PL&HA
Precision Landing and Hazard Avoidance

Safe and Precise Landing –
Integrated Capabilities Evolution



Active Terrain Relative Navigation with Surface Mapping Sensors

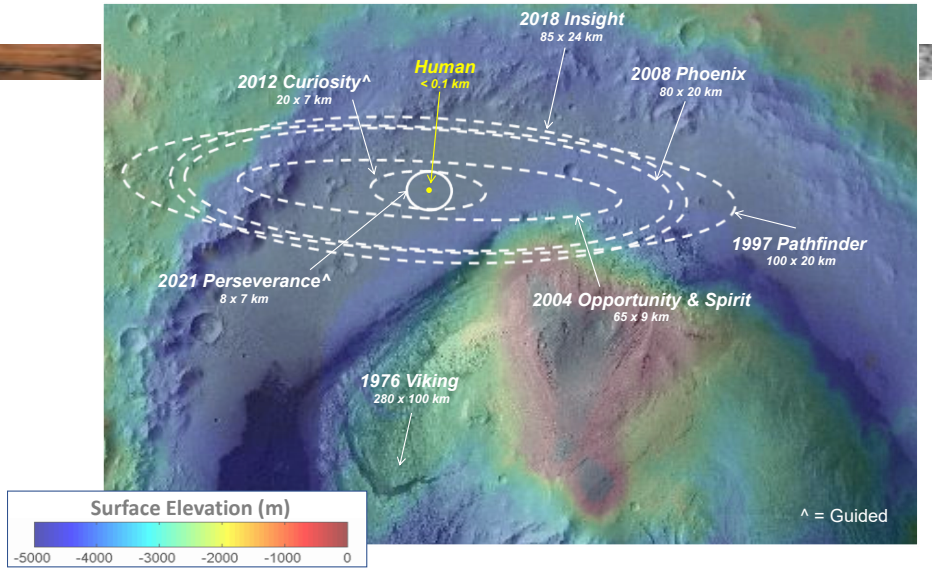
AIAA SciTech January 12, 2026

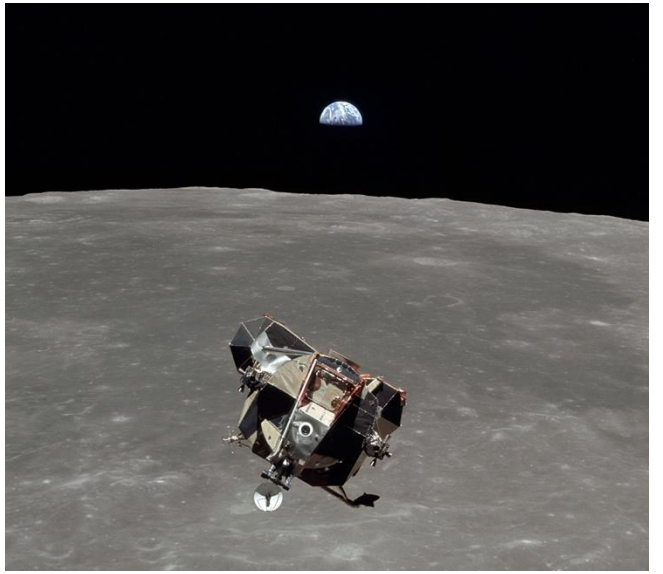
Davis W. Adams
NASA Johnson Space Center
Vikas Patel
Stanford University
Isaac Rowe
Aerodyne Industries – Amentum JETS II Contract

This material is a work of the U.S. Government and is not subject to copyright protection in the United States

Motivation

- Artemis program requirements of precision landing within 50m of predefined target site
  - Current SOTA:
    - Mars: 7-8 km (Perseverance)
    - Moon – Equatorial: < 60m (JAXA Slim)
    - Moon – Polar: ~250 m (IM-2)
- Passive (camera-based) approaches are impractical for permanently shadowed or poorly mapped regions
- <u>Sensing Need:</u> Active 3D terrain mapping sensors for navigation and hazard detection/avoidance
- Recent development of space rated terrain mapping sensors to facilitate hazard detection/avoidance activities for precision landing and surface mobility applications
  - ➢ Opportunity to leverage same data products to enhance navigation system
- <u>Algorithmic Need:</u> robust identification and description method that to facilitate LiDAR-based TRN or Active TRN (ATRN)
- 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 homogonous terrain
  - Inconsistent feature locations due to variable ground plane definition





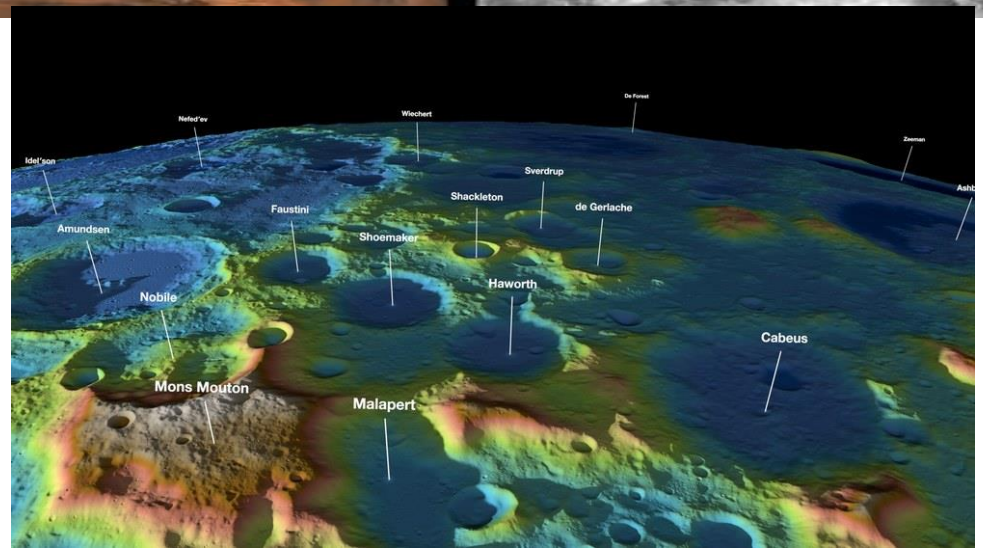
Objectives



- 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

Use Cases

- Applicable to systems with any terrain mapping sensor (not just LiDAR) that yields a digital elevation map (DEM)
- 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.)









