



Space Technology Mission Directorate Game Changing Development Program

Carolina Restrepo | Noah Petro / Adnan Ansar | FY22 LuNaMaps Annual Review Presentation | 09.16.22

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Project Overview

➤ Technology Product Capability

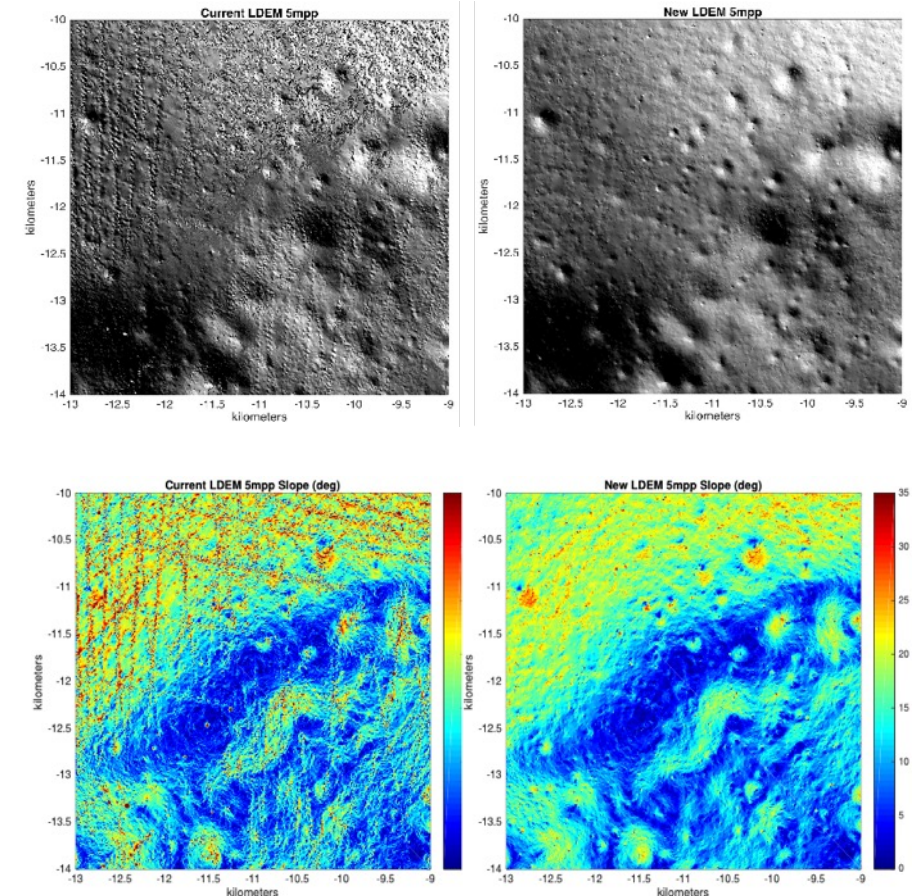
- Improve the coverage, accuracy, and resolution of existing lunar maps by merging orbital reconnaissance data to meet TRN requirements for precision landing
- Synthetically enhance map products derived from orbital imagery to include lander-scale features for use in the development and testing of hazard detection systems
- Evaluate terrain rendering tools to determine performance limitations and future needs for simulation, testing and V&V of lunar maps and EDL sensors and algorithms.

➤ Technical Capabilities

- Develop a suite of methods and tools to combine all sources of orbital imagery to ensure Digital Elevation Maps (DEMs) meet precision landing navigation requirements
- Develop a benchmark data set as well as basic requirements for high-fidelity simulations of precision landing functions such as Terrain Relative Navigation and Hazard Detection

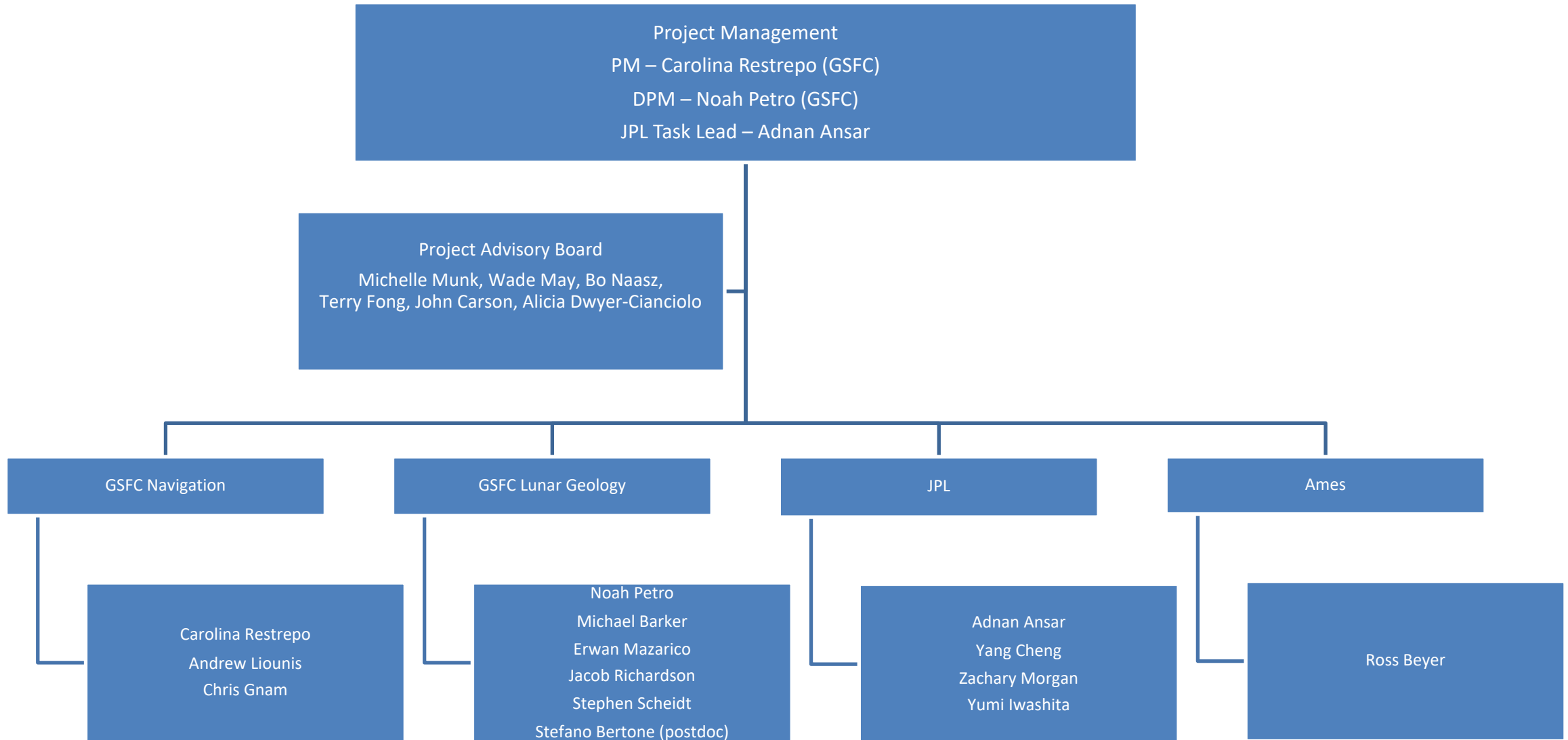
➤ Exploration & Science Applicability

- Landing systems



LOLA DEM (top) and slope map (bottom) of a high-priority landing site at the lunar south pole (5 m/pix) before (left) and after (right) cleaning.

Team Members / Project Org Slide



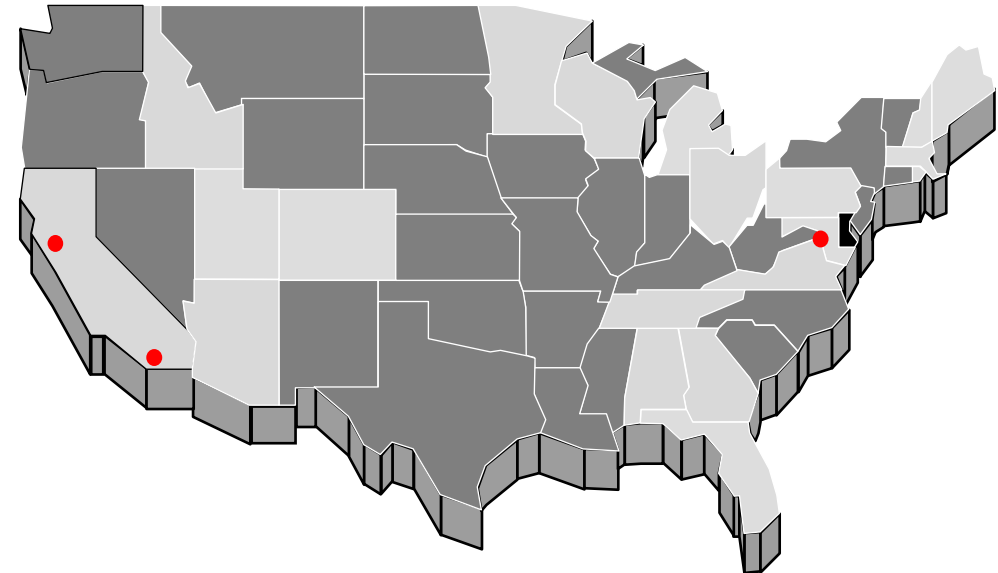
Mission Infusion & Partnerships



- Contributing NASA centers
 - GSFC – lead center
 - JPL
 - Ames

- Lunar map products and software tools will be made available to NASA projects as well as industry partners

