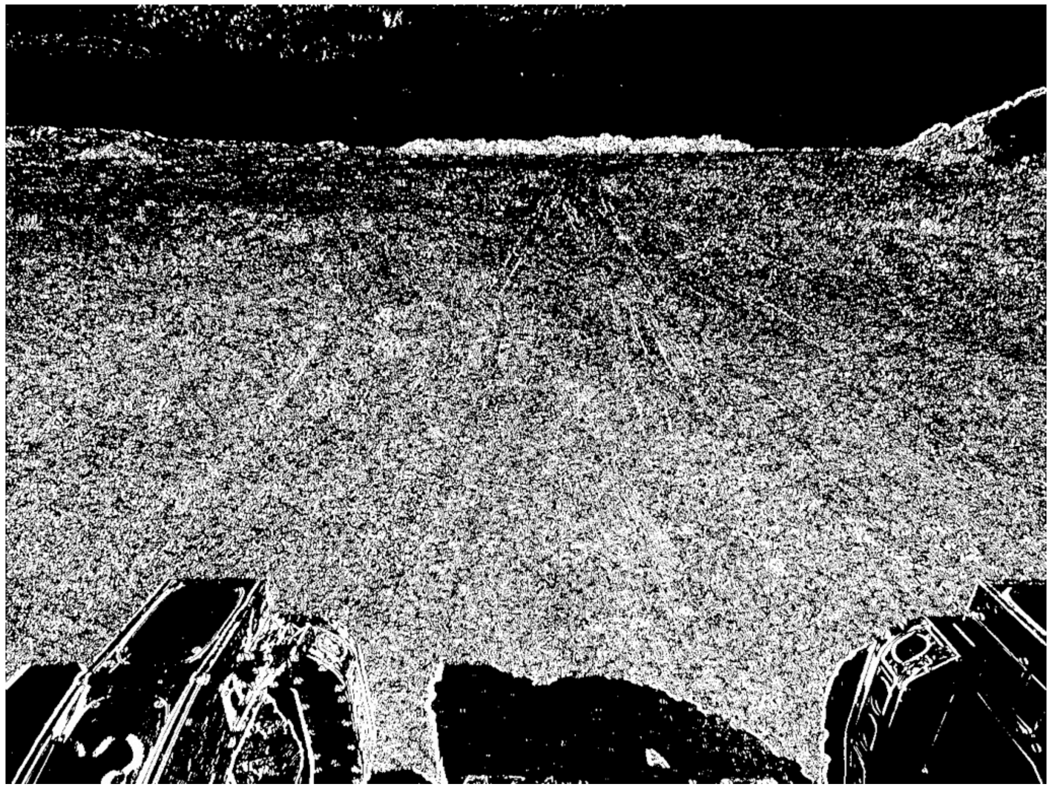


Rectified rover image



Sky and ground distribution

Horizon Detection



Edge detection response.

Intensity and edge density pixel segmentation

Edge detection

↓

Block average (integral image)