Surface Relative Navigation with DEMs

Surface Relative Navigation with DEMs

Reference DEM is defined by:

- Origin in planet centered coords *(F)*
- Transformation from planet centered frame to local ENU frame

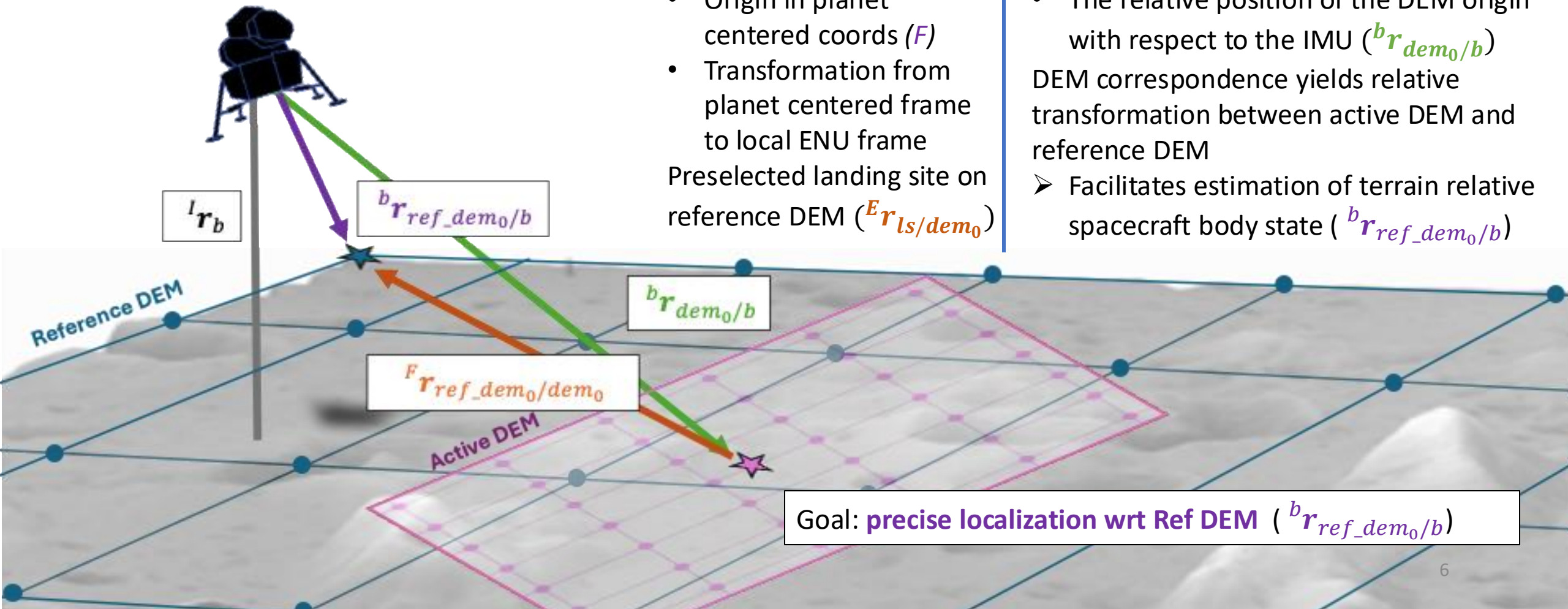
Preselected landing site on reference DEM ($^{E}\boldsymbol{r}_{ls/dem_0}$)

From the LiDAR scan, navigation receives:

- DEM altitudes and measurement noise
- The relative position of the DEM origin with respect to the IMU ($^{b}\boldsymbol{r}_{dem_0/b}$)

DEM correspondence yields relative transformation between active DEM and reference DEM

➢ Facilitates estimation of terrain relative spacecraft body state ($^{b}\boldsymbol{r}_{ref_dem_0/b}$)

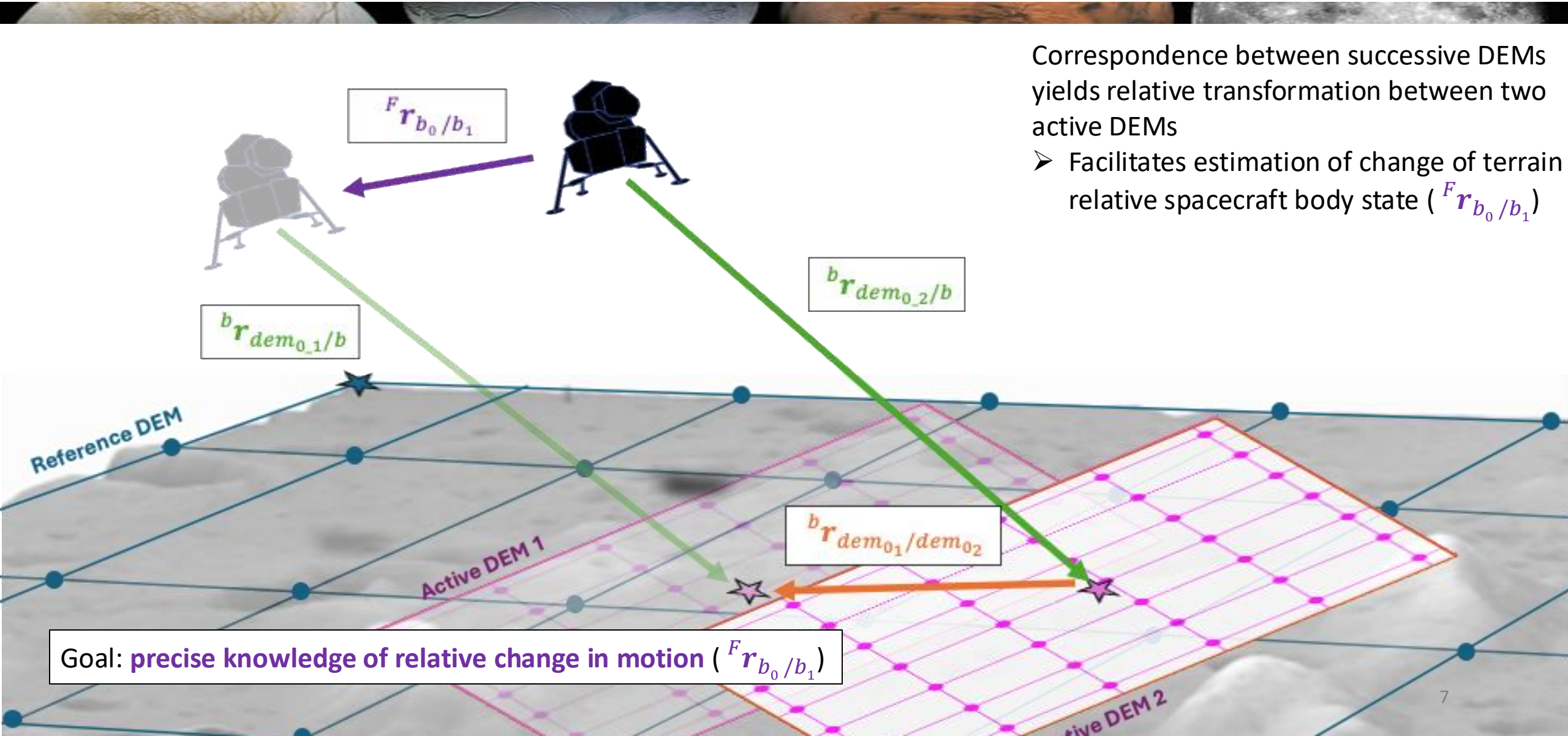


Goal: **precise localization wrt Ref DEM** ($^{b}\boldsymbol{r}_{ref_dem_0/b}$)

