



Active Terrain Relative Navigation with Surface Mapping Sensors

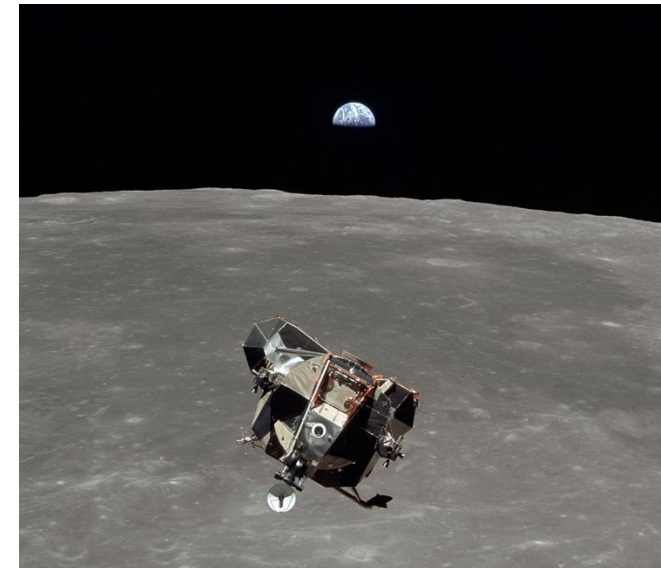
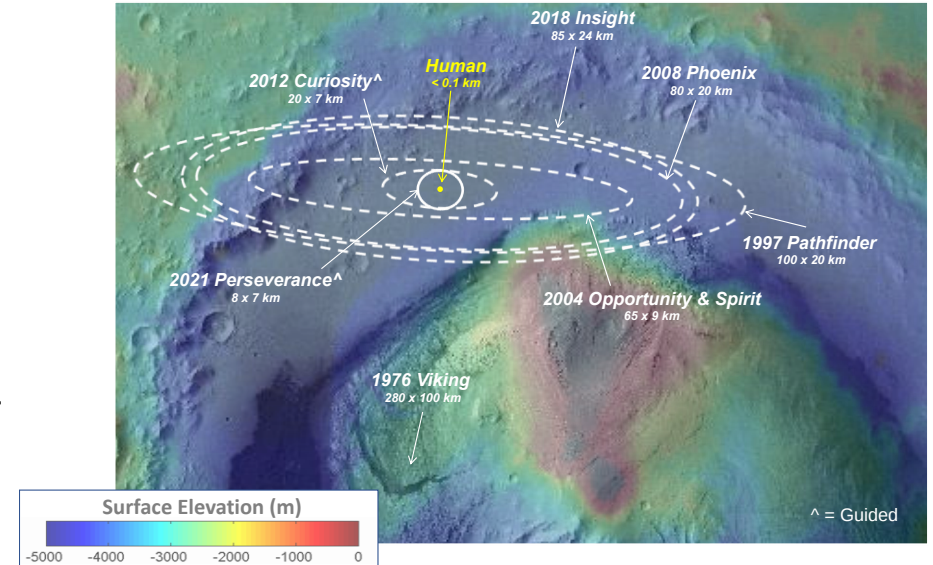
JSC Center Innovation Fund (CIF) Project

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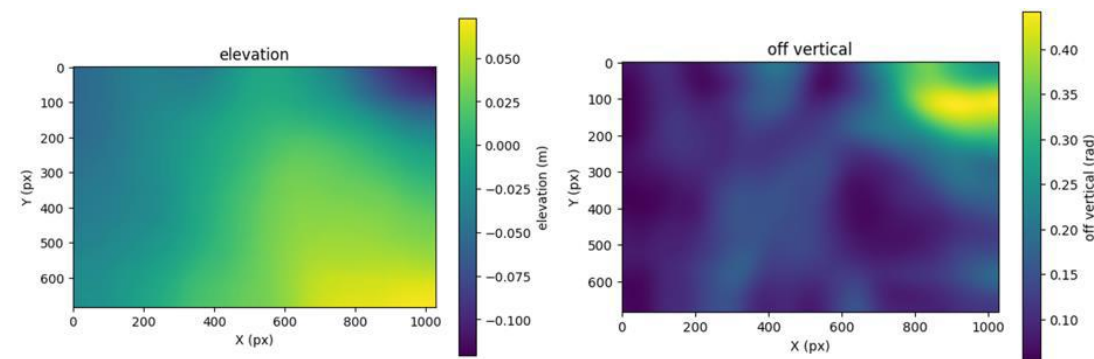
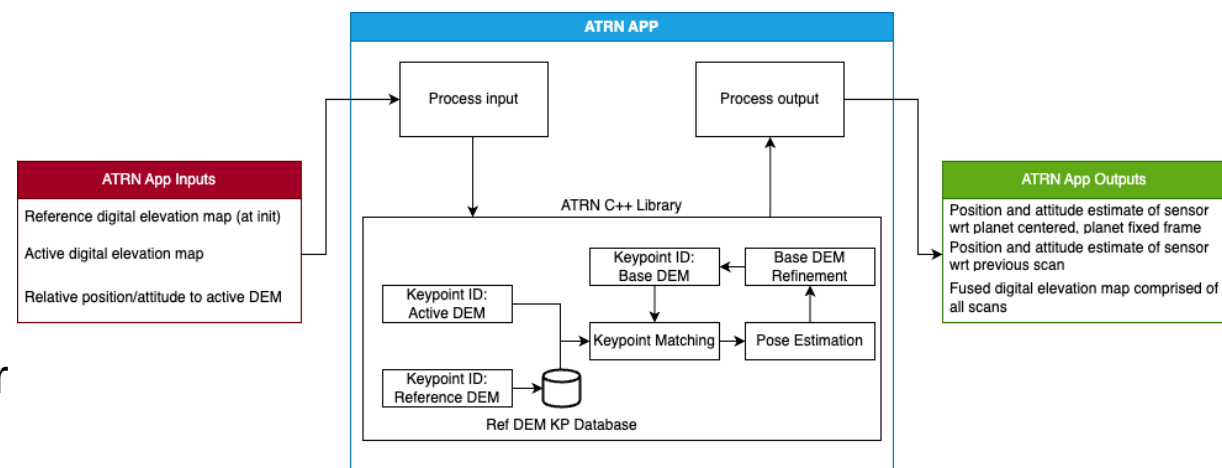
Motivation