- NASA missions impacted by the technology
 - HLS – App N – Blue Origin
 - CLPS



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Technology Goals & Project Objectives



Technology Goals

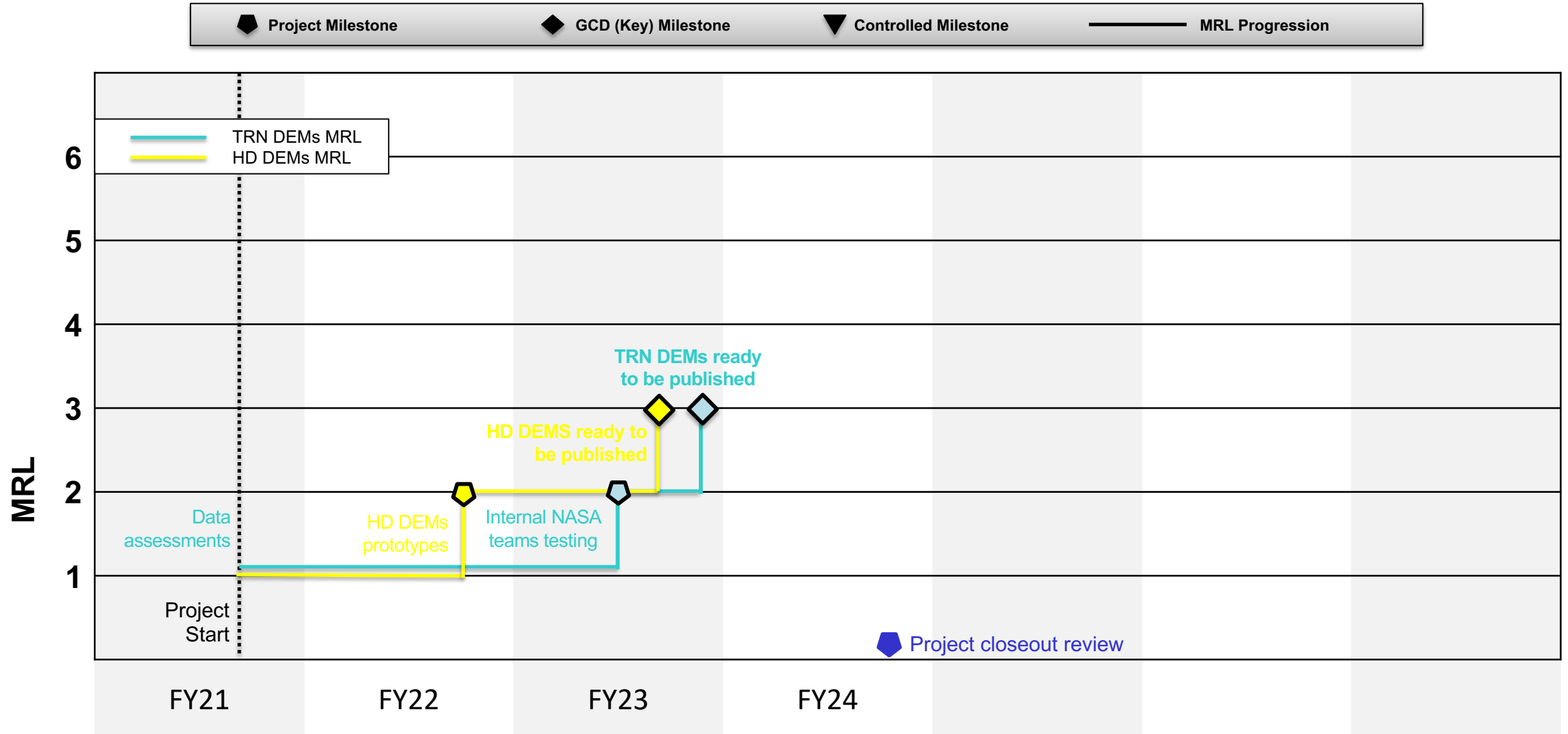
Goal #1	Improve the coverage, accuracy, and resolution of existing lunar maps by merging orbital reconnaissance data to meet TRN requirements for precision landing.
Goal #2	Synthetically enhance map products derived from orbital imagery to include lander-scale features for use in the development and testing of hazard detection systems.
Goal #3	Evaluate terrain rendering tools to determine performance limitations and future needs for simulation, testing and V&V of lunar maps and EDL sensors and algorithms.
Goal #4	Deliver map products and applicable software tools to government and commercial partners.

Project Objectives

Objective #1	Develop Terrain Relative Navigation maps from orbital reconnaissance data
Objective #2	Develop synthetically enhanced high-resolution maps with lander-scale features
Objective #3	Test map products and software tools through collaborations with other NASA projects and industry partners to simulate, test and V&V lunar maps and closed-loop EDL GNC systems
Objective #4	Deliver map products to government and commercial partners and prepare applicable software tools for technology transfer.