Surface Relative Navigation with DEMs

Correspondence between successive DEMs yields relative transformation between two active DEMs

- Facilitates estimation of change of terrain relative spacecraft body state (${}^{F}\boldsymbol{r}_{b_0/b_1}$)



Goal: **precise knowledge of relative change in motion** (${}^{F}\boldsymbol{r}_{b_0/b_1}$)



3D Keypoint Extraction from DEMs

PL&HA

Numerical Gradient-Based Feature ID



High-Gradient

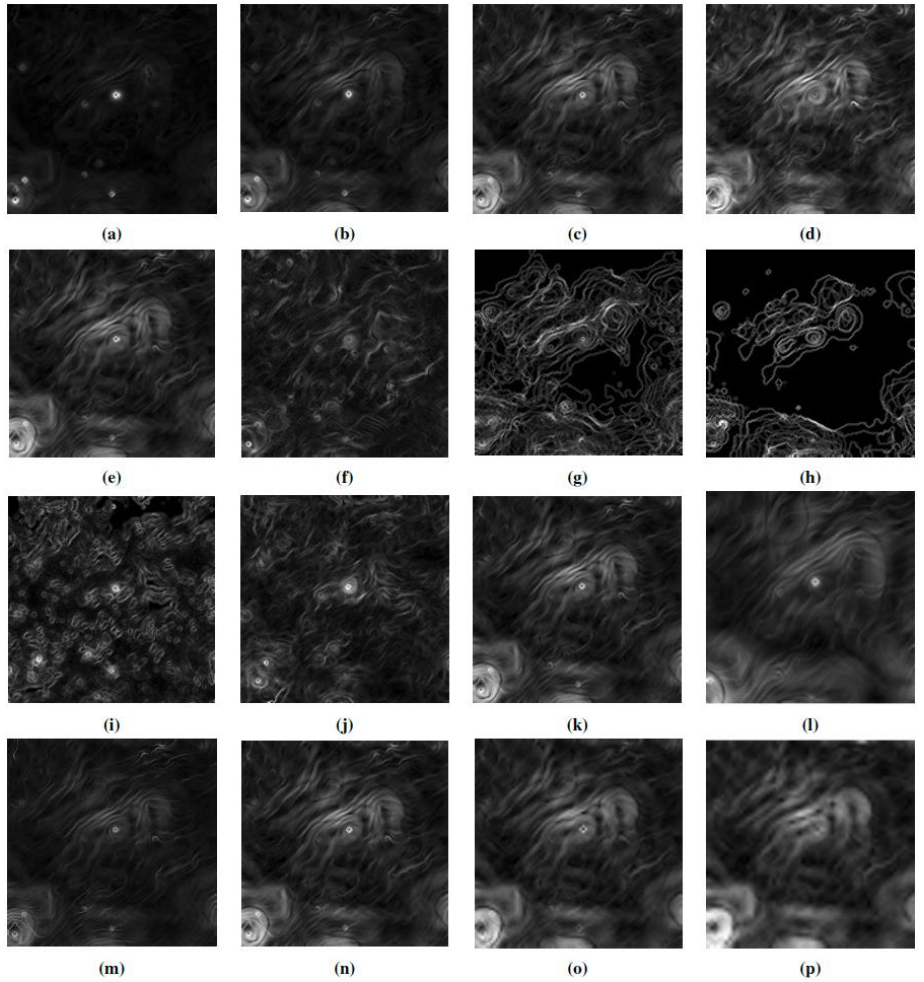
- Spatial gradient-based methods with variable keypoint size
  - Precondition DEM (optional) and compute off-vertical map
  - Search terrain off-vertical map for max value
  - Compute surface statistics for descriptor vector within concentric circles
- Consistent between maps with similar ground plane definitions (< 8 deg) but not theoretically rotationally invariant

Laplacian

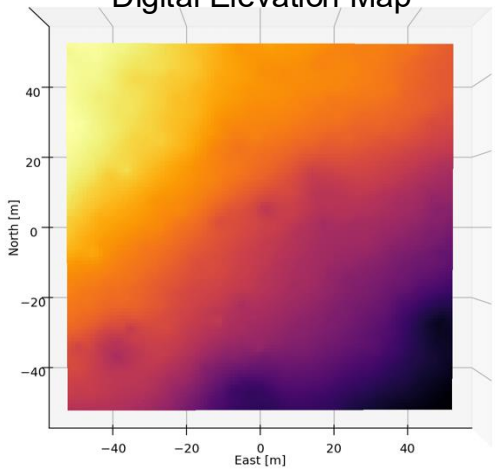
- Spatial Laplacian-based methods with variable keypoint size
  - Precondition DEM (optional) and compute Laplacian map
  - Apply windowing to mitigate Gibbs phenomena
  - Search terrain Laplacian map for max values
  - Compute surface statistics for descriptor vector within concentric circles
- Laplacian-Beltrami operator is theoretically rotationally invariant!

Zernike Invariant-Based Feature ID

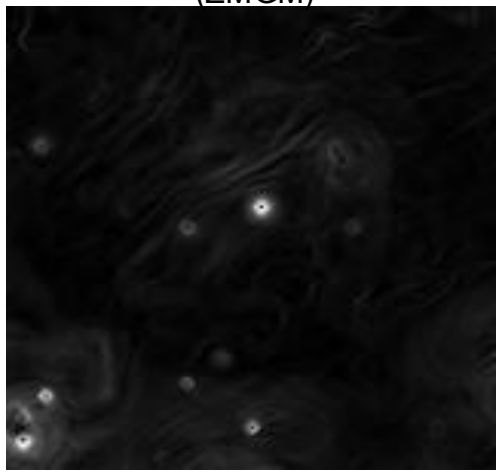
- Zernike Invariant Gradient (ZIG) Map method
  - Computes 3D Zernike Moment spatial gradient map to reduce the dimensionality of the digital terrain map
  - Extract 3D features using proven 2D methodologies (SIFT, SURF, ORB, etc.)
  - Robust to sensor noise
  - Mathematically rigorous framework
  -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