- Beginning with Artemis 4, HLS has a requirement to land within 50m of targeted landing site under **any lighting condition**
- Current SOTA for planetary landing precision:
 - Mars: 7-8 kilometers (Perseverance)
 - Moon – Equatorial: < 60 meters (JAXA Slim)
 - Moon – South Pole: 250 meters (IM-2)
- Passive (camera-based) approaches are impractical for permanently shadowed or poorly mapped regions
- Sensing Need: Active 3D terrain mapping sensors for navigation and hazard detection/avoidance
- New algorithmic methods for onboard processing are also required to realize terrain map-based navigation and overcome 3D feature identification challenges exhibited by SOTA methods including:
 - Feature extraction failure due to a lack of sharp contrast regions (topographically)
 - Non-uniqueness in the presence of homogenous terrain
 - Inconsistent feature locations due to variable ground plane definition
- Algorithmic Need: robust identification and description method that is **rotationally and scale invariant**



Objectives

- Develop new rotationally and scale invariant 3D keypoint identification and correspondence methods to enable navigation with **errors on the order of meters**
- Develop a universally compatible and computationally efficient pipeline that can be run on current SOTA space flight hardware
- Address challenges associated with existing methods for 3D feature extraction of natural landscapes
- Develop modular standalone C++ library which:
 - Produces point-wise 3D position measurements which can be fed to a navigation filter
 - Generates high-resolution terrain map informed by successive LiDAR scans which can also inform hazard detection and safe-site-identification
 - Performs absolute localization (inertial position and attitude) using reference digital elevation map
 - Performs relative localization (LiDAR-based odometry) using opportunistic features