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Model Readiness Levels



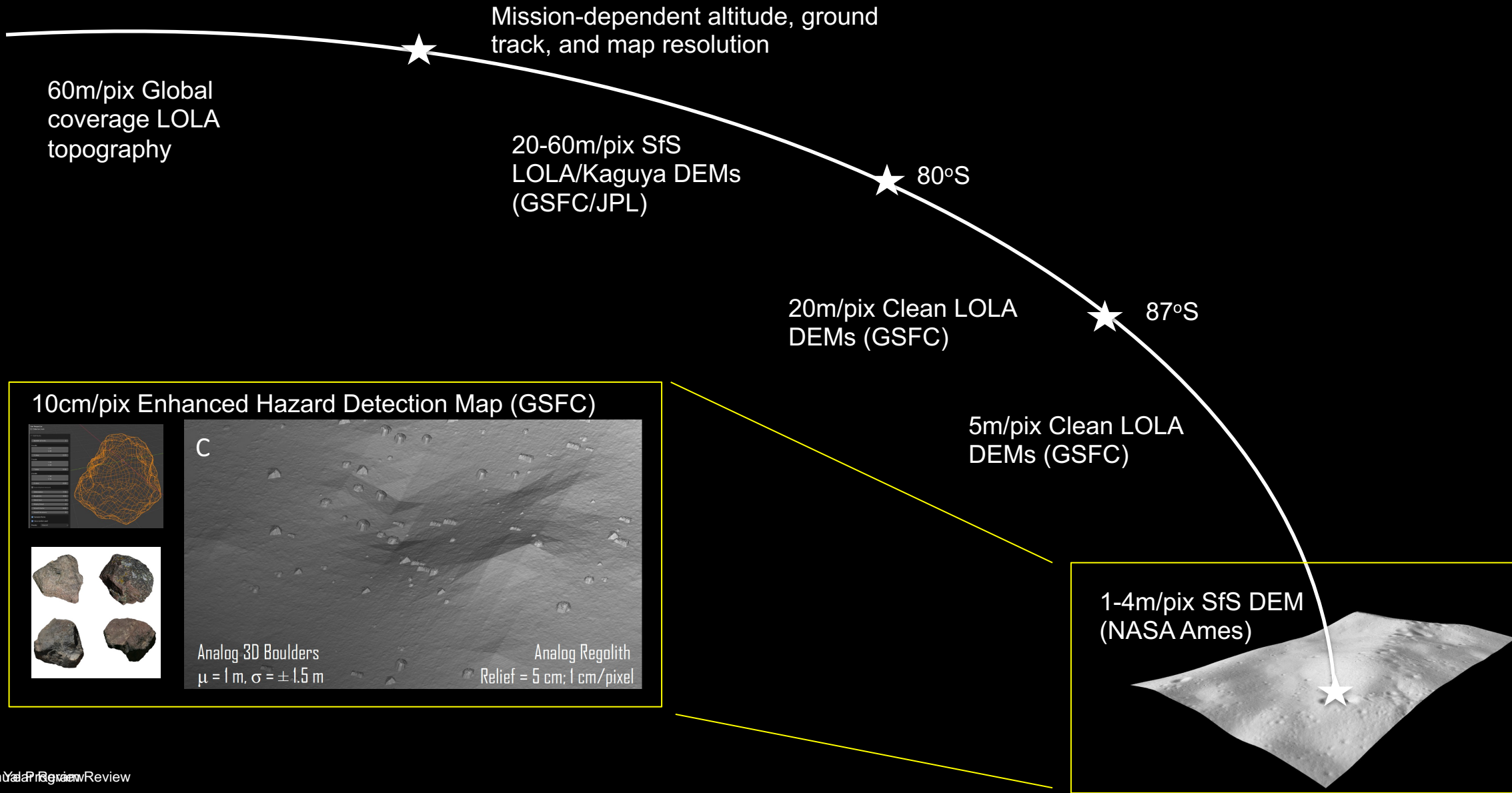
Accomplishments



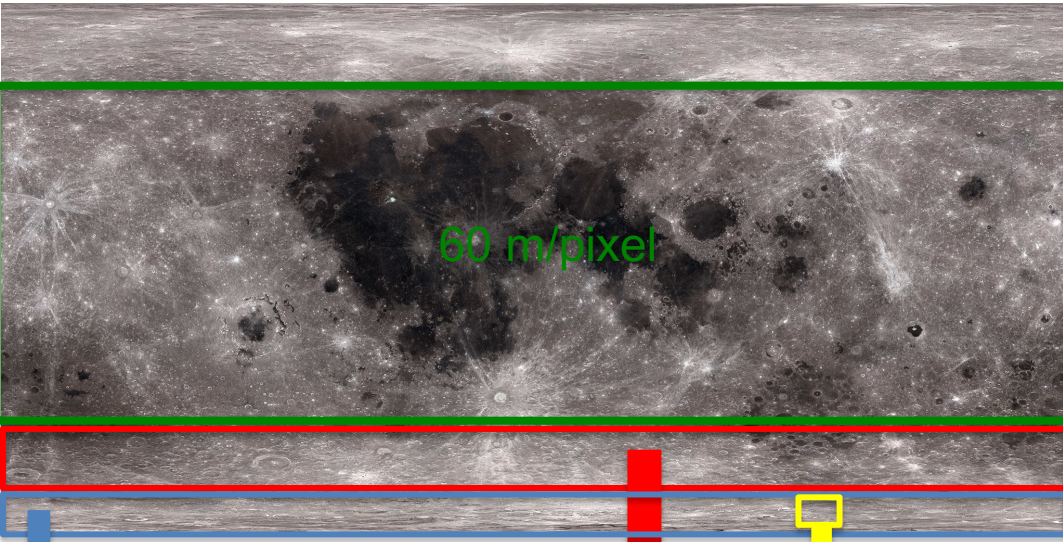
- Project team has developed a clear problem statement and a clear path on how to provide the necessary map products for TRN/HD for a given site/trajectory
- Team has defined criteria used to decide when DEMs must be “made-to-order” for a given trajectory or when publicly available DEMS can be used
- Several TRN/HD map products have been generated for 2 sites
- Team has developed a workflow to merge TRN DEMs with high-frequency lunar surface features and textures to generate enhanced cm/pixel resolution DEMs for Hazard Detection
- Team has identified new error sources in lunar imagery and associated methods to mitigate these errors

LuNaMaps Project is on track to perform full EDL simulation runs to evaluate TRN performance with new DEMs

Map Products for a South Pole Landing



Currently Available DEMs for TRN



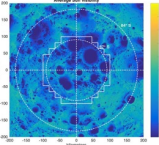
➔
Currently
available
global DEM
before
LuNaMaps

➔
Clean LOLA DEMs

 NASA's Planetary Geology, Geophysics and Geochemistry Laboratory
Goddard Space Flight Center

South Pole LOLA DEM Mosaic
Michael Kenneth Barker

This product was constructed from 97 individual 20x20 km fields with 2 km overlaps. Each field was processed with the same method as the individual regions previously created (see [here](#)) and as described in Barker et al. (2021). The fields were then individually aligned to the original DEM with a rigid 3-D translation and blended together with a cosine taper weight in the overlap regions. The counts (dsc) and slope (dsmp) maps of the individual fields were blended in the same way. Hence, non-integer counts exist in the overlap regions of the final mosaicked product (solid white lines in figure).
Due to the track adjustment, cleaning, and tile blending procedures, this 87-90 deg mosaic product has a typical RMS residual of 30-55 cm with the individual fields (from [here](#)).

 5-20 m/pixel

Data

5 m/pix GeoTIFFs with south polar stereographic X/Y coords in meters, MOON_ME reference frame of ephemeris DE421.
X/Y coords follow the Generic Mapping Tools 'pixel-registered' convention (i.e., they are the centers of the pixels).

Idem_87s_5mpps: 3.3GB GeoTIFF of surface height Z (meters) with interpolation filling empty pixels
Idem_87s_5mpps_hillshade: 820MB GeoTIFF hillshade of Idem
Idem_87s_5mpps: 4.9GB GeoTIFF of surface slope (degrees)
Idem_87s_5mpps: 140MB GeoTIFF of the number of LOLA returns in each pixel (count map)

Landing Site -Specific
Shape from Shading (SfS)
DEMs need to be built by
team 1-4 m/pixel

Mission-Specific Shape
from Shading (SfS) DEMs
Need to be built by team
20-60 m/pixel



NASA's Planetary Geology, Geophysics and Geochemistry Laboratory
Goddard Space Flight Center

High-resolution Lunar Topography (SLDEM2015)

Michael Kenneth Barker

Download SLDEM2015:

<http://imbrium.mit.edu/DATA/SLDEM2015/>

Global maps (for latitudes between 60 deg South and 60 deg North) can be downloaded from the following links:

FLOAT IMG format:

[256 and 128 pixels per degree](#)

JPEG2000 format:

[512, 256, and 128 pixels per degree](#)

Alternatively, if you are interested in just a few specific regions, then you can download the maps split up into tiles at these links:

FLOAT IMG format:

[512 and 256 pixels per degree](#)

JPEG2000 format:

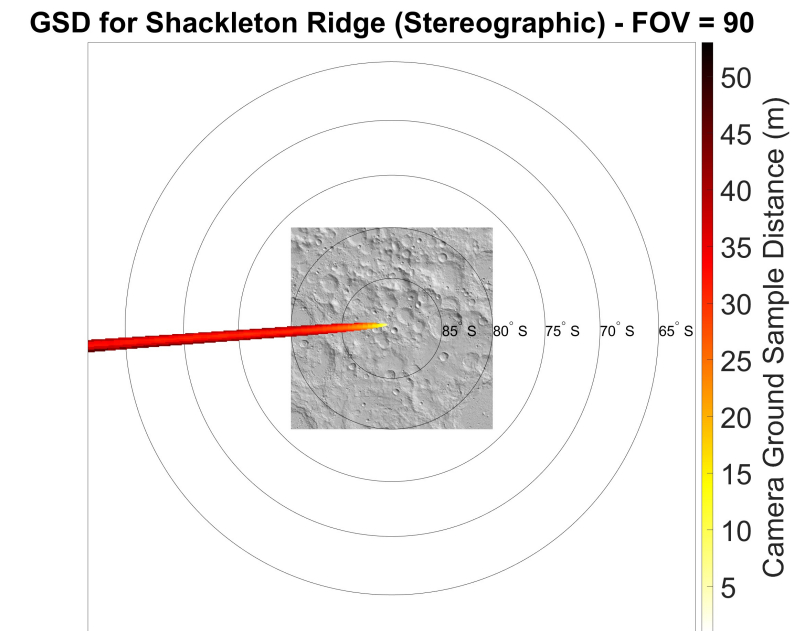
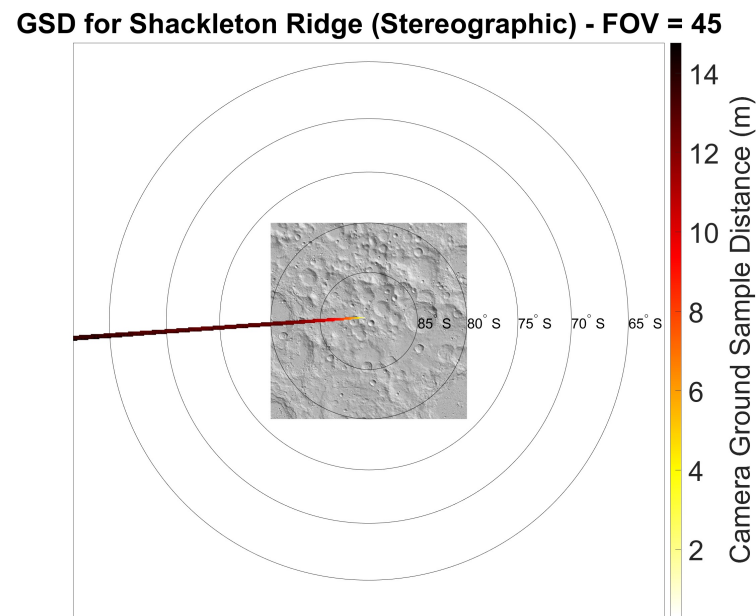
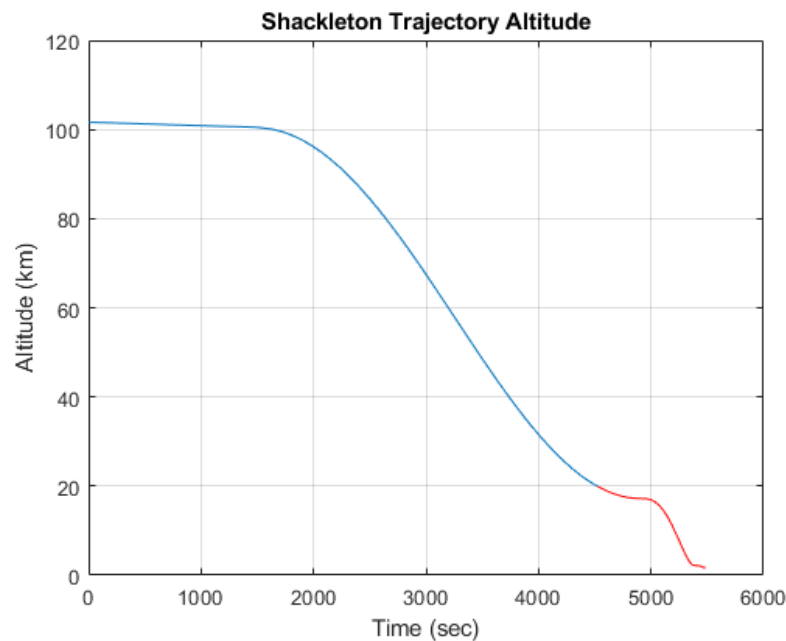
[512 and 256 pixels per degree](#)