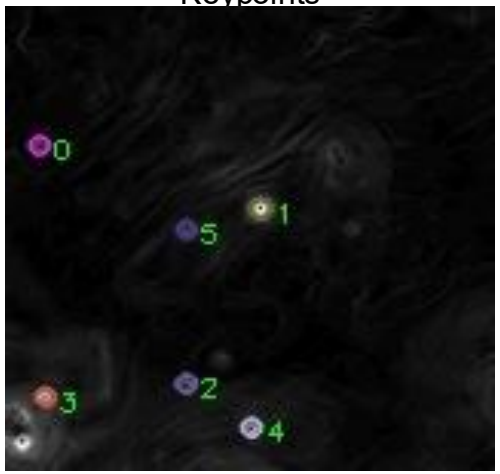
Digital Elevation Map



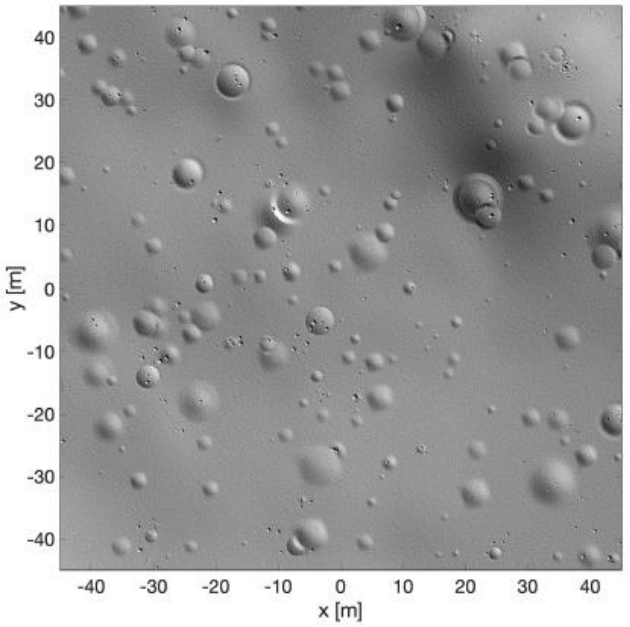
Zernike Invariant Gradient (ZIG) Map (ZMGM)