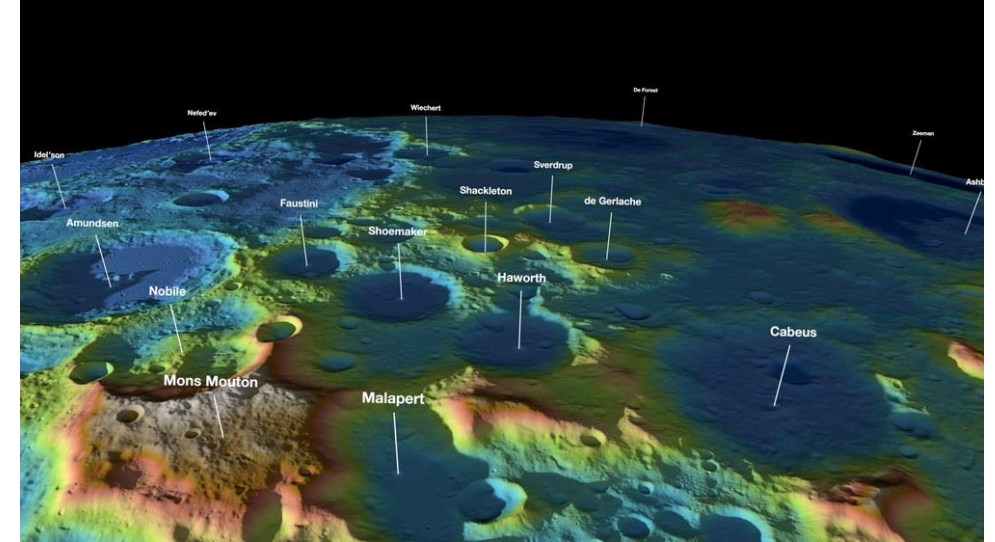


TOP: Localization pipeline framework

BOTTOM: Example output DEM and off-vertical map

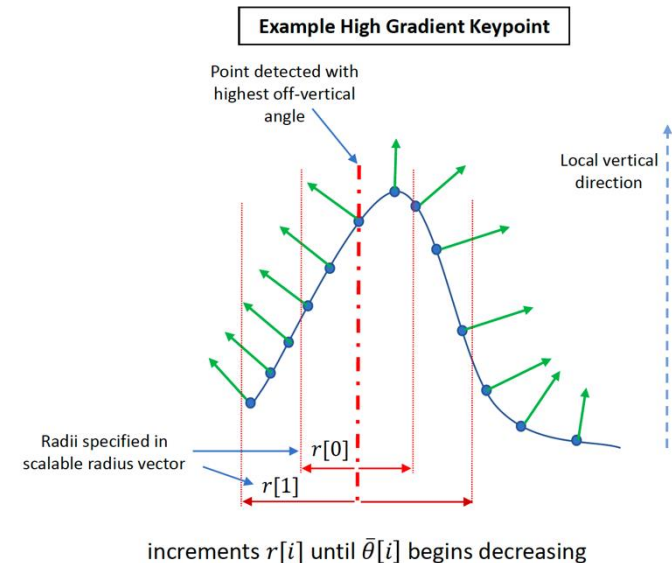
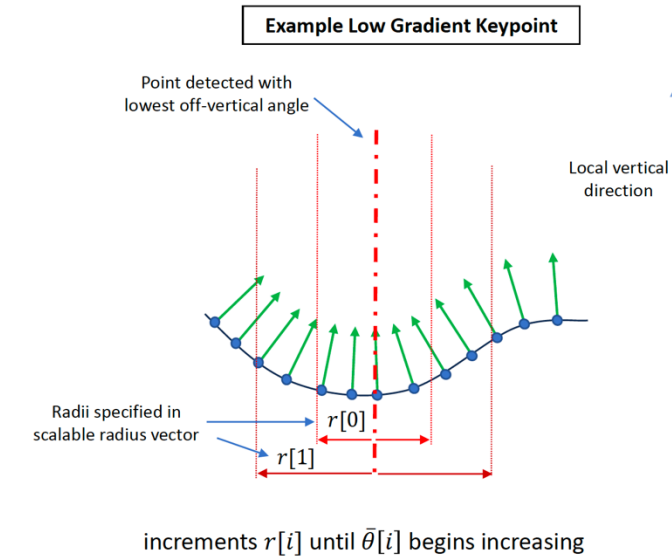
Use Cases

- Applicable to systems with any terrain mapping sensor (not just LiDAR) that yields a digital elevation map
- Descent and landing in unknown and/or dark terrains for vehicles equipped with active sensors
- Ground surface navigation
- No peripheral sensor input required (IMU, star tracker, etc.)



Methodologies – Feature ID

- Spatial gradient-based methods (low and high) with variable keypoint size
 - Search terrain off-vertical map for min/max values (low/high gradient method, respectively)
 - Modulate keypoint size until surface variation reaches max/min (low/high gradient method, respectively)
 - Compute surface statistics for descriptor vector
- Consistent between maps with similar ground plane definitions (< 5 deg) but not theoretically rotationally invariant