NOTE: As part of map validation plan,
some DEMs will be built both at GSFC and
JPL separately for comparison and
mitigation of errors

GSFC: Mission-Specific Shape from Shading (SfS) DEMs



Geodesy and Geophysics Lab (Code 698) at Goddard is generating new SfS DEMs along the ground track for a specific polar landing trajectory

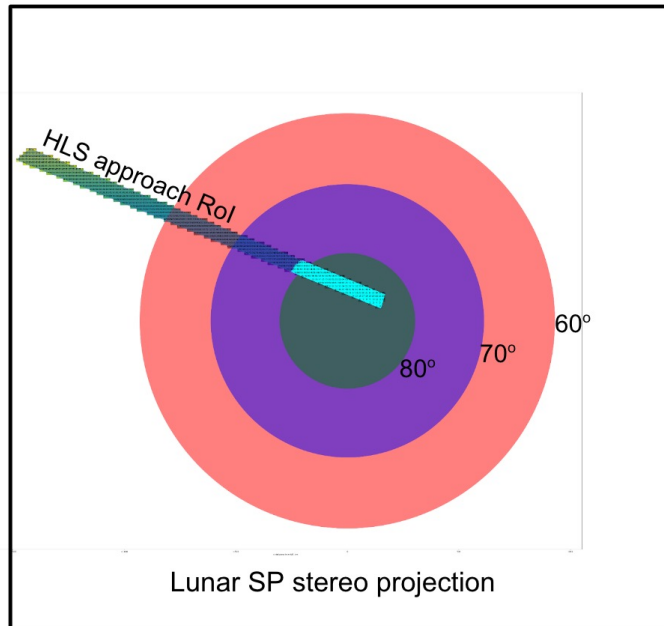


These DEMs are made to order and it's a tedious/manual process for now

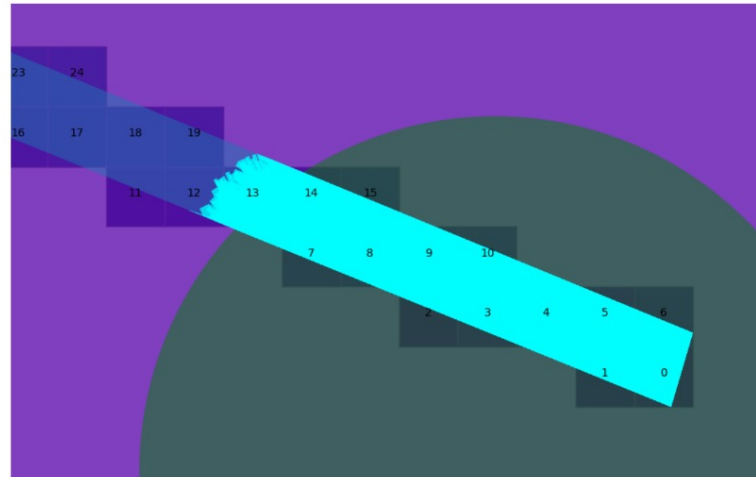
- GSFC/Mike Barker has produced 20m/pixel DEMs above 80deg South and 5m/pixel DEMs above 87deg S
- Above that, global coverage resolution remains at about 60m/pixel

GSFC Approach for Ground track SfS DEMs

- LOLA + SLDEM2015 helps but doesn't always provide sufficient resolution for TRN during the approach
- Goal: improve resolution along HLS approach RoI
- Tools: Ames Stereo Pipeline and custom python libraries

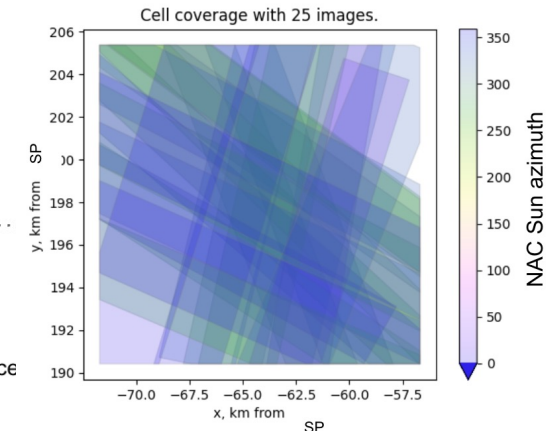


- Divide HLS “interest region” in overlapping “tiles” (10x10 km + 10% overlap per side)
- Get ground coverage, resolution, illumination angle of all LROC NAC images
- Assign images to each tile (remove if <10% overlap, incidence angle > 88°, mostly shadow)
- Select ~20 images for each tile to maximize spatial AND azimuthal coverage
- (Optional) Check selection visually, add/remove



Can use larger or smaller tiles, which affects coverage with N images and mosaic-ing effort

ID	Sun lon	Resol	Incidence
nacl0002492c	300	1.688	85.38
nacr000291aa	330	1.681	84.67
nacl001a8df0	240	1.329	87.75
nacr001acfd6	270	1.348	84.57
nacl001b77d5	0	1.38	84.38
nacl001cb901	30	1.381	85.83
nacr0020b35d	240	1.375	86.85
nacr0020e136	270	1.39	85.06
nacr0020e80f	270	1.395	84.74
nacl002120ba	300	1.411	82.84
nacr0021e5f4	270	1.509	86.85
nacr00221b80	300	1.519	85.22
nacl0022531e	330	1.525	85.04
nacl00225320	330	1.53	83.49
nacr0024b188	0	1.428	85.43
nacl00255da4	0	1.438	84.55
nacl002599a3	30	1.447	87.72
nacl0026ca0f	270	1.499	86.32
nacr0026ca11	270	1.506	86.84
nacr0027408a	330	1.541	83.66