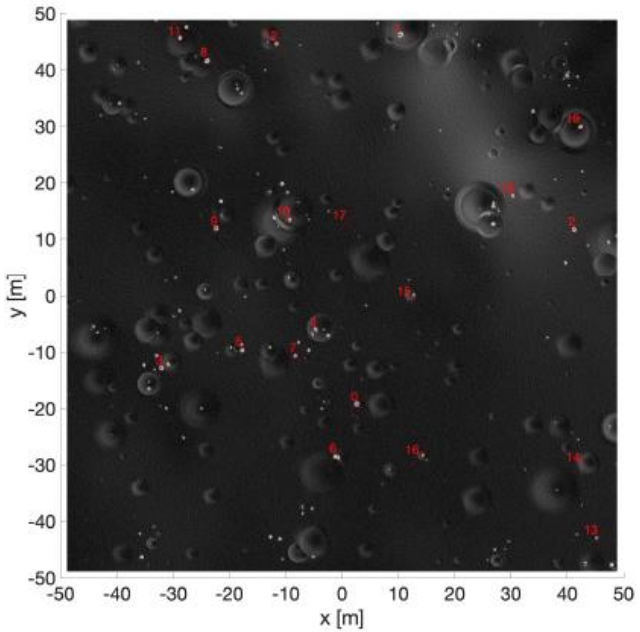
Extracted 3D Keypoints



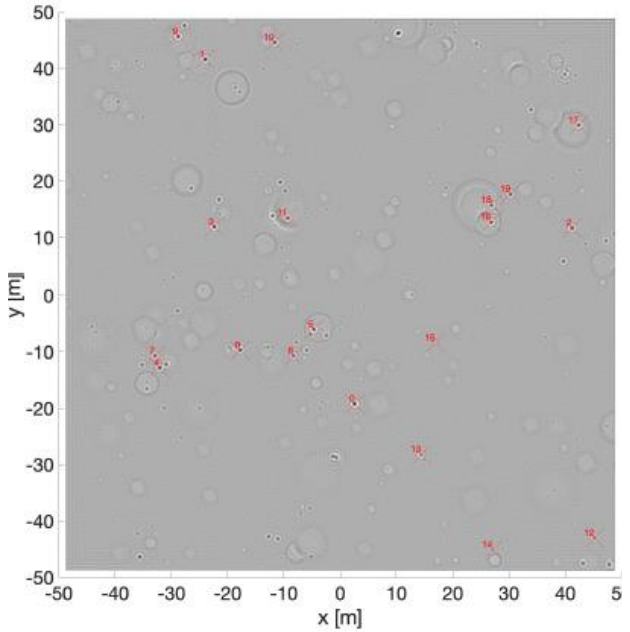
Keypoint Extraction Comparison



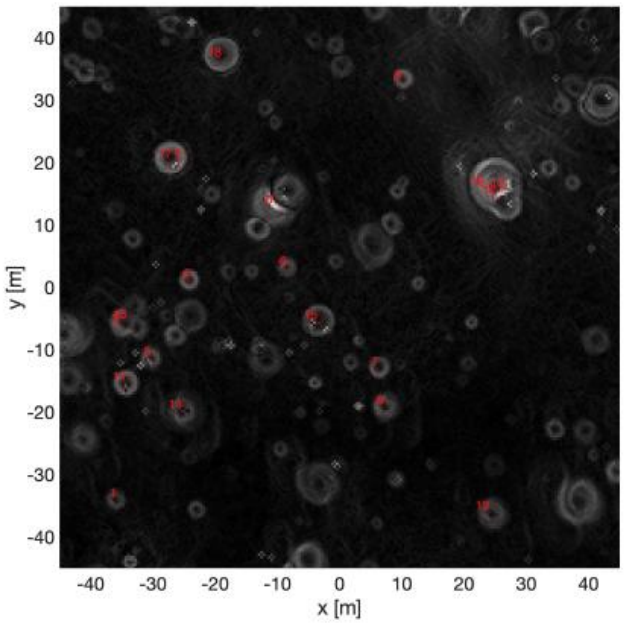
(a) Hillshade



(b) Off-vertical map with high-gradient keypoints



(c) Laplacian map with extracted keypoints



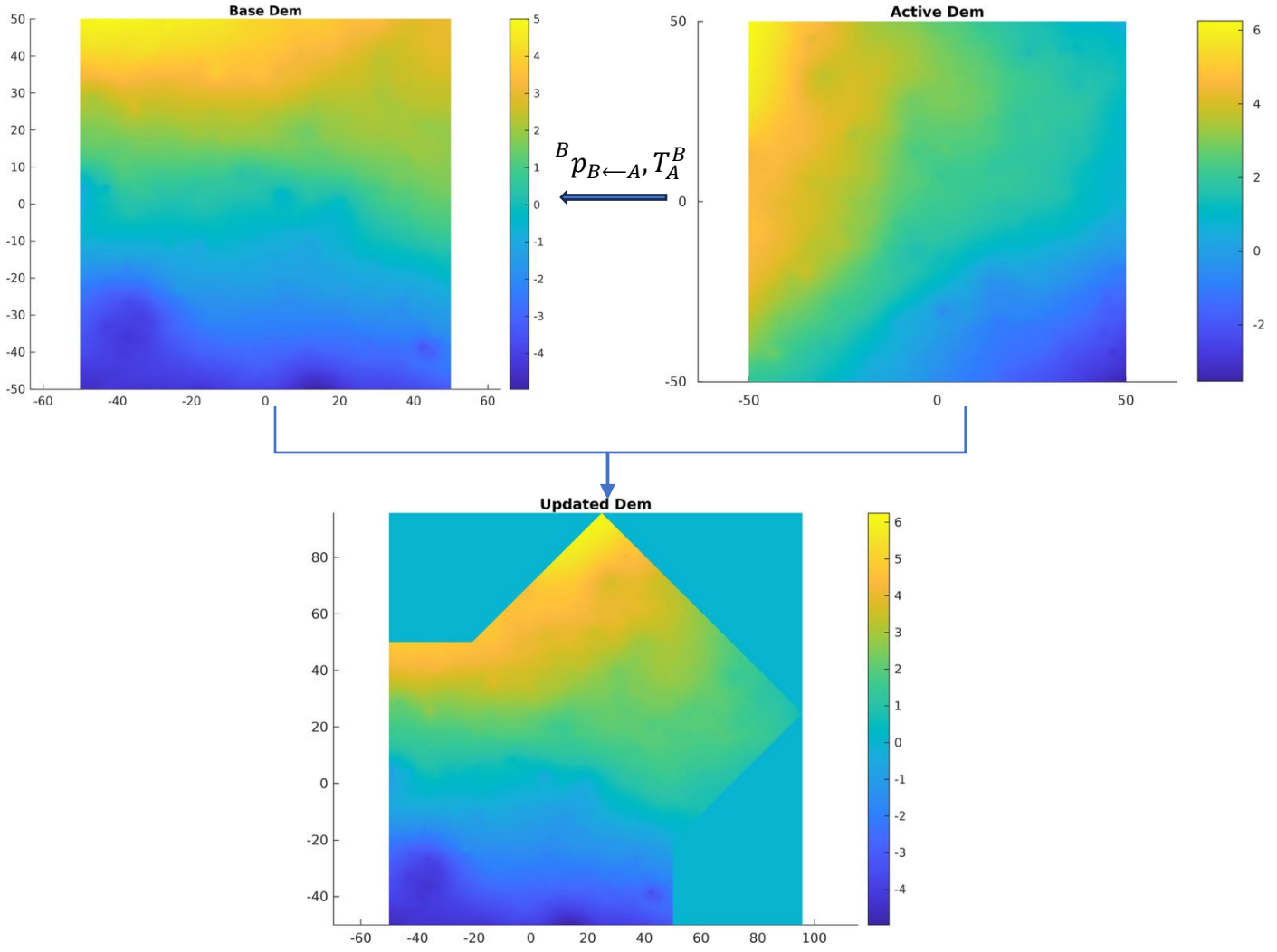
(d) Zernike Invariant Gradient map with extracted keypoints



Localization with 3D Keypoints

SLAM-Lite

- Descriptor vector covariance minimization for initial keypoint correspondence
  - Outlier rejection to prevent false matches
    - RANSAC
    - Point triad geometric invariant logic
- 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





FSW Implementation

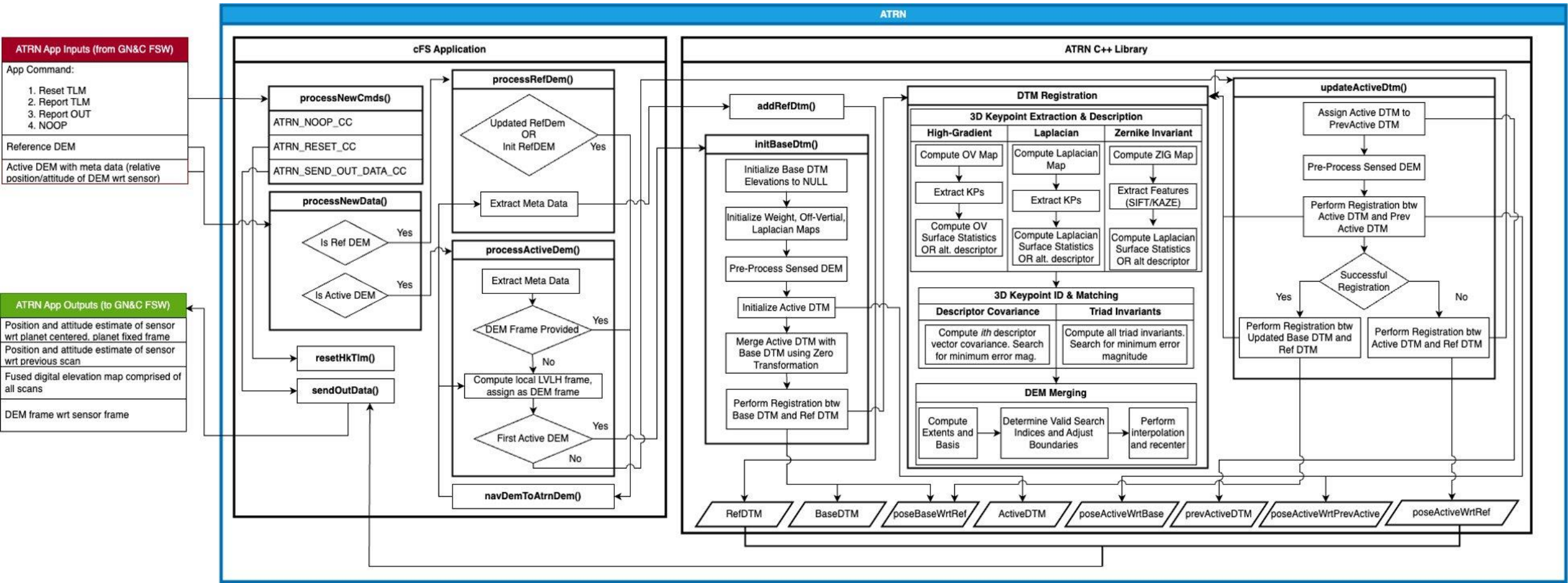
C++ FSW Library and Flight Integration

PL&HA

SPLICE

FSW / Space Compute Deployment Considerations

- Templated classes and functions for generalization and avoidance of dynamic memory allocation
- Pre-allocated global memory buffers to minimize stack usage
- Minimal external library dependencies
- Re-factor loop operations to remove branches and iteration dependences to enable auto-vectorization
- Specific compiler constructions for optimization
- Ensure all data types have correct memory alignment for SIMD compilation