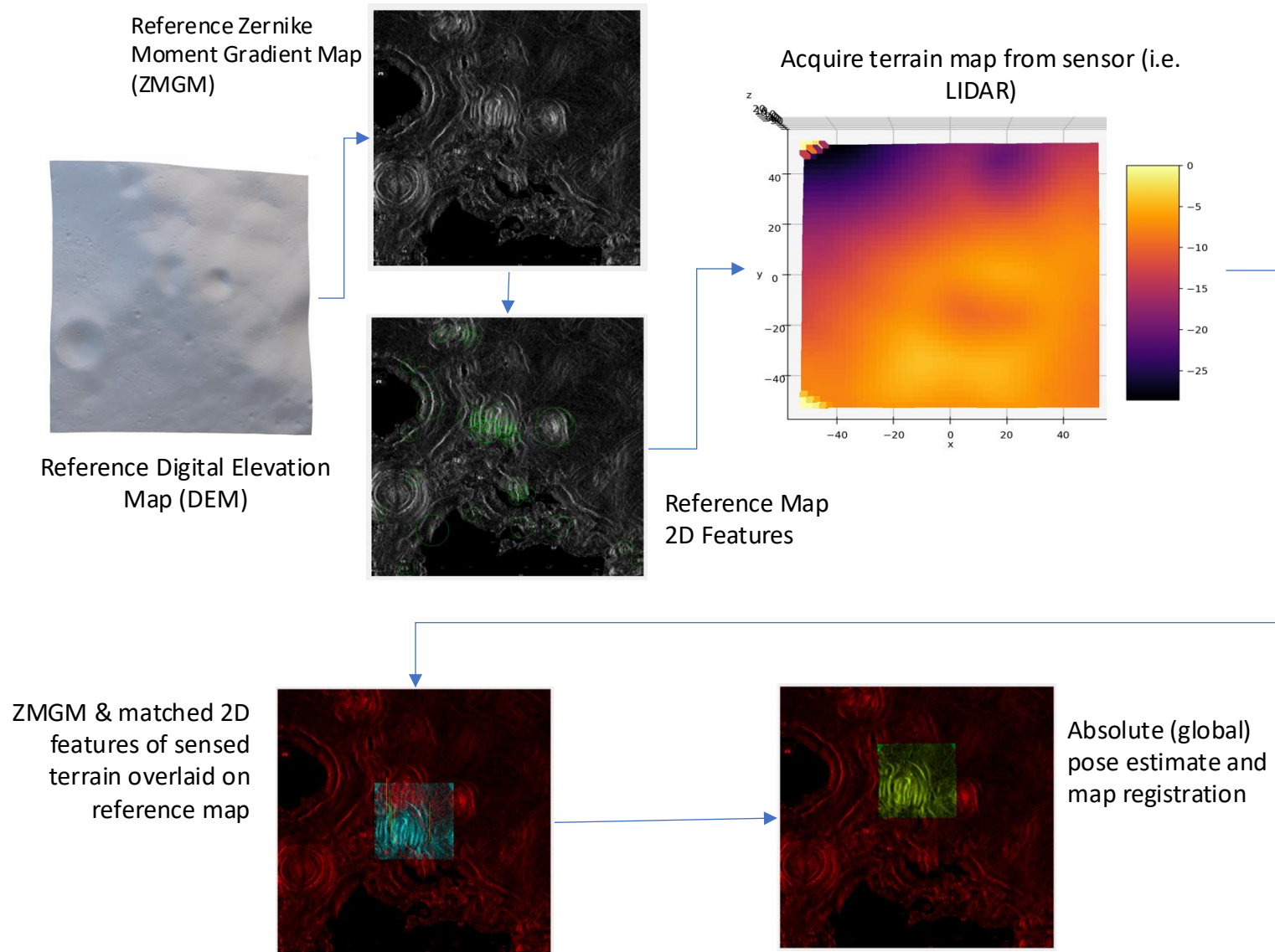


Methodologies – Feature ID

- Zernike Moment Gradient Map (ZMGM) method
 - Computes 3D Zernike Moment spatial gradient map to reduce the dimensionality of the digital terrain map in a rotationally invariant manner
 - Extract 3D features using proven 2D methodologies (SIFT, SURF, ORB, etc.)
 - Robust to sensor noise
 - Mathematically rigorous framework
 - Not dependent on ground plane definitions