↓

Intensity and edge density pixel probability computation

↓

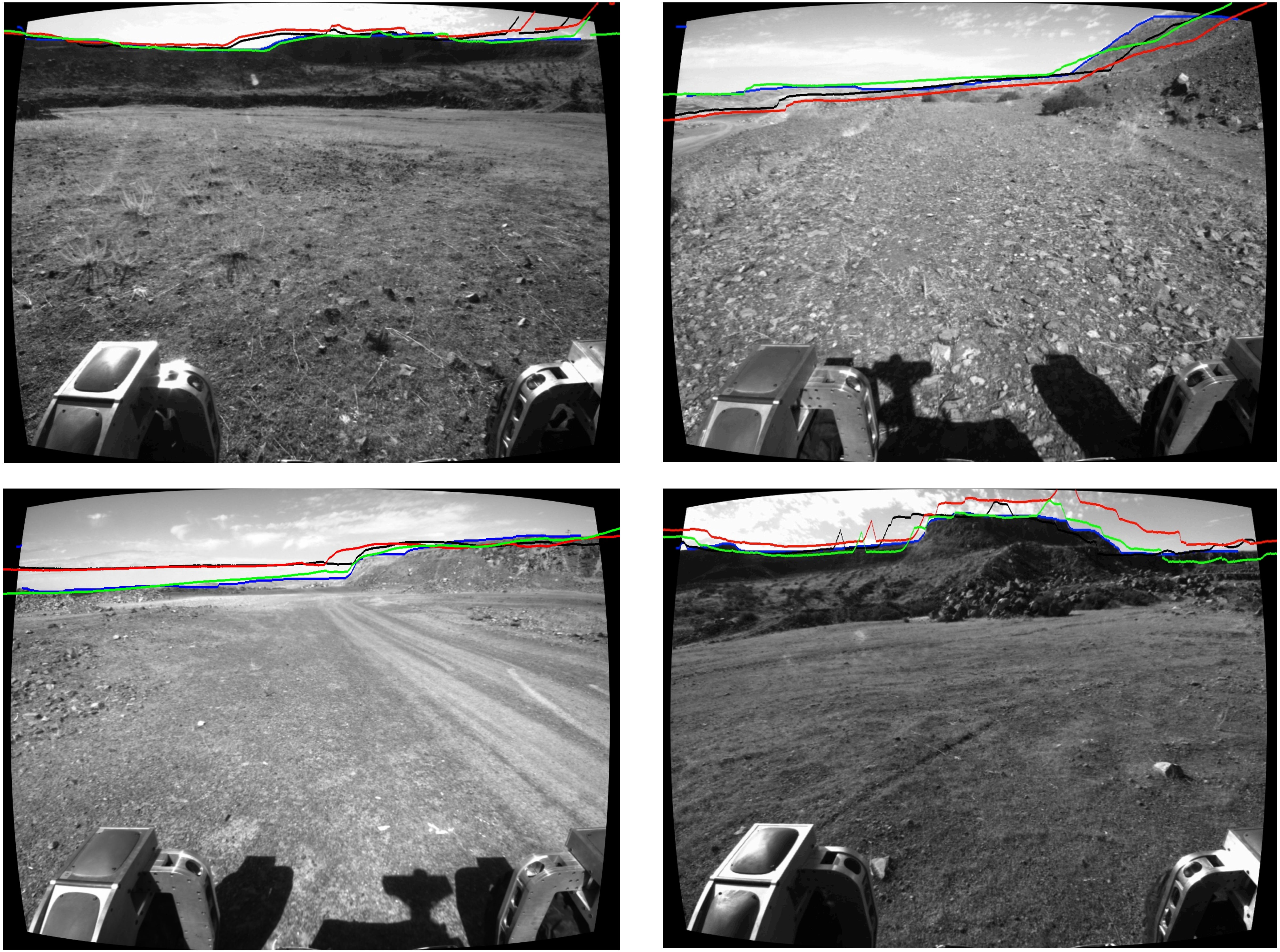
Column probability computation

$$P(\mathbf{O}_j|\mathbf{Q}_j) = \prod_{i=1}^{k} P(q_{ij} = s) \prod_{i=k+1}^{H} P(q_{ij} = g)$$

↓

Left to right segmentation smoothing

Horizon Matching



Horizon Rendering and Matching

Horizon Matching Cost Function $Q_h(\mathbf{R},\mathbf{T}) = \sum_i (Hd_i - Hr_i(\mathbf{R},\mathbf{T})))^2$

i is the image column

Hd_i, Hr_i are the rows corresponding to the detected and rendered horizon.