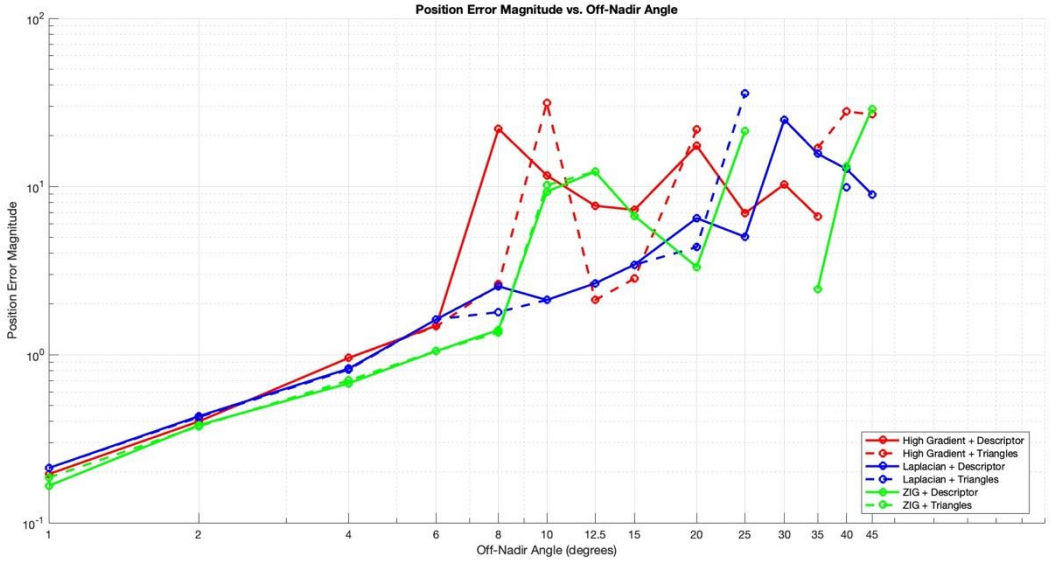


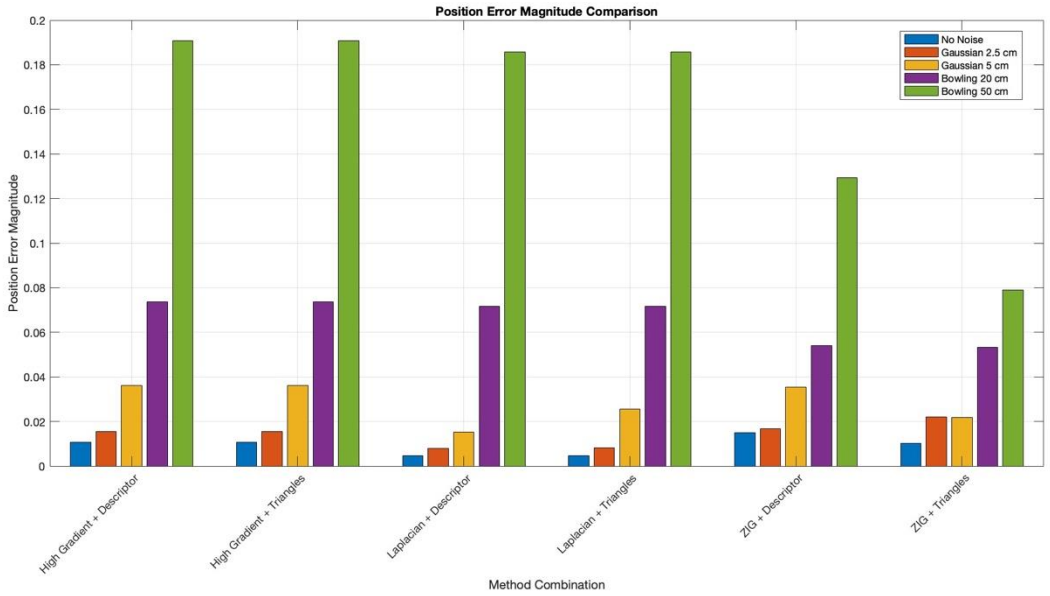


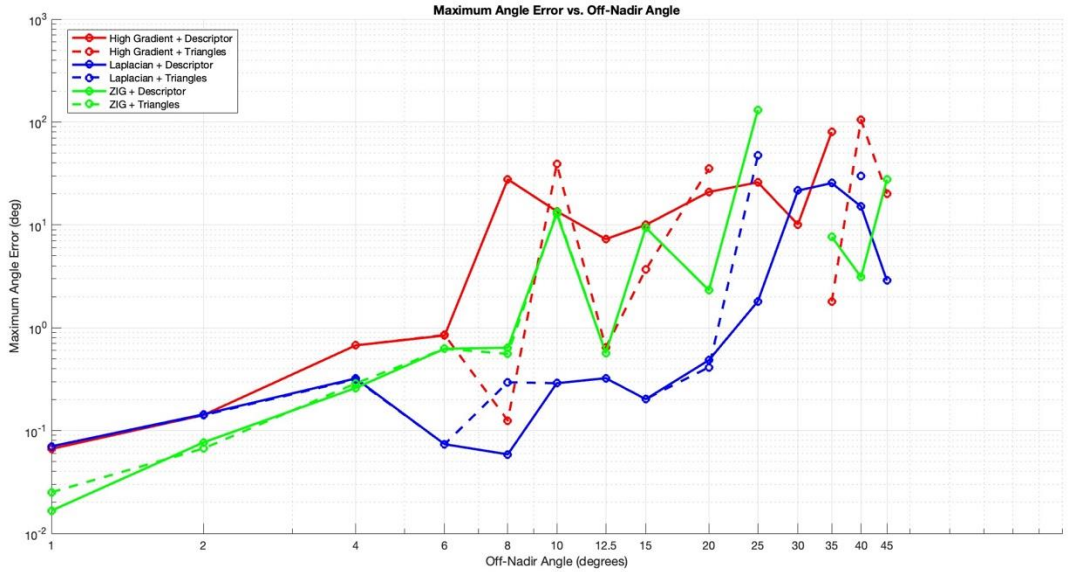
ATRN System Testing & Results

Sensitivity Study and Performance Analysis

- Sensitivity study objectives:
  - Evaluate performance and stability effects cause by common LiDAR product artifacts including:
    - Elevation noise
    - Global "bowling" phenomena induced by spiral scan patters
    - Ground plane definition errors
  - Determine optimal algorithmic configuration parameter values
  - Determine conservative outlier rejection cutoff thresholds
  - Isolate impactful stress cases