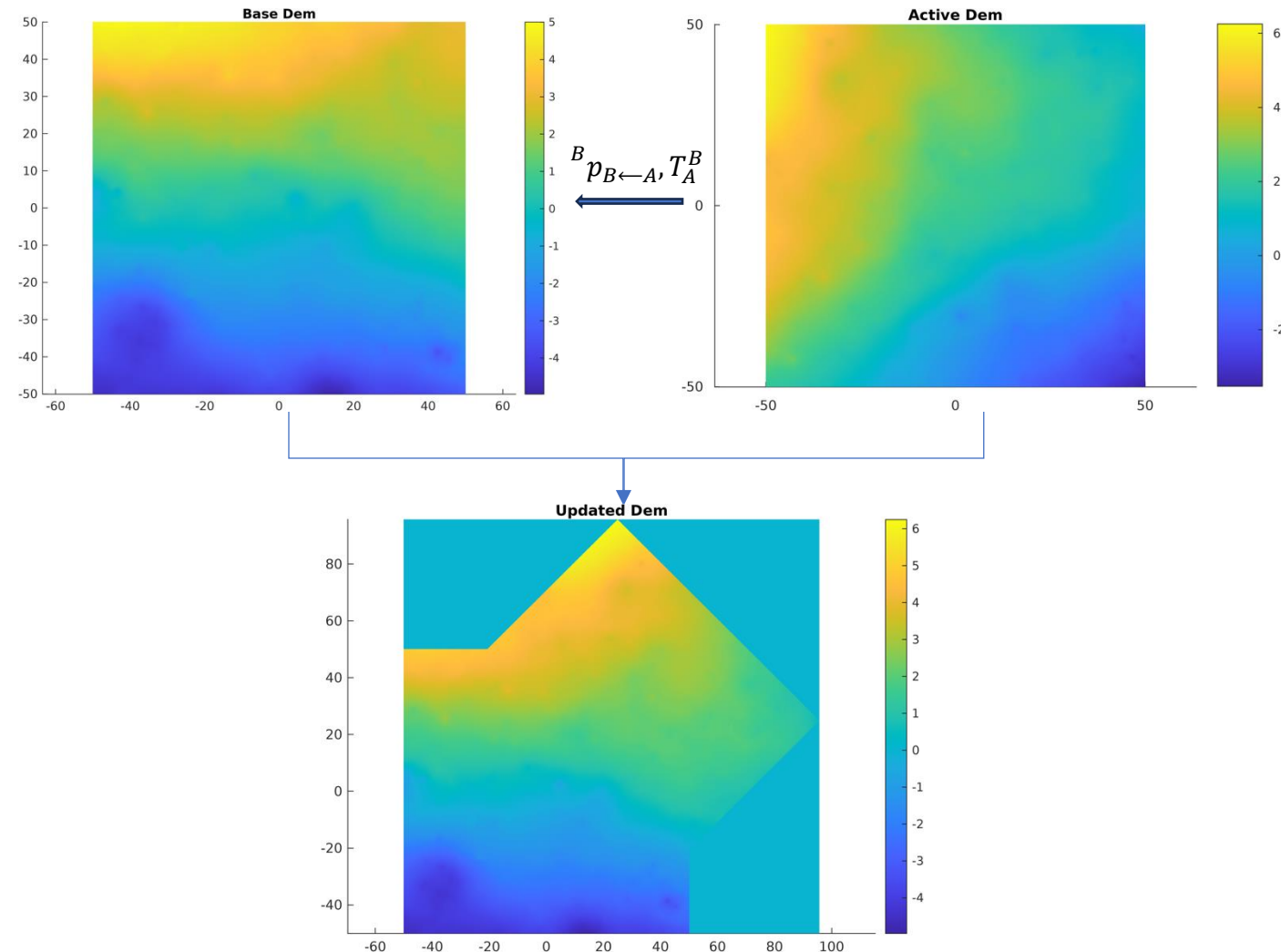


Methodologies – Localization w/ ZMGM



Methodologies – SLAM

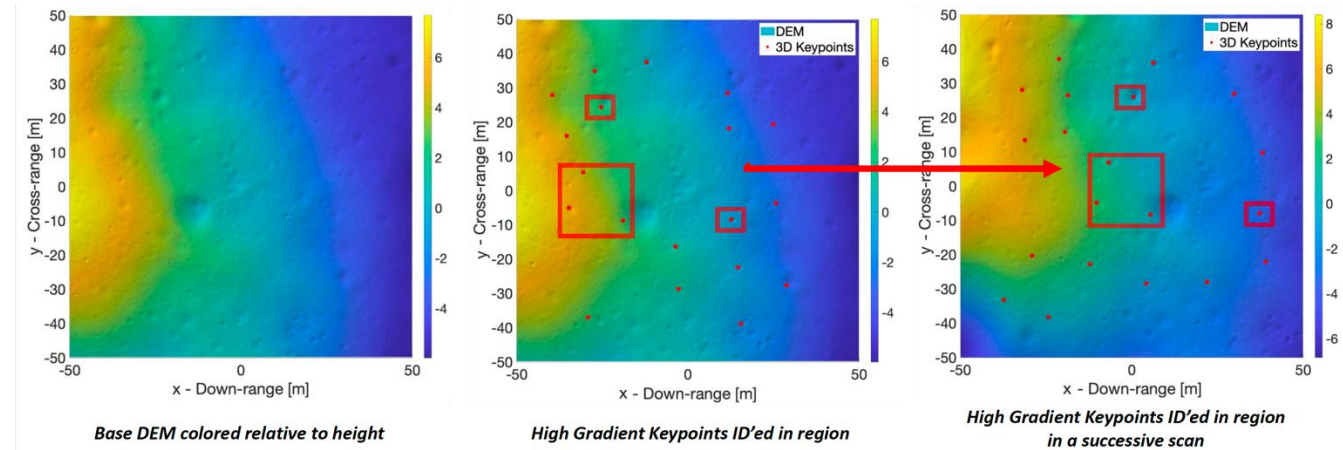
- Absolute and relative localization using SLAM methods
 - Yields position and attitude with respect to reference map frame and relative position and attitude between successive observations
 - Builds high-resolution map of observed terrain across multiple observations
- Outlier rejection to prevent false matches
 - RANSAC
 - Geometric invariant logic



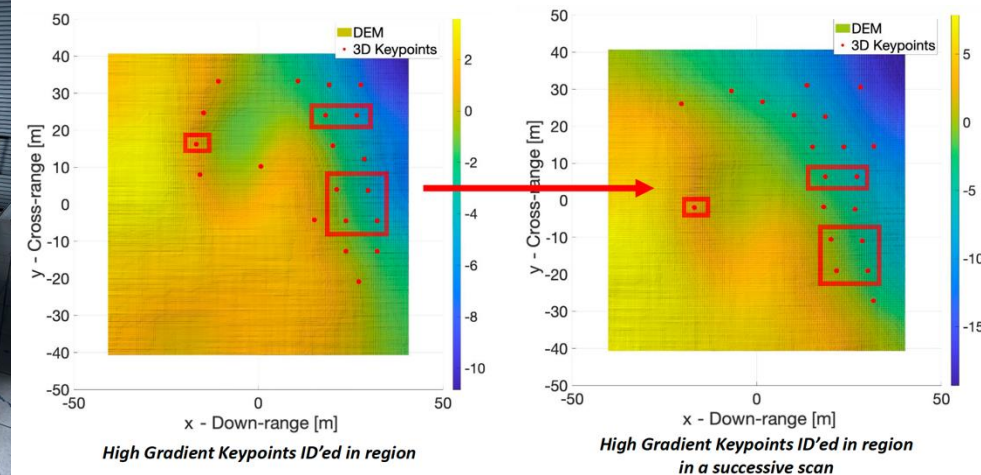
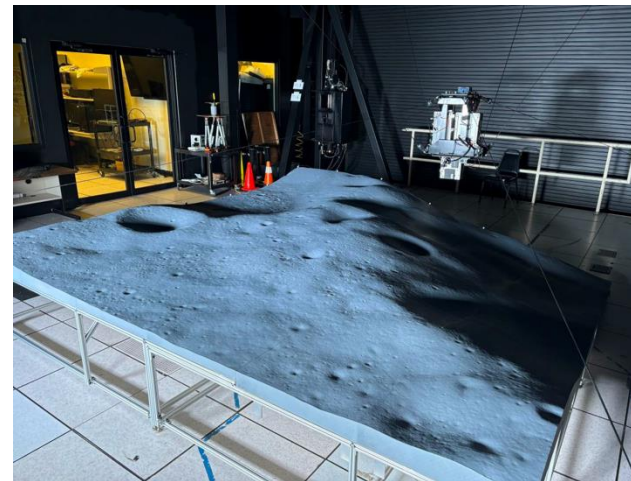
Simulation and Experimental Testing

- Prototype Python library tested with:
 - Simulated LiDAR scans from SPLICE project's high-fidelity Lunar descent and landing simulation
 - Real LiDAR point-clouds from Aeva Aeries II FMCW LiDAR in real-time HWIL environment in NASA JSC SENSS Lab
 - Absolute and relative localization error on the order of meters (dependent on onboard reference map)