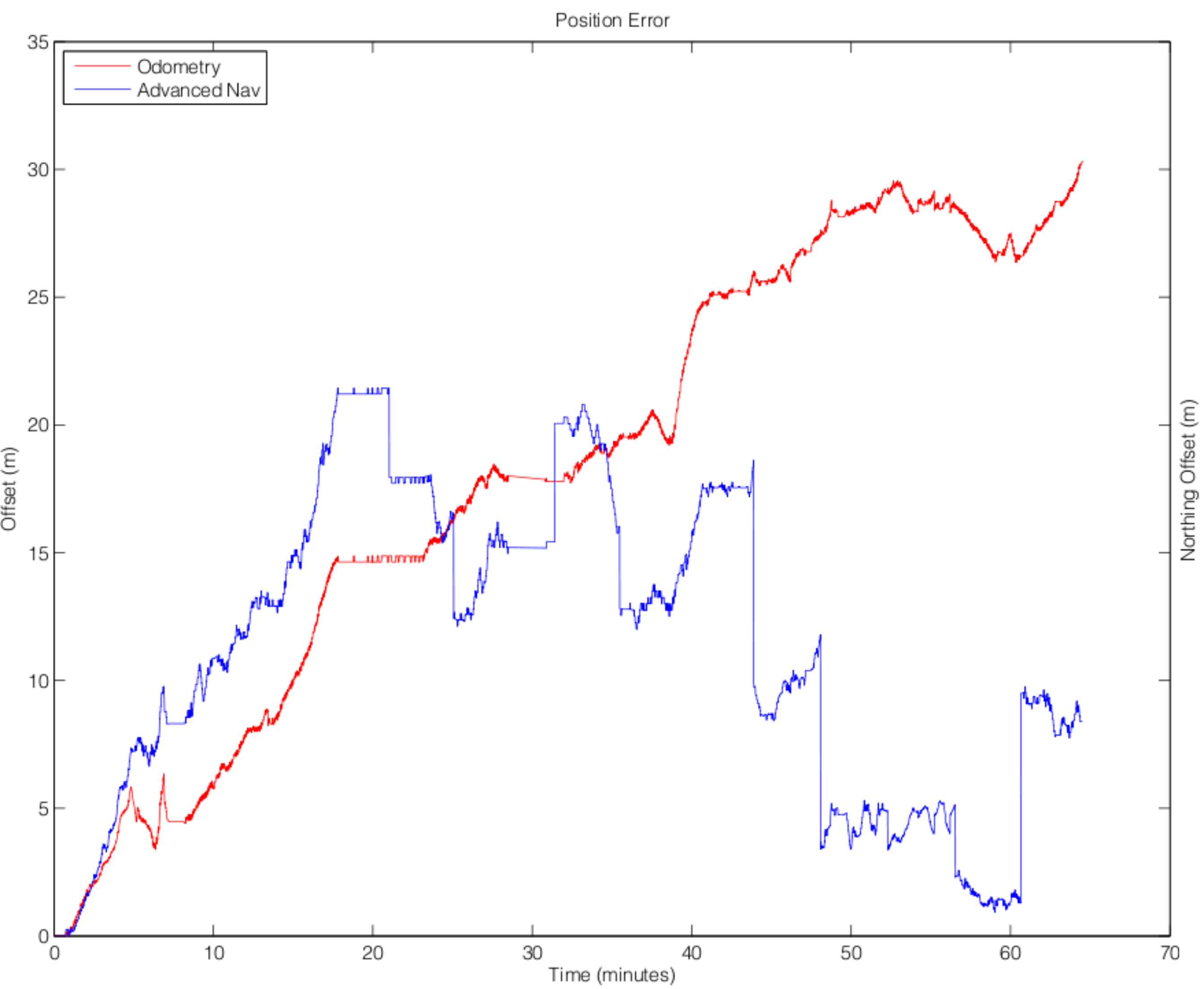
- multiple restart solution
- number of restarts increases over time to account for accumulated errors
- every 500 frames, <5s/frame.

$$Conf(\mathbf{R},\mathbf{T}) = \frac{Q_h(\mathbf{R},\mathbf{T})}{\sum_k Q_h \mathbf{R}_k, \mathbf{T}_k}$$