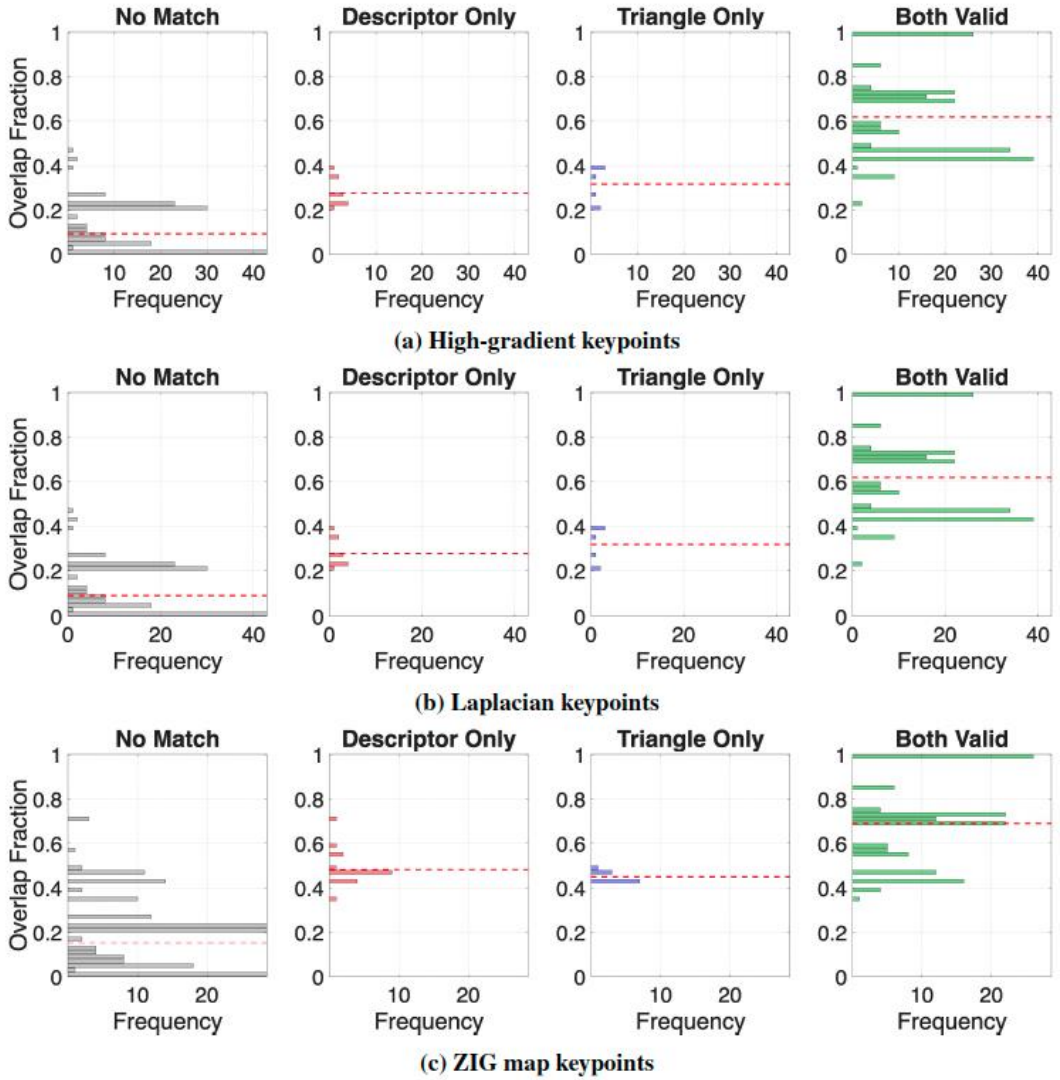


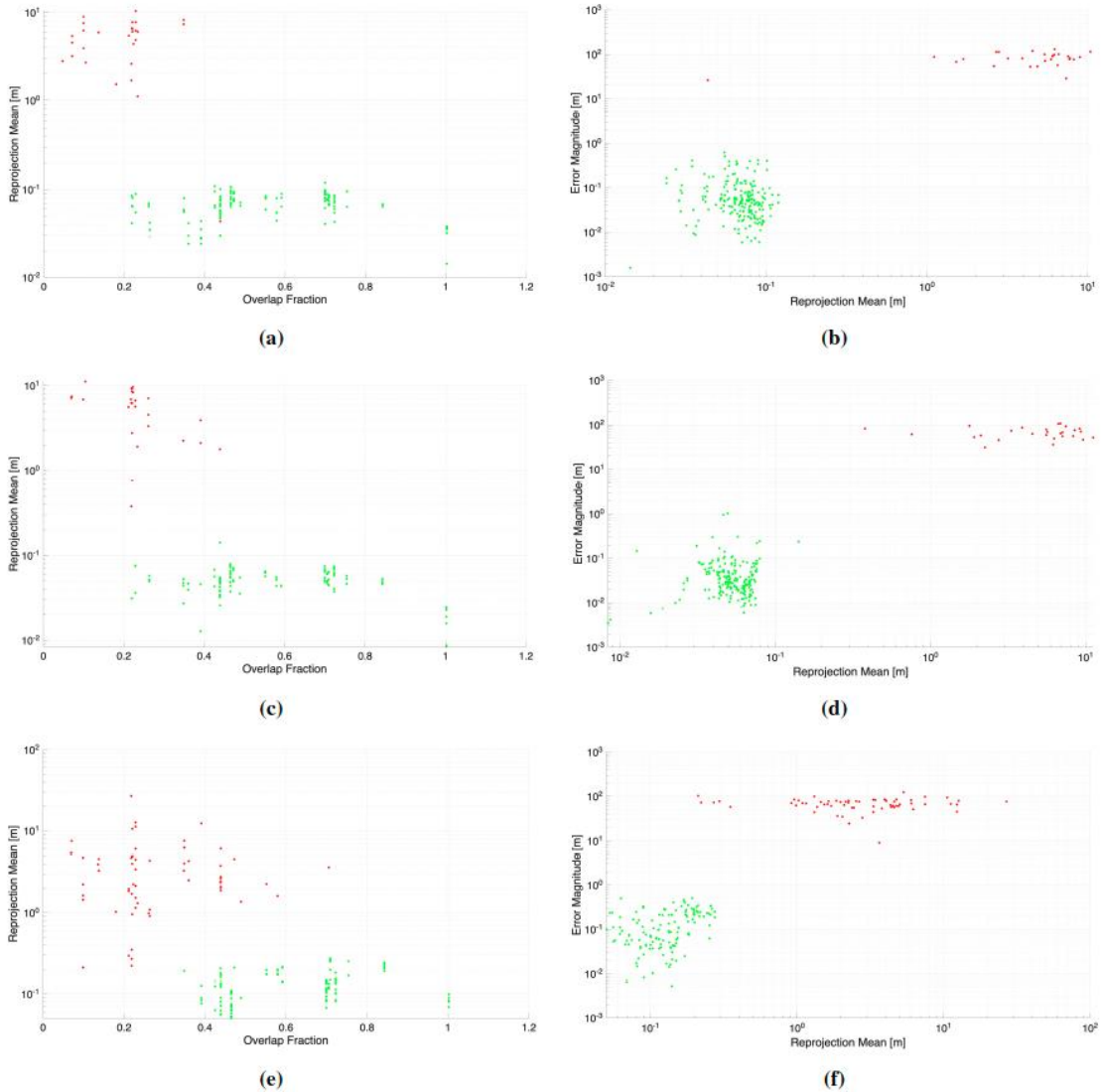




Sensitivity Study and Performance Analysis

Overlap Fraction Testing

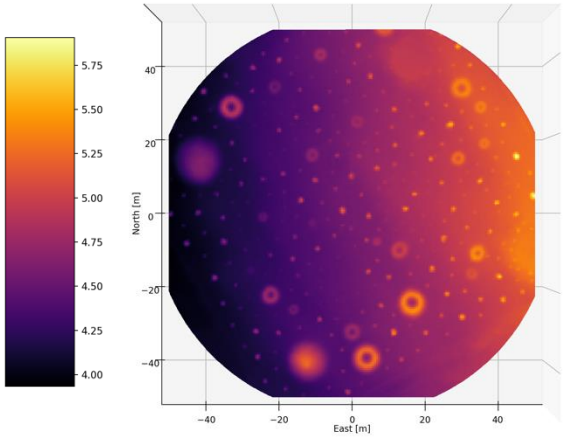


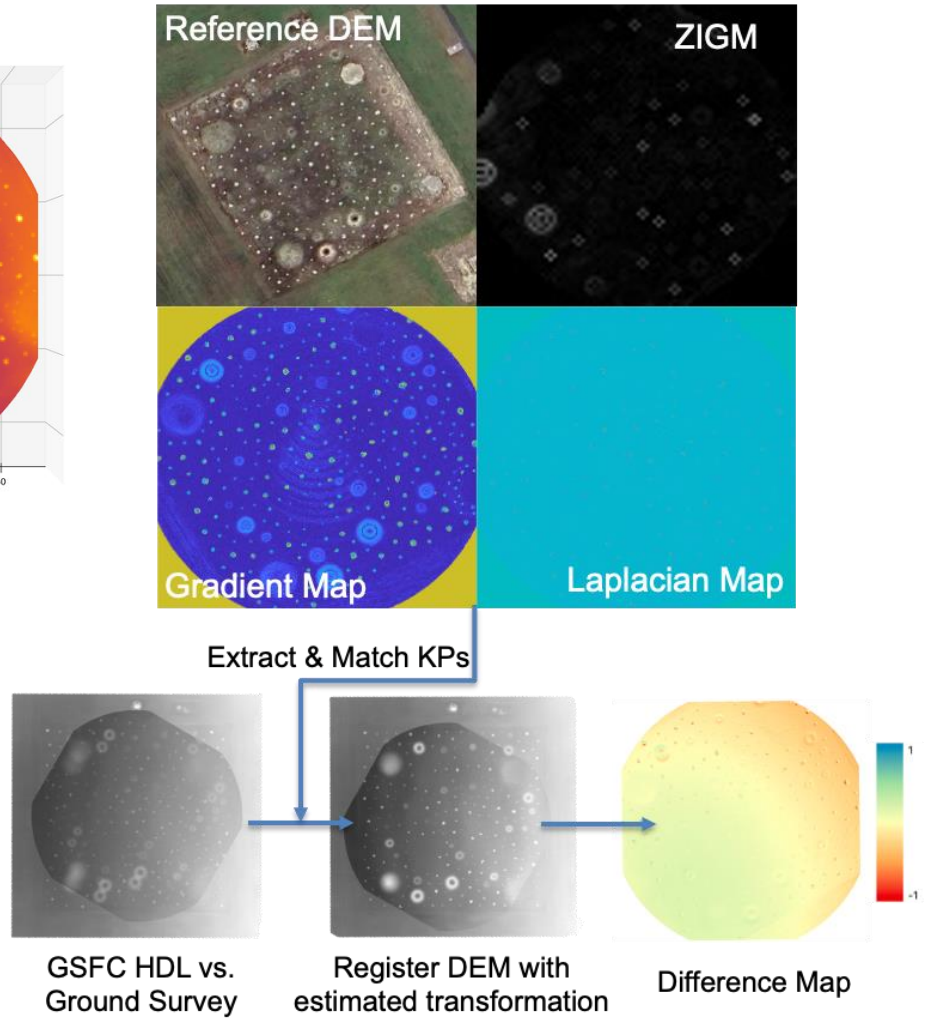


Flight Test Results

- Goddard Hazard Detection LiDAR data acquired during helicopter flight test campaign at KSC hazard field
- Analysis objectives:
  - ✓ Validate DEM processing and localization pipelines with flight data from representative terrain mapping sensor
  - ✓ Aid in KPP evaluation for GSFC HDL (mapping precision/accuracy)
  - ✓ Evaluate baseline performance metrics for ATRN system
  - ✓ Compare results to offline DEM registration tools by JPL
- Performance analysis compared to high-resolution survey DEM
  - Difference map mean: -0.3 cm
  - Difference map std: 14 cm
  - Compared to JPL offline analysis (used template matching):
    - ~4 cm, 0.003 rad localization difference
    - Identical difference map statistics (-0.27 cm mean, 14 cm std)
    - < 1 s vs 10s of minutes

HDL DEM





Computational Performance

Table 1 3D keypoint ID and DEM transformation desktop runtimes on 1000×1000 DEMs

Method	ZIG Window Size	ZIG Window Step Size	ZIG Voxel Size	Zernike Order	Run Time [s]
High-gradient	-	-	-	-	0.190
Laplacian	-	-	-	-	0.176
ZIG	8	0.6	0.3	3	0.520
ZIG	10	0.6	0.3	3	0.499
ZIG	15	0.6	0.3	3	0.497
ZIG	15	0.8	0.3	3	0.490
ZIG	10	0.8	1.0	3	0.479
ZIG	10	1.0	0.5	3	0.191

Computational Performance Scaling

- Zernike method scales significantly better with larger DEMs
  - Reduction in dimensionality and sliding window reduce impact of data power scaling
- FSW library deployed onto SPLICE DLC and Intel NUC for platform dependent characterization