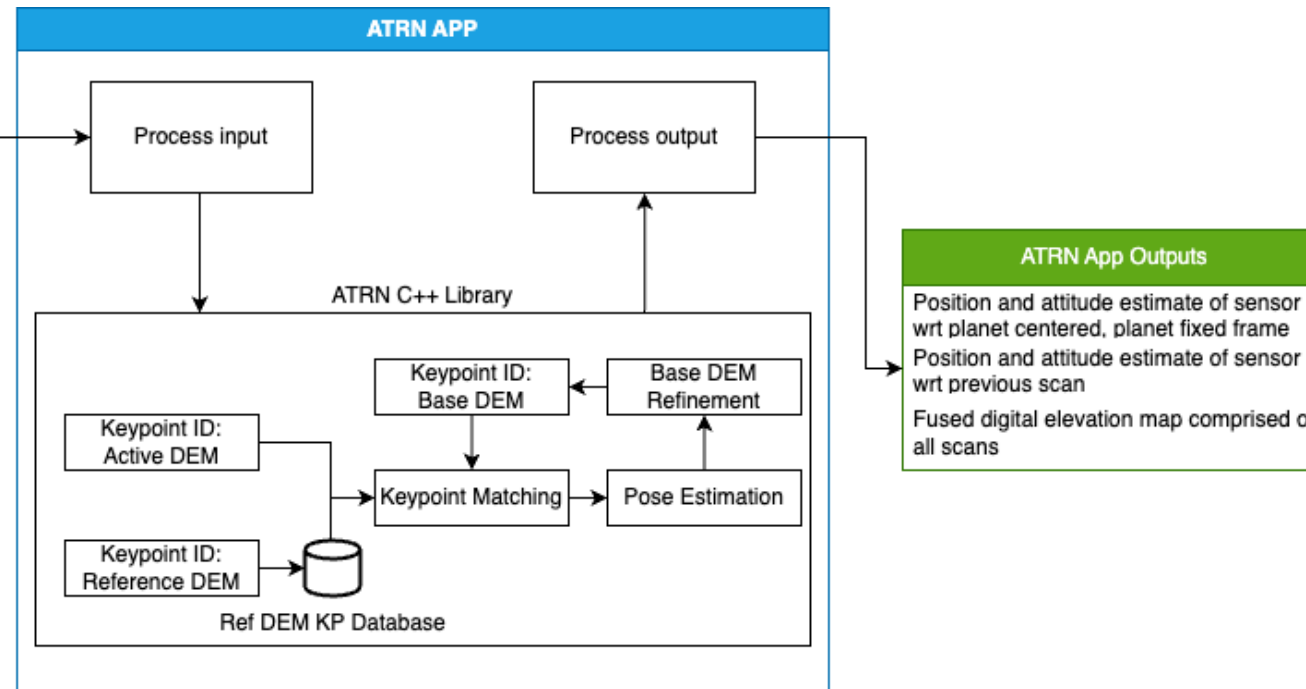
SPLICE Simulation DEMs



SENSS Lab Testing



ATRN C++ Library Development and Testing



Current Status:

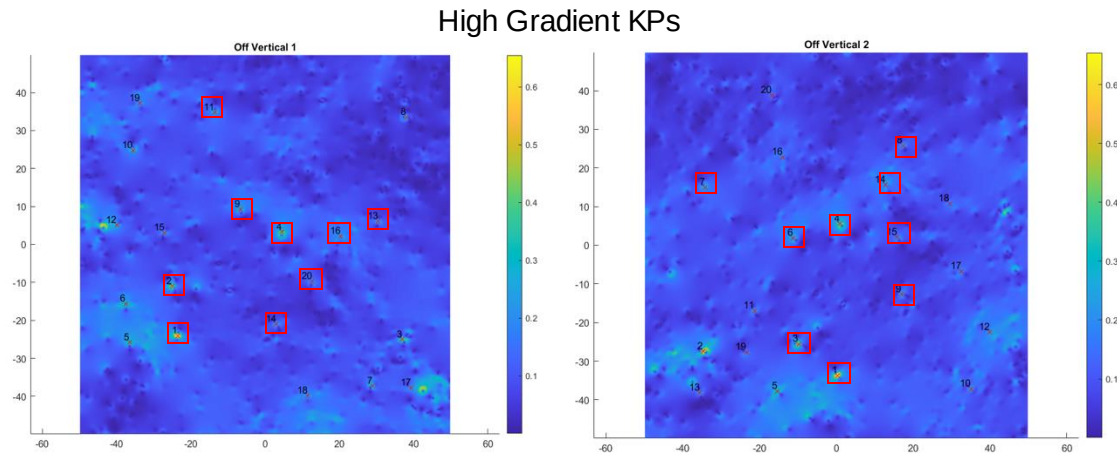
- All baseline functionalities implemented
- Hooks for SPLICE FSW integrated
- Initial optimization effort reduced full pipeline run-time from > 100s to < 5 s (sum of run-time of all components)
- Satisfactory preliminary test results with synthetic digital elevation maps

Next Steps:

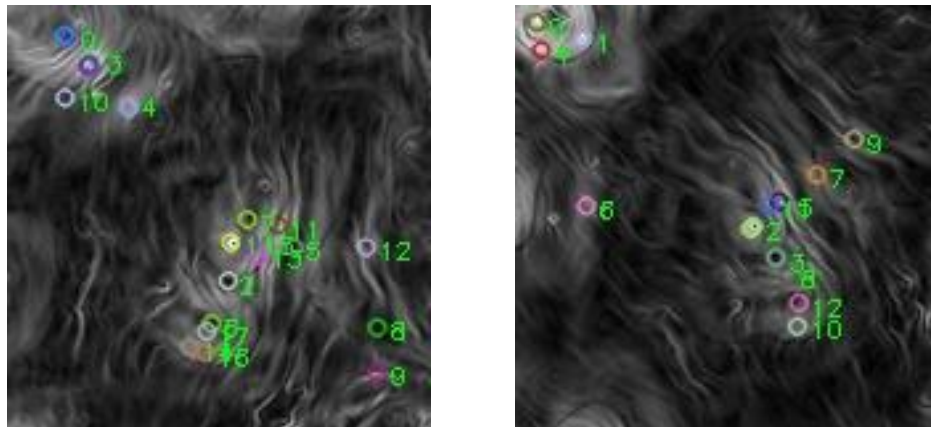
- Build test to flex entire pipeline
- Integrate with FTRT and RT SPLICE simulation
- Apply coding standards
- Build and perform unit-tests

ATRN C++ Library Development and Testing

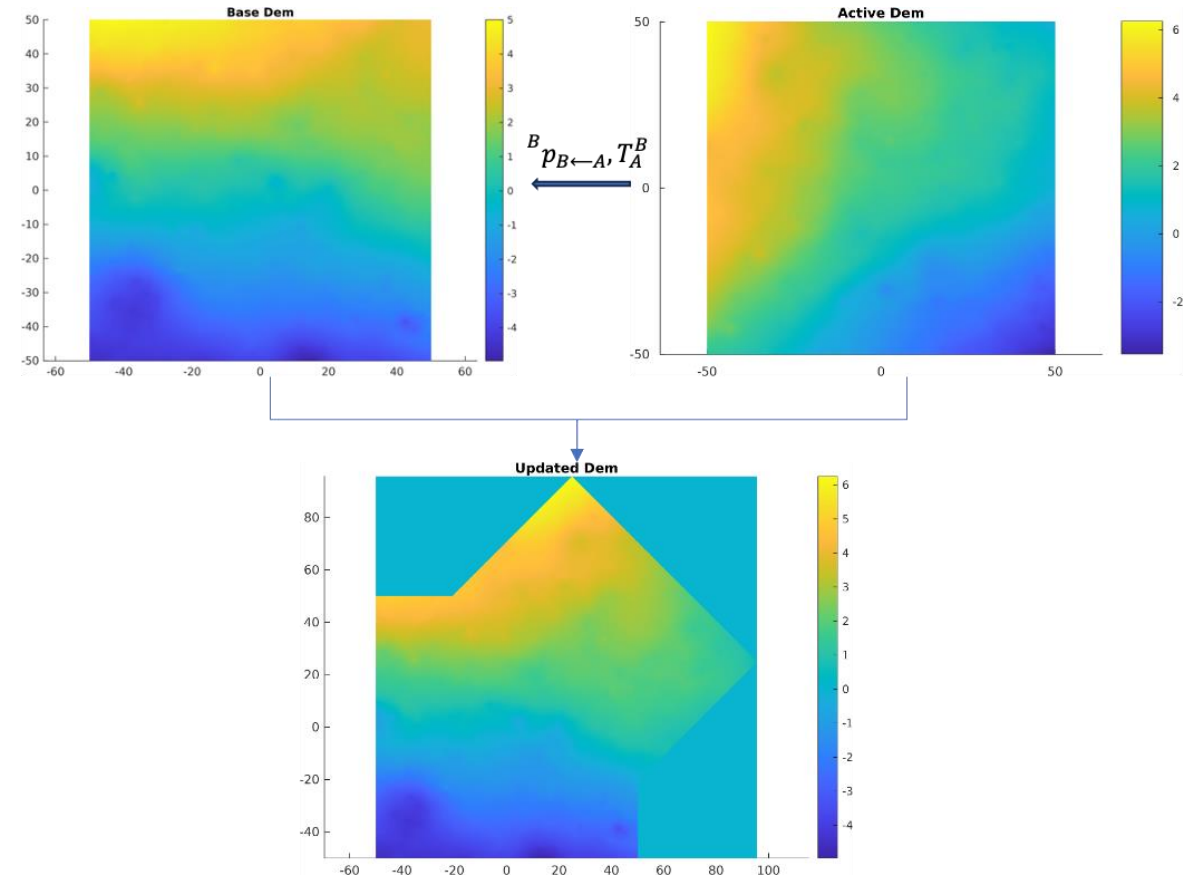
Keypoint Identification/Matching



Zernike Moment Gradient Map (ZMGM) KPs

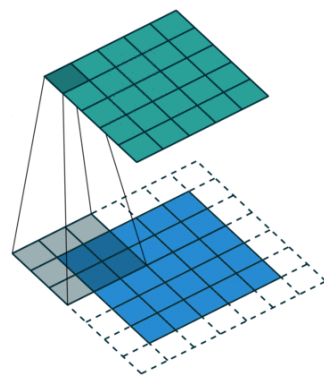
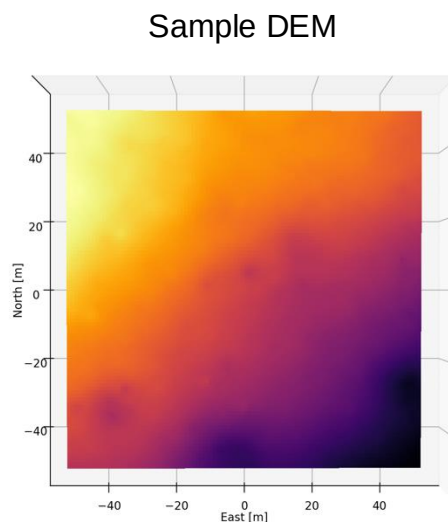