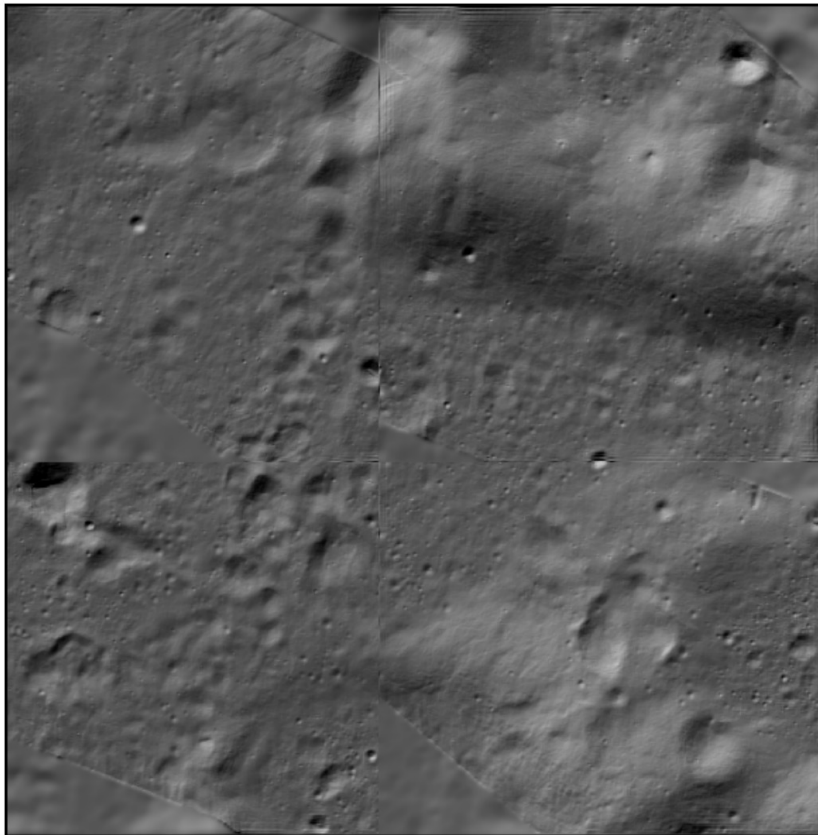


GSFC: Example SfS DEM Along HLS Approach



Example on tiles @ ~60S : preliminary results

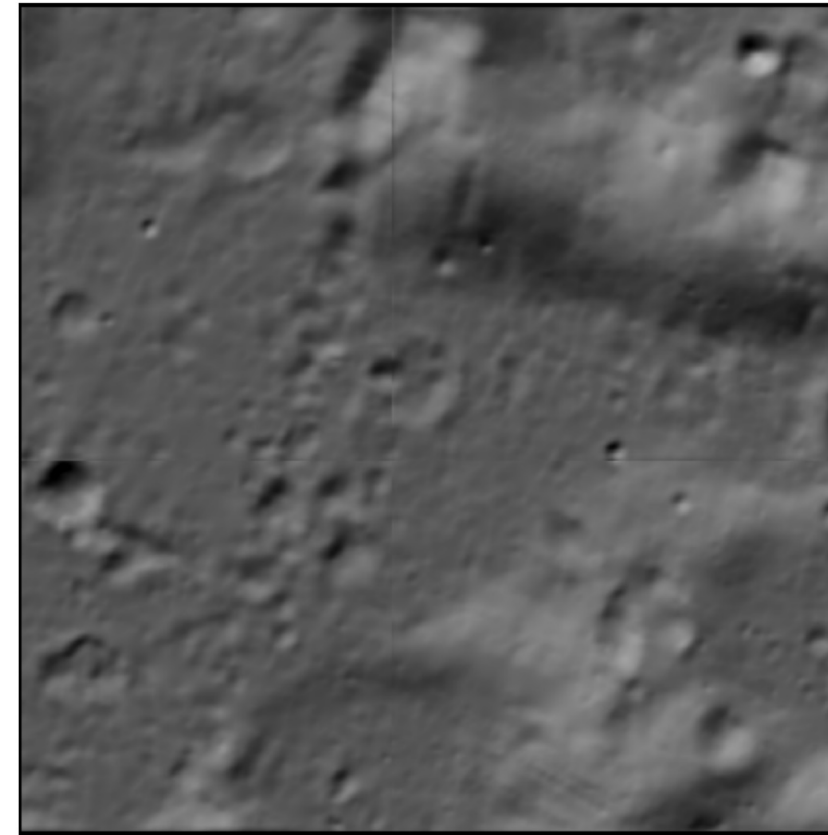
- 4 tiles per DEMs (just overlapped, yet to align+mosaic) interpolated at 5mpp before hill-shadow
- Still missing: preliminary check of shadowed areas in input images, to ensure “real” full coverage



SfS

SfS: Higher-Resolution with artifacts

Tiles 485-486-468-469



LDEM

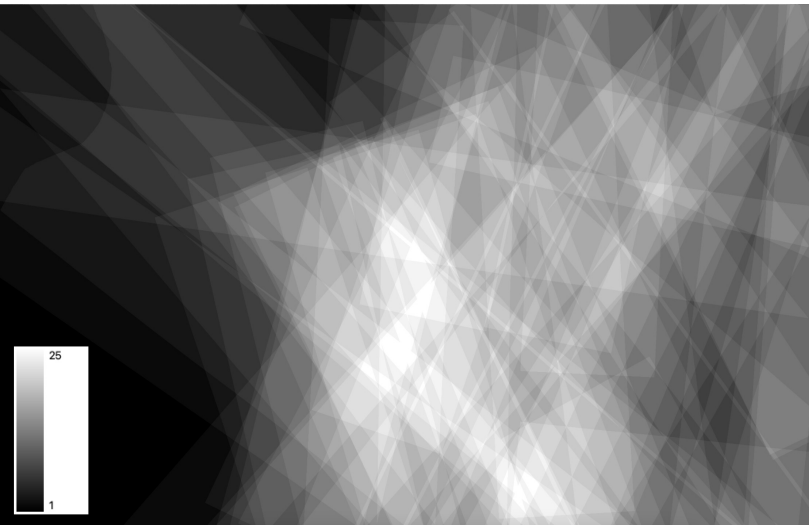
SfS: Lower-Resolution without artifacts

Ames: Landing Site High-Resolution Shape from Shading DEMs

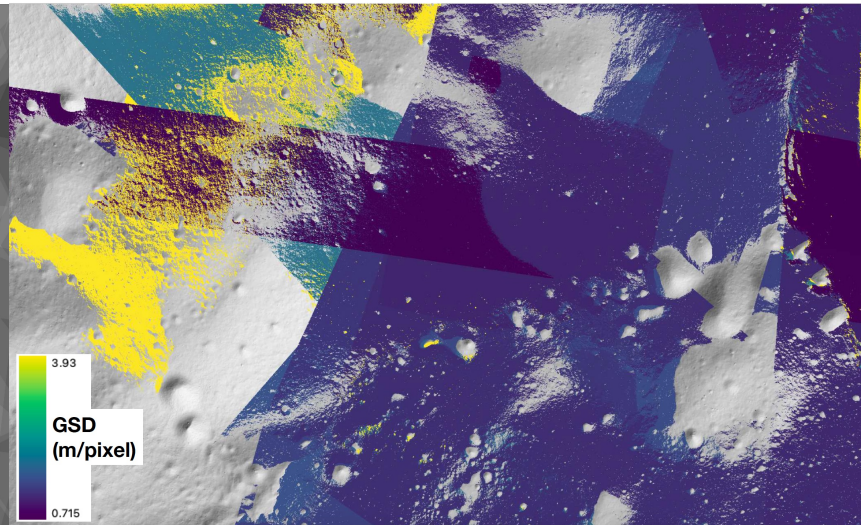


- Using the Ames Stereo Pipeline tool suite
- Start with clean 5m/pixel LOLA DEMs
- Gather all overlapping NAC images (1-3mpp)
- Create SfS DEM (1-3mpp depending on available images)
- *Ames team worked on this site ~4months and it's an area of 16x10km*

Image Count Map



Ground Sample Distance Map



SfS 2 m/pixel



TRN DEMs @ JPL – Overview and Data Assessment

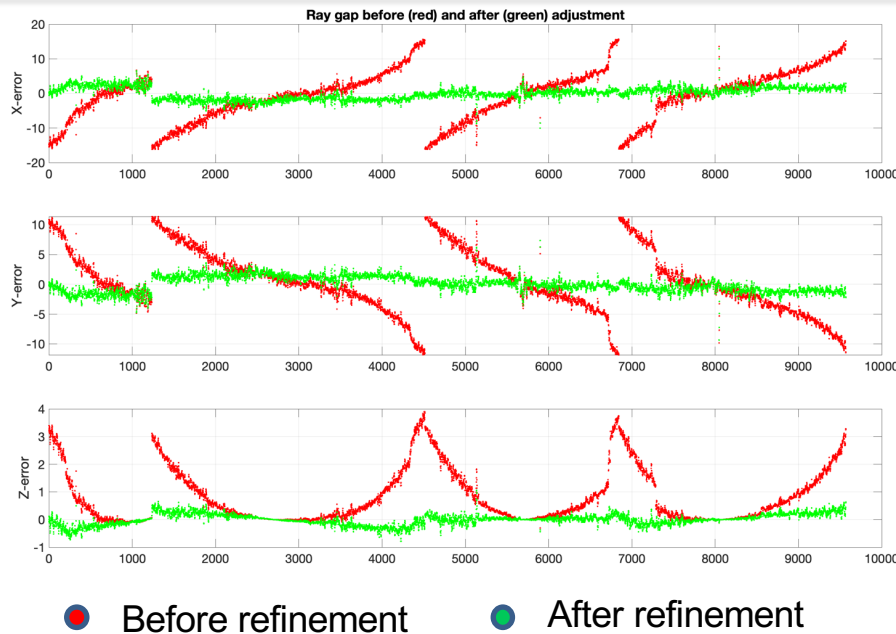


JPL has developed a stereo/mapping pipeline to generate DEMs/maps from Kaguya data

- Independent mid-resolution DEMs for comparison and validation against LOLA/SLDEM2015
- Internal V&V process
- Possibility of extracting higher resolution than native JAXA products

Kaguya data assessment

- Stereo cross-validation across different datasets shows minimal artifacts from timing and jitter ← concern based on experience with M2020
- Camera model induced errors at image edges ← Mitigate by data driven update of camera model



Least-squares update of camera models to force consistency across stereo datasets. Errors before correction in red, after correction in green.

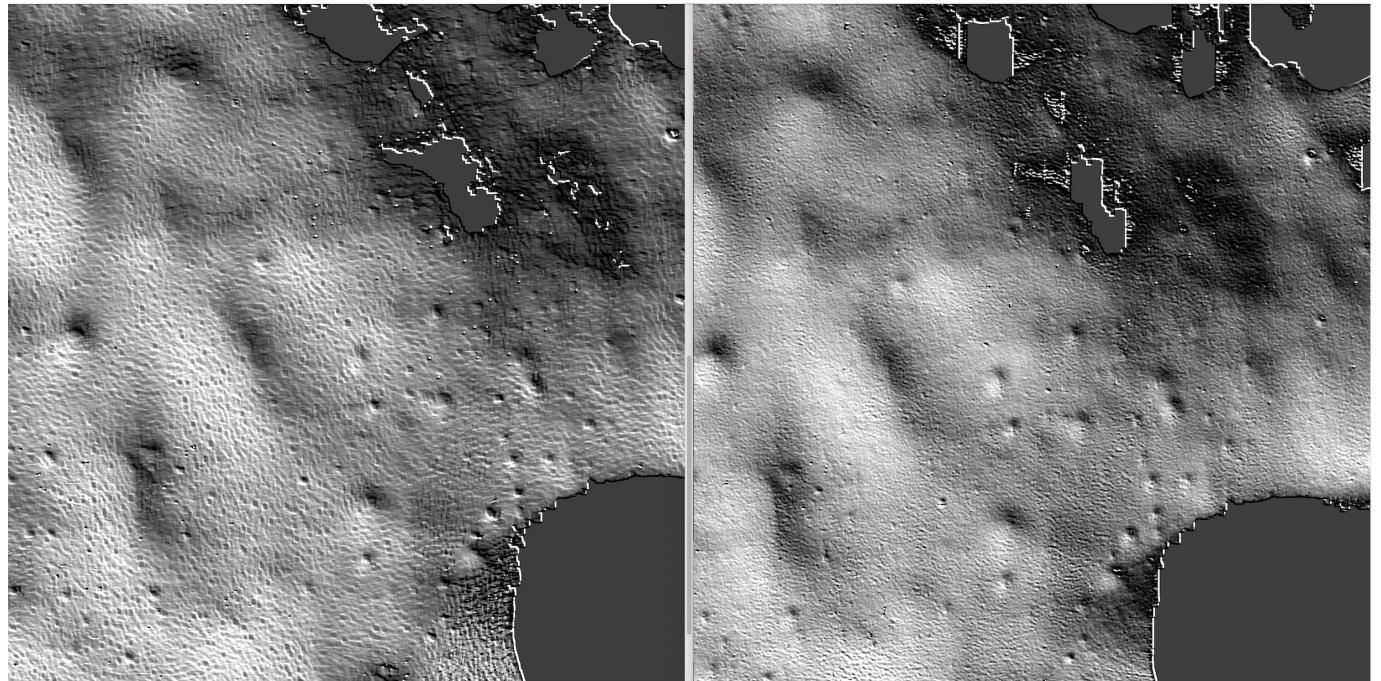
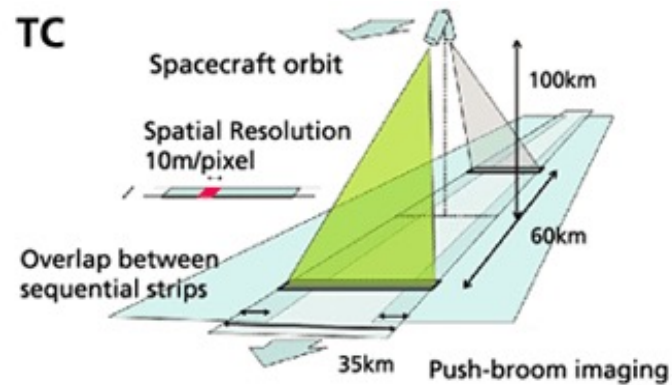
TRN DEMs @ JPL – Extracting more from Kaguya



Nature of Kaguya stereo geometry allows for possibility of higher fidelity sub-pixel stereo matching.

- **Fixed pushbroom pair configuration allows for approximate epipolar constraint ← leverage prior work on binocular stereo**
- **Allows for both improvement in native resolution of Kaguya DEMs/maps (final resolution TBD) and more meaningful validation of other high-res products**

Kaguya TC configuration

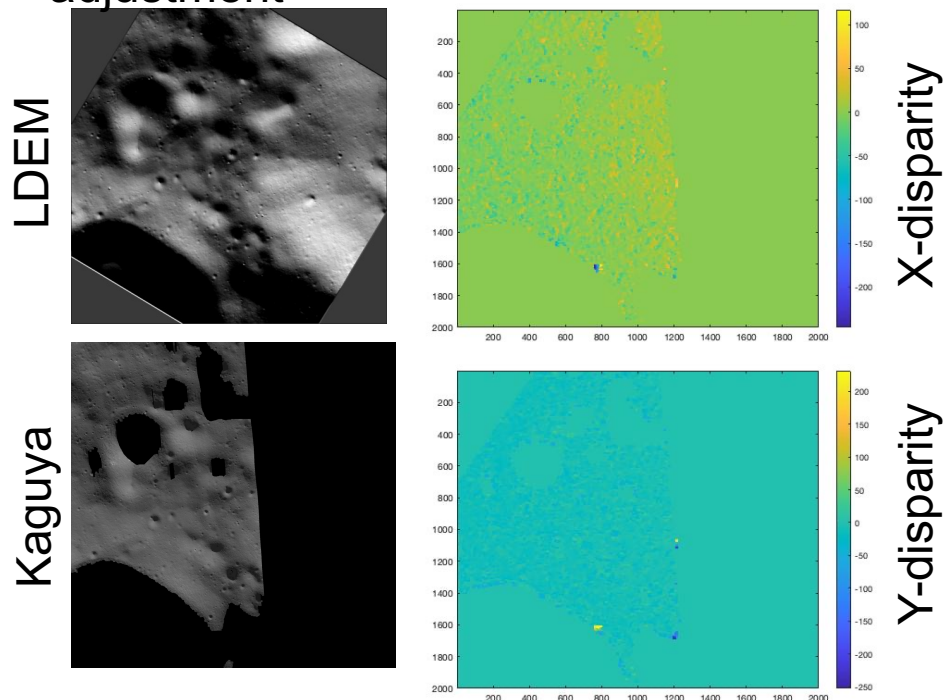


Standard stereo photogrammetry on left. New approach on right.

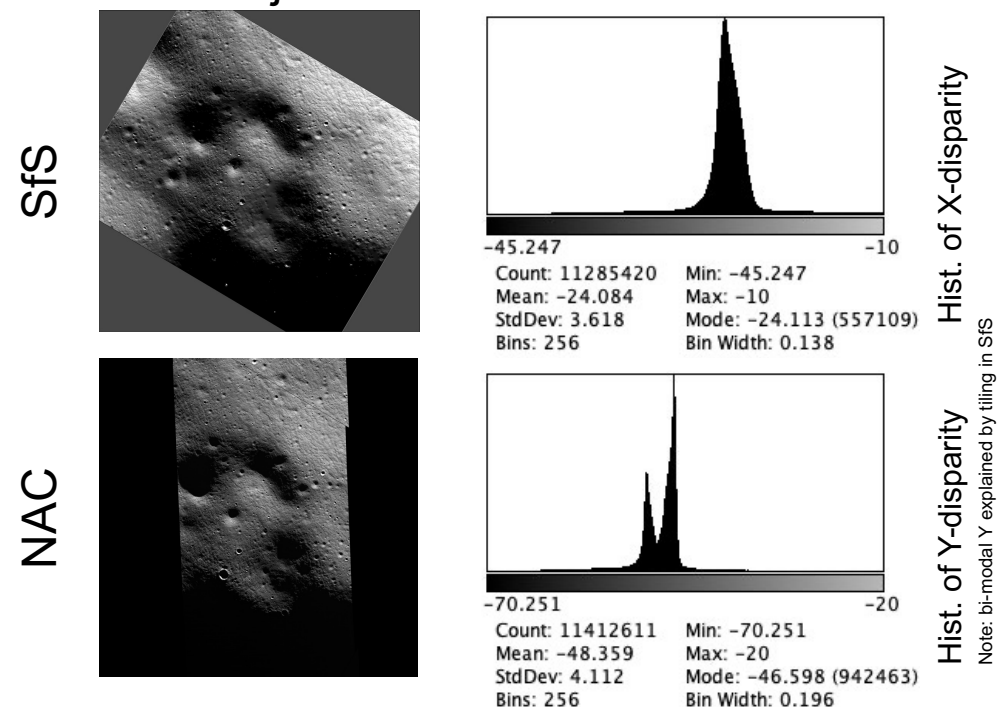
TRN DEMs @ JPL - Validation



Comparison of render from LDEM and processed Kaguya Ortho shows no local distortion. Disparities are post bundle adjustment



Comparison of Ames SfS DEM to JPL-produced NAC Ortho shows no local distortion. Disparity histograms are pre bundle adjustment



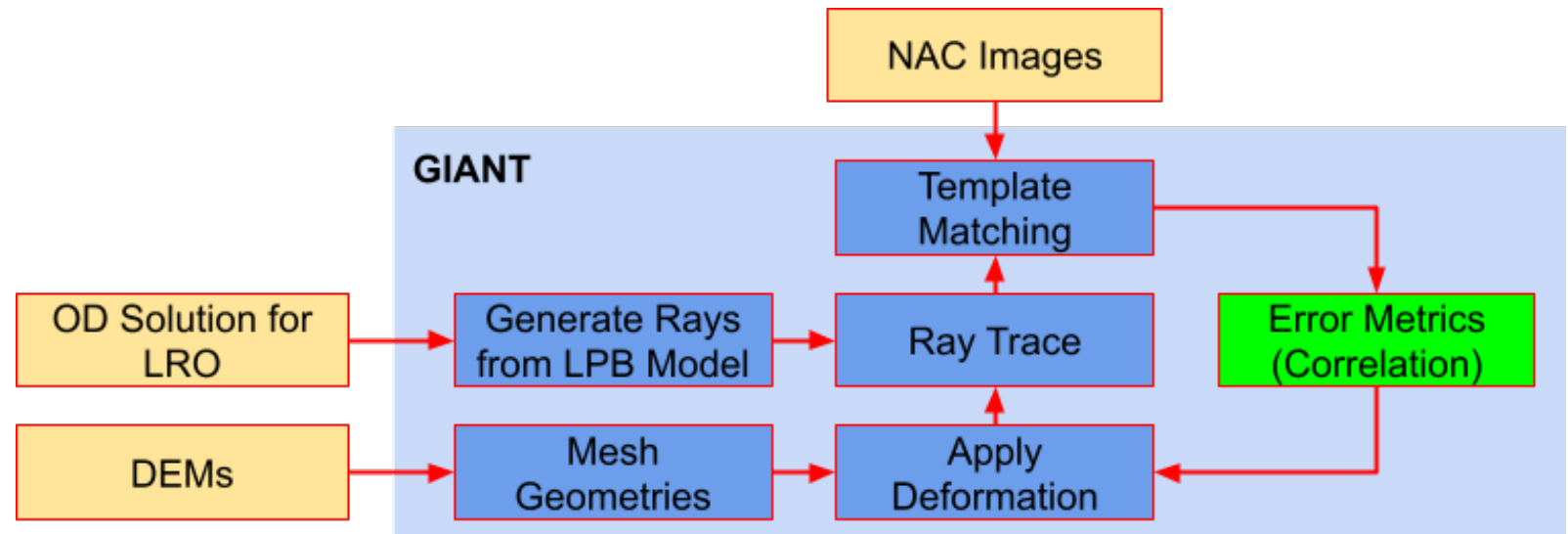
Cross-product validation shows no appreciable local distortion. This is a key requirement for TRN DEMs as demonstrated by M2020 example.

GSFC TRN Map Validation and Verification



Using Goddard's Image Analysis and Navigation Tool (GIANT), specific NAC images will be compared to rendered images of the same terrain.

Rendered images will be distorted systematically in order to extract potential error sources that could then be computed analytically



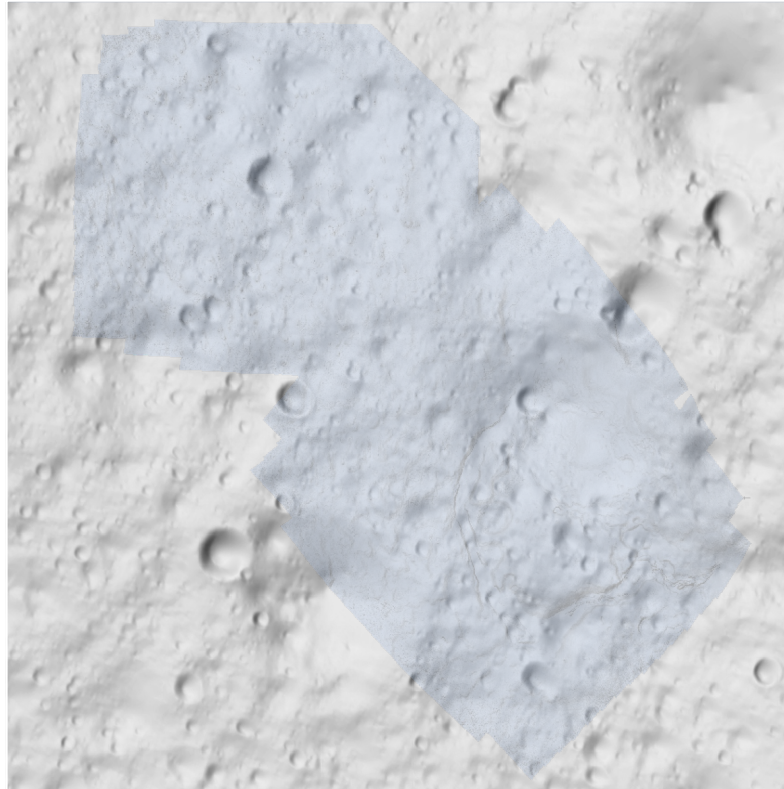
<https://github.com/nasa/giant>

Representative HD DEM 'Prototype' – Earth Analog Site



Iceland drone
stereoimagery data

+



Shape from Shading DEM
of the Moon (1-3m/pixel)

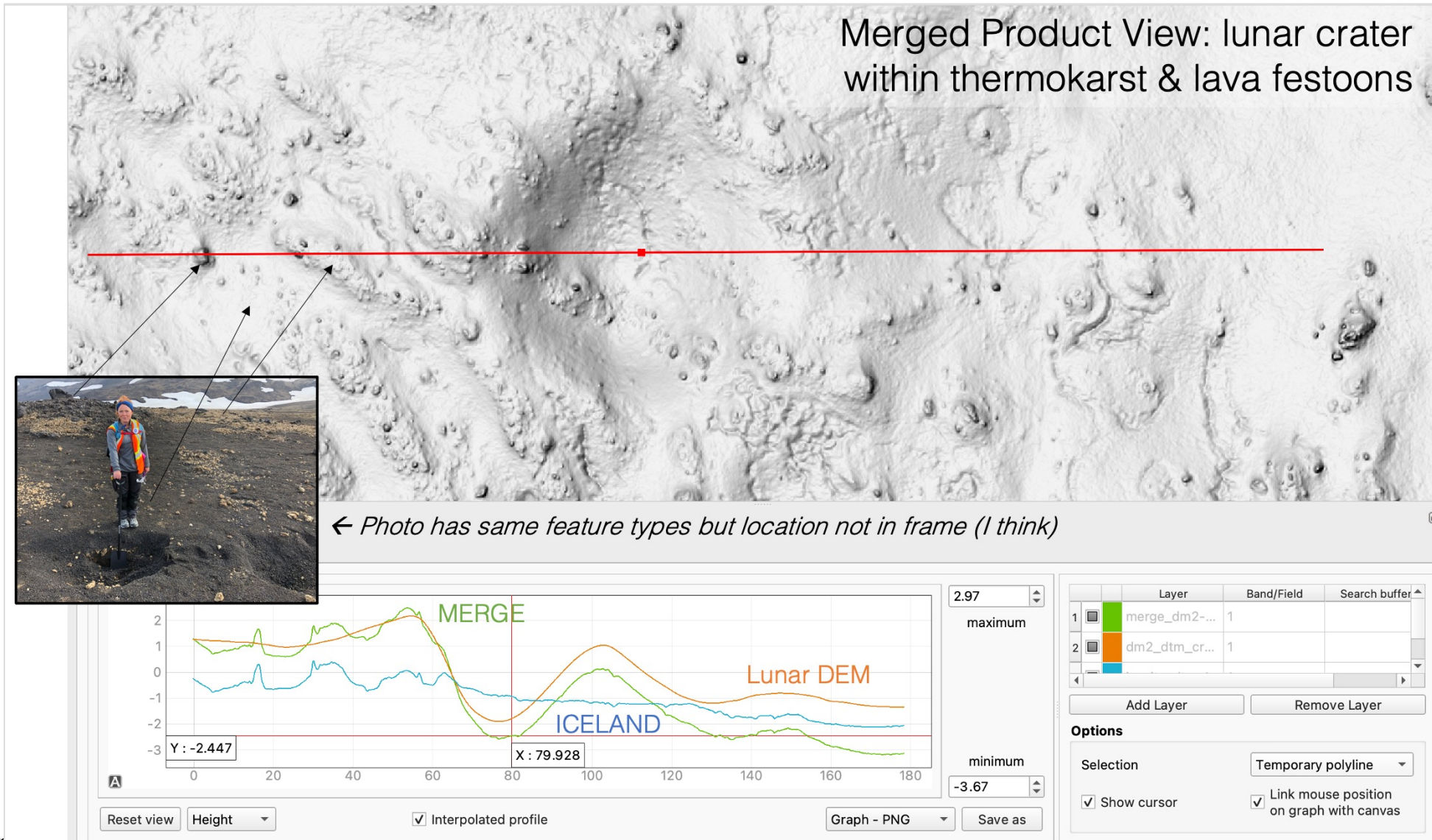
=



Merged 10 cm/pixel DEM

Views are 1 km x 1 km

Low + High Frequency Terrain Data



Representative HD DEM 'Prototype' – Synthetic Features



Methodology: Generating 3D terrestrial assets

We used our multi-view stereophotogrammetry workflow and Agisoft Metashape Professional software to generate shape models of individual 0.2 – 2.5 m sized rocks and regolith analog textures from the field. Rocks were chosen with characteristics similar to boulders encountered by lunar landers, rovers, and astronauts in the past surface exploration of the Moon.

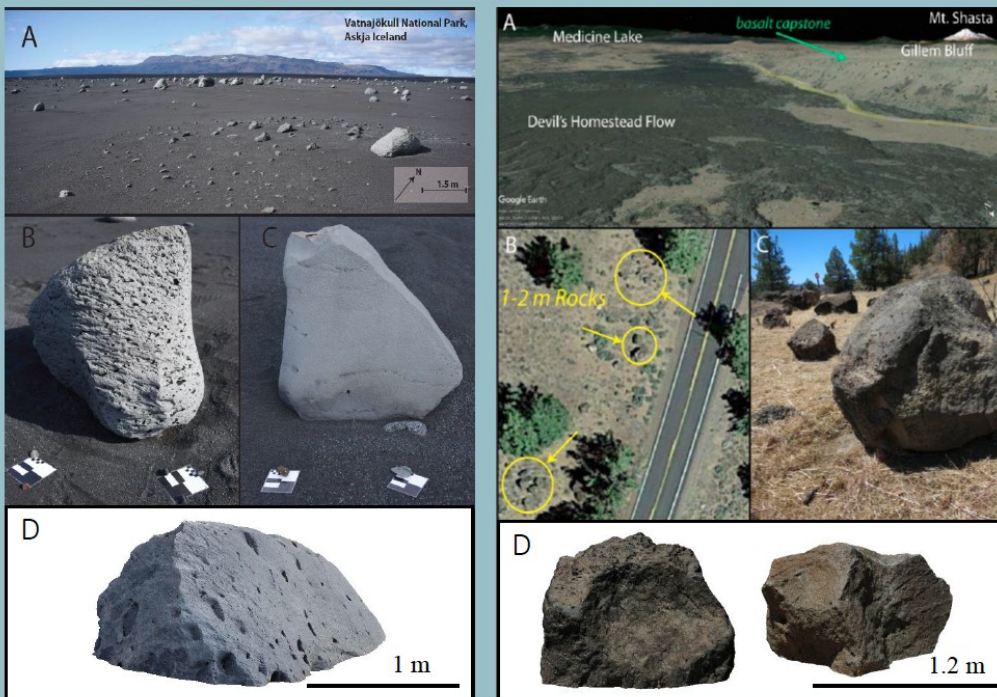


Figure 3. (A) Field perspective from Askja, Iceland (left) and Medicine Lake CA, USA (right). (B,C) in-situ images of large meter-scale lunar-like clasts. (D,E) virtual 3D renderings showing sub-centimeter rock surface textures.

Integrating 3D assets into lunar terrain

Building an aDEM required processing of several terrain elements in 3D file formats, such as 3D point clouds (*.ply) and meshed surfaces (*.obj) in a variety of 3D data manipulation software packages, including Blender, CloudCompare, and Meshmixer. Custom python code utilizing the PyMesh library was written to integrate 3D elements, change the size, shape, and distribution of 3D assets. Data can be exported as raster data for integration into other applications, including ArcGIS and Matlab.

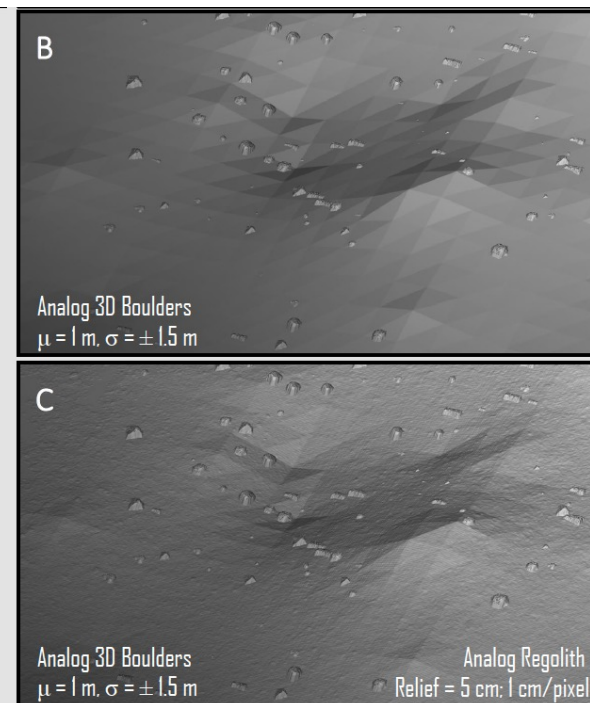
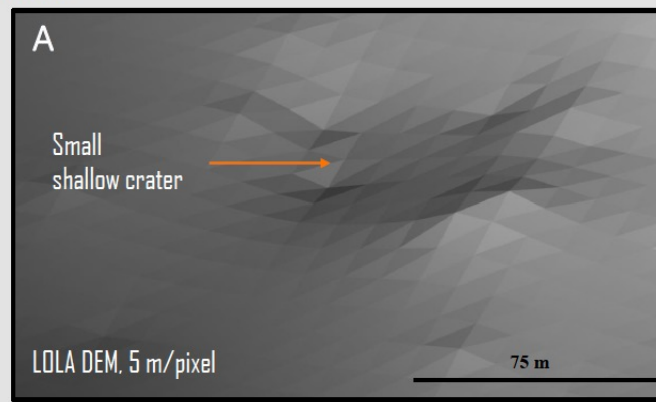
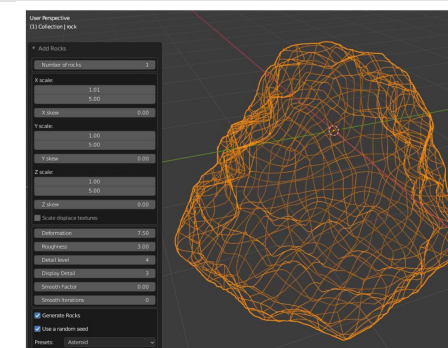


Figure 6. 3D perspective view of rendered lunar terrain at Shackleton Crater. (A) LOLA DEM. (B) Lunar terrain populated with analog 3D boulder assets. (C) Lunar terrain populated with 3D boulder and regolith assets.

Parametric Rock Generation in Blender (wire frame)



TRN Performance Evaluation Pipeline @ GSFC

For a given reference trajectory and target landing site:

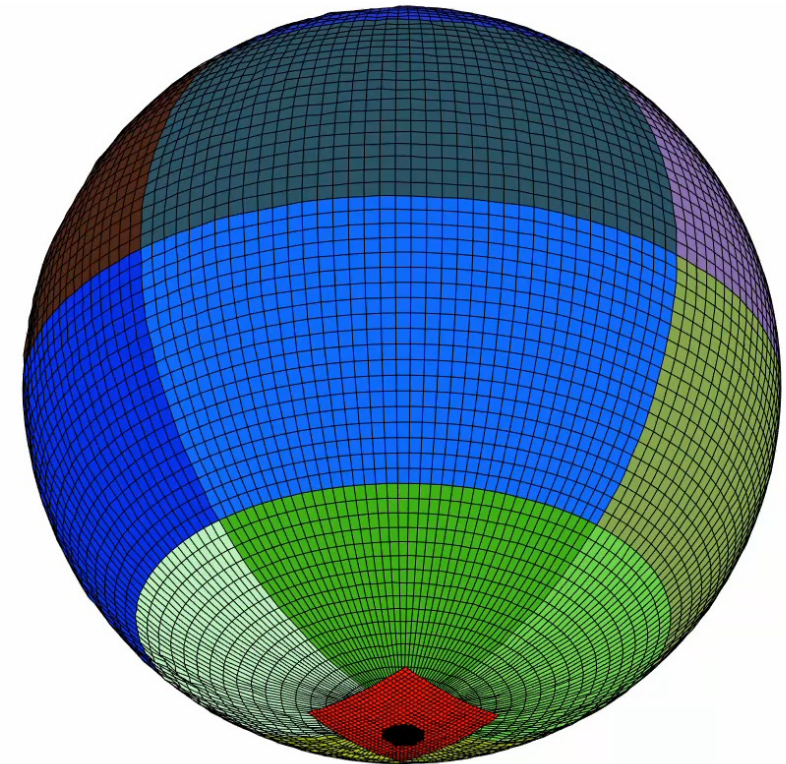
- Load reference trajectory
- Load meta data for all topographic maps (of all resolutions) to be considered
- Pre-process the trajectory to determine which maps/portions of maps are visible, and identify what resolution for each should be used
- Divide large maps into tiles such that only the relevant data is loaded
- Construct ray tracing acceleration structure for all visible tiles and maps
- Render image sequence
- Simulate TRN Camera and/or LiDAR altimetry measurements
- Run EKF with TRN and altimetry measurements to evaluate nav performance

All of the highest resolution tiles

Each color is a different dataset (DEM)

Each rectangle represents ~1.5M vertices

Black patch is 87deg South DEM:



Project Assessment Summary



Project Name	Performance				Comments
	C	S	T	P	
Mid Year					Technical – Provide rationale for yellow and red color determination Cost – First half of the year CR funds were not enough Schedule – Progress halted due to lack of funds towards the end of CR period Programmatic -
Annual					Technical – Cost – Schedule – Programmatic -

Plans Forward and Transition / Infusion Plan



- Perform full analysis of TRN performance with new DEMS along a polar trajectory
 - Compare clean vs. old DEMs in TRN performance and derive map quality metrics
 - Develop specific error metrics for DEMs after map validation exercises
- Continue collaboration with Blue Origin for TRN maps through Fall 2022 and deliverables for this are due early Dec.
- Set up collaboration with Georgia Tech (postdoc) to help us answer research questions related to TRN algorithm types and how each can handle different types of DEM errors (first deliverables likely in the spring semester of 2023)
- Continue to coordinate with HLS EDL teams on their needs for map products and timelines, now that the 13 landing sites were announced.

Education/Public Outreach

EPO Involvement

- Team is presenting several talks at the Space Imaging Workshop in Atlanta and we are discussing leading a breakout discussion or small workshop 'class' on map products for all attendees
- Presenting 2 papers at AIAA Scitech EDL sessions in January 2023

EPO Calendar Outlook (High Priorities):

6 Month Look-Ahead

3 rd Space Imaging Workshop, Atlanta, GA	October 10-12, 2022
AIAA Scitech Forum, National Harbor	Jan 2023

Summary



- As far as we know, ***this is the only methodical/deliberate effort*** to generate these map products out there and we have all the right people working on each piece of the puzzle
- TRN performance analysis will need both high-fidelity TRN simulations and DEMs. As of now, some of the high-fidelity sims do not have an easy way to load these new DEMs, and our team sims can load these DEMs but are not yet optimized for nav performance
- Missions are likely to require new (not readily available for download) DEMs made specifically to cover their ground tracks on the approach to the landing site whether it's a polar or non-polar site. Each has different challenges (i.e. polar sites have low illumination conditions, but non-polar sites have less available imagery)