  - Similar trends to results obtained on desktop machine
  - Large reference DEMs should be processed pre-flight

Table 2 3D keypoint ID and DEM transformation desktop runtimes on 3500×3500 DEMs

Method	ZIG Window Size	ZIG Window Step Size	ZIG Voxel Size	Zernike Order	Run Time [s]
High-gradient	-	-	-	-	15.7
Laplacian	-	-	-	-	15.6
ZIG	10	1	0.5	3	3.29

Table 3 3D keypoint ID and DEM transformation runtimes on the DLC

Method	DEM Sizes (Rows×Columns)	Run Time [s]
High-gradient	1000×1000	2.94
Laplacian	1000×1000	2.94
ZIG	1000×1000	3.28
High-gradient	3500×3500	545
Laplacian	3500×3500	545
ZIG	3500×3500	46.9

Table 4 3D keypoint ID and DEM transformation runtimes on an Intel NUC

Method	DEM Sizes (Rows×Columns)	Run Time [s]
High-gradient	1000×1000	0.125
Laplacian	1000×1000	0.118
ZIG	1000×1000	0.140
High-gradient	3500×3500	20.3
Laplacian	3500×3500	20.0
ZIG	3500×3500	2.99

Conclusions

- Created rotationally and scale invariant 3D feature ID/description algorithms
- Developed computationally efficient C++ library 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
- All proposed methods suitable for SOTA spacecraft computing platforms
- Recommendation: Employ either Laplacian or ZIG approach (or both in parallel!)
- Software to be released to NASA Software Catalog ~10/26

Table 5 3D keypoint ID method comparative analysis

Method	Algorithmic Complexity	Mean Runtime [s] 1k×1k	Mean Runtime [s] 3.5k×3.5k	Min. Overlap Fraction	Mean Pos. Err. [m]	Mean Att. Err. [deg]	Mean RMS Reproj. Err. [m]
High-gradient	Low	0.125	20.2	21%	0.076	0.158	0.065
Laplacian	Low	0.118	20.0	23%	0.049	0.097	0.049
ZIG	High	0.140	2.99	35%	0.126	0.164	0.121



STMD-GCD / HEOMD-AES / STMD-FO

Questions?

Active Terrain Relative Navigation with Surface Mapping Sensors