DEM Merging

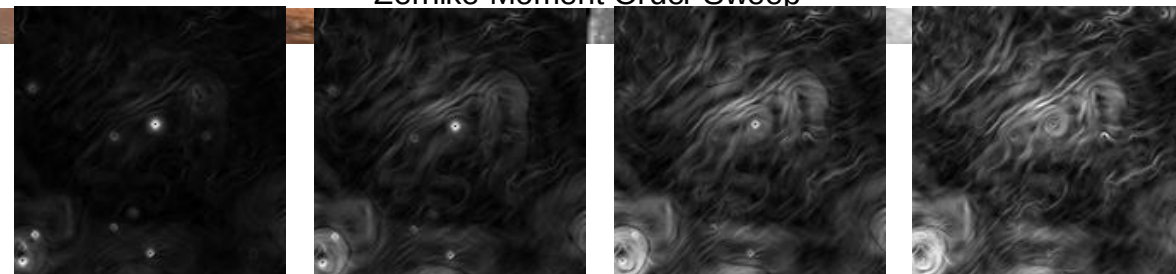


ATRN C++ Library Development and Testing

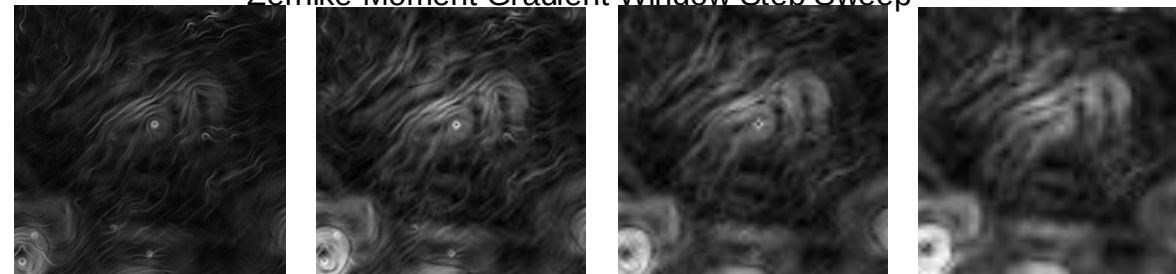
- Keypoint localization errors (mean):
 - Goal: < 1 m
 - High-gradient: 0.07 m
 - ZMGM: 0.28 m
- Pose estimation errors:
 - Goal: < 1 m position error, $< 1^\circ$ attitude error
 - High-gradient: 0.027 m, 0.03°
 - ZMGM: 0.257 m, 0.07°
- Parameter Optimization:
 - Automated test framework to sweep through potential configuration variable values for keypoint extraction and matching methods
- Memory Optimization:
 - FSW standards mandate no dynamic memory allocation
 - DEM products are inherently large data structures and manipulation requires large temporary memory allocation



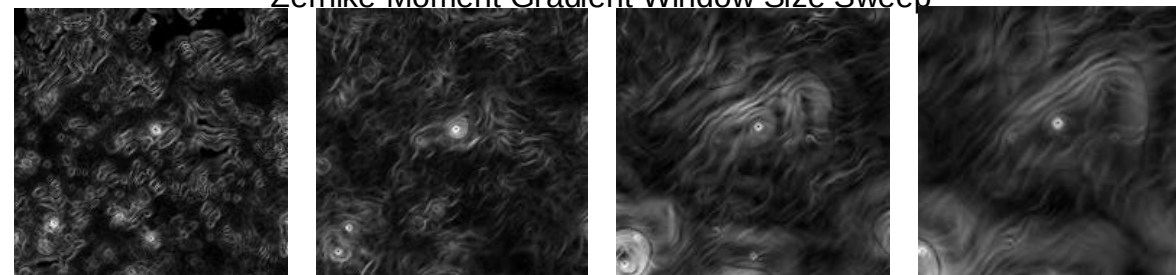
Zernike Moment Order Sweep



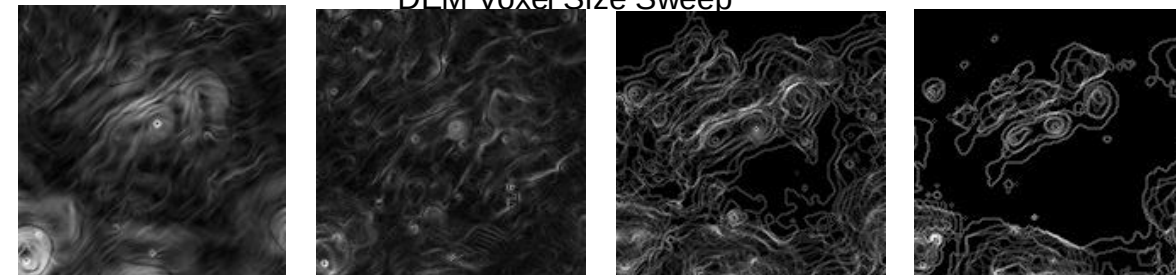
Zernike Moment Gradient Window Step Sweep



Zernike Moment Gradient Window Size Sweep



DEM Voxel Size Sweep



Overview and Next Steps

- Overview:
 - Created rotationally and scale invariant 3D feature ID/description algorithms
 - Developed computationally efficient pipeline which:
 - Yields absolute position/attitude of vehicle given reference map
 - Yields relative position/attitude between successive scans
 - Builds high-resolution terrain map of entire observed area given successive scans
 - Applicable for any scenario using a 3D terrain map for navigation
- Next Steps:
 - Standalone, Class C, C++ library in development (Expected October 2025)
 - Post process performance evaluation using helicopter flight data from Goddard HDL at KSC hazard field
 - Flight/mission infusion for planetary precision landing and/or ground surface navigation