



Mobile LiDAR as a Tool for Terrestrial and Planetary Cave Exploration and Mapping

W.E. King, M.R. Zanetti, E.G. Hayward, K.A. Miller
Arizona Regional Association Winter Technical Meeting
January 27th, 2024



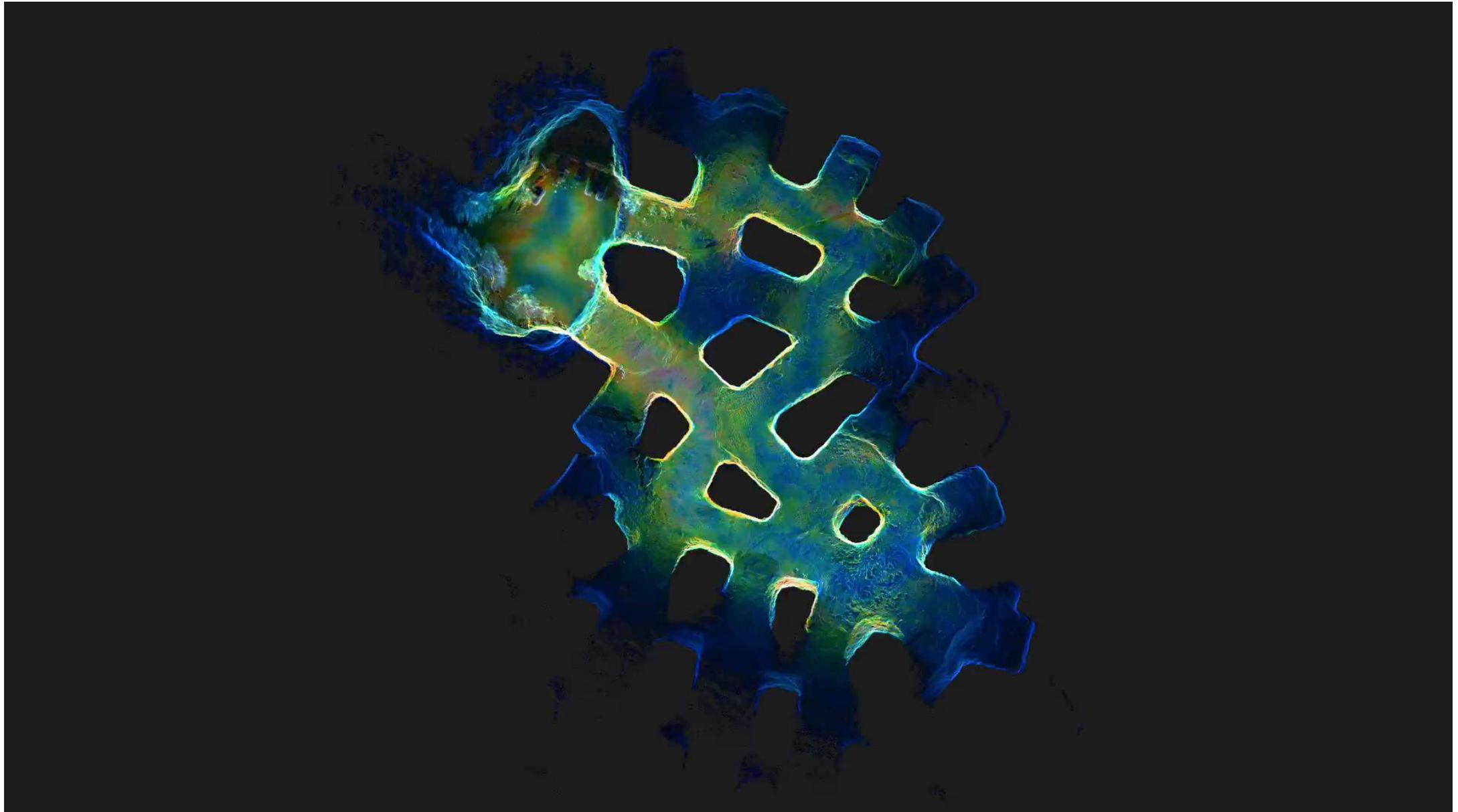
Three Caves Quarry



Kinematic Navigation and Cartography Knapsack.
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Overview



Kinematic Navigation and Cartography Knapsack.
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KNaCK (Kinematic Navigation and Cartography Knapsack) is a backpack-mounted mobile LiDAR (Light Detection and Ranging) system. It can map its surroundings in 3 dimensions and localize itself in space.

The project objective is to explore how LiDAR can advance terrain mapping and navigation at the lunar south pole. KNaCK is lead by Dr. Michael Zanetti of NASA MSFC's Heliophysics and Planetary Science Branch.

Mobile LiDAR

- Not dependent on illumination conditions
- Does not require GPS
- Rapid survey potential
- Sufficient detail for geoscientific and architectural use (cm scale)
- Compatibility with EVA suits and exploration vehicles

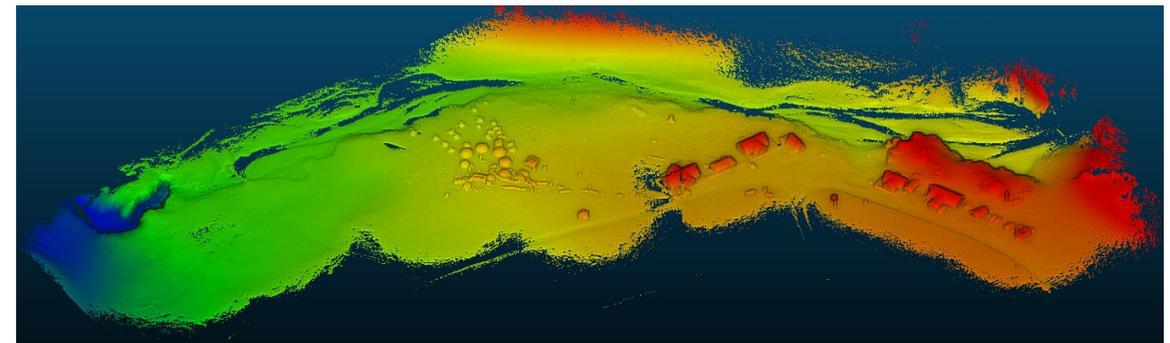
SLAM—Simultaneous
Localization and Mapping



Fig. 1. The KNaCK Instrument.



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walter.e.king@nasa.gov

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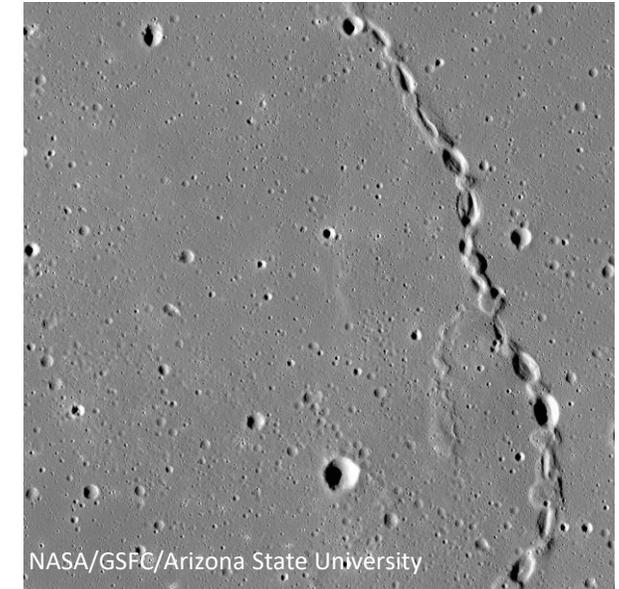
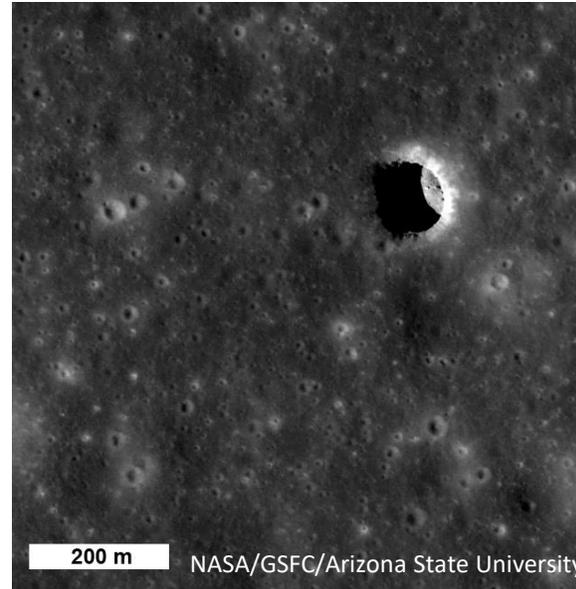
Planetary Caves



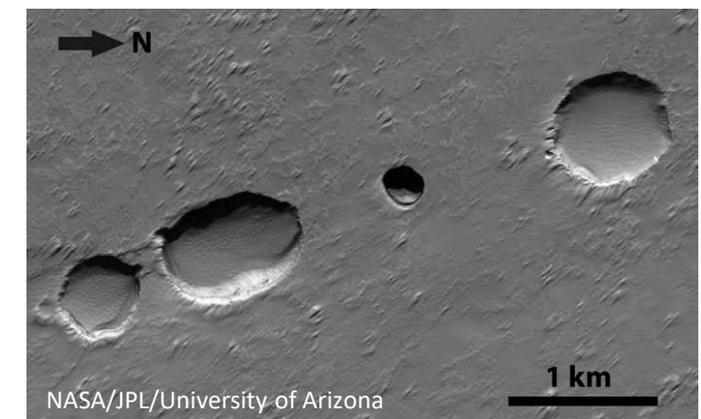
Potential cave entrances have been identified throughout the solar system.

- Moon
- Mars
- Titan
- Enceladus
- Europa
- Triton
- Pluto
- Charon
- Ceres

Moon



Mars



Caves as Planetary Analogs



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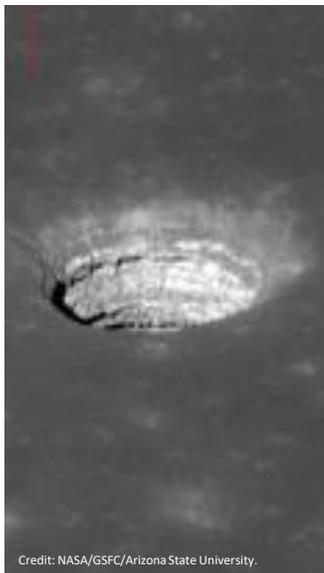
Terrestrial caves share similarities with lunar and martian surfaces. They are also analogs for lava tubes and other subsurface voids on the Moon, Mars, and other planetary bodies (Fig. 2). Many terrestrial caves have maps and survey data available that can be used as a ground truth to assess system performance.

Convergent design: Algorithms and hardware that succeed in the cave environment bring us closer to systems suitable for lunar and planetary use.

There are more than 200 known caves within the city limits of Huntsville and roughly 5000 known caves in the state of Alabama.

Cave environments provide:

- GPS denial
- Highly rugged and irregular terrain
- Challenging illumination conditions
- A size and mass constrained environment



Credit: NASA/GSFC/Arizona State University.

Fig. 2a. Mare Tranquillitatis Pit, Oceanus Procellarum, Moon.



Fig. 2b. Skylight in Three Caves Quarry, Huntsville, AL, USA, Earth.