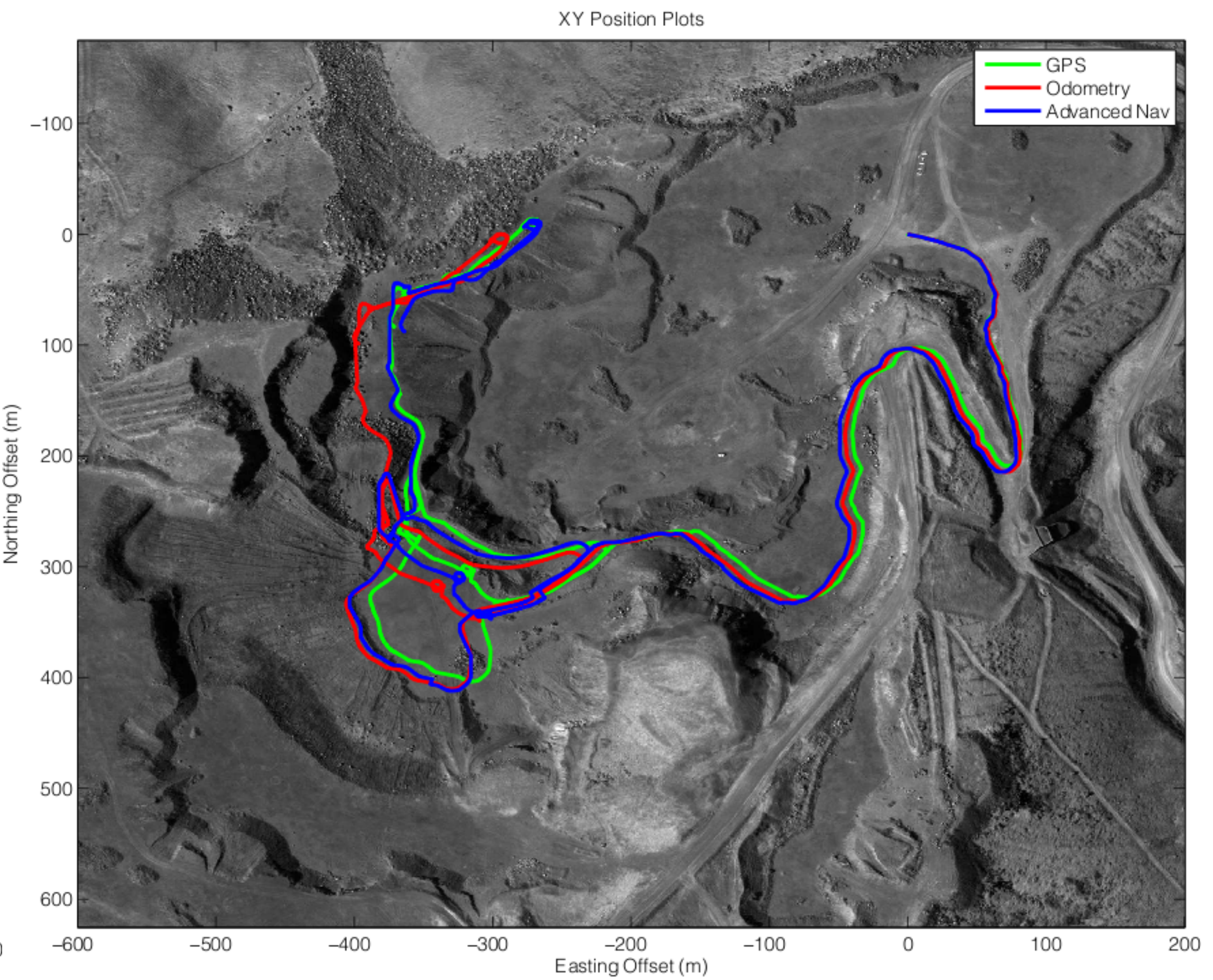
Horizon Rendering

Orbital Terrain Generation Ames Stereo Pipeline form Digital Globe Imagery 0.5m/pixel
Overlay over USGS Terrain models at 10m/pixel.
OpenGL or Mesa based solution for terrain rendering.

Localization Results



Localization errors wheel odometry (red) vs advanced navigation (blue)



Estimated traverse tracks over Basalt Hills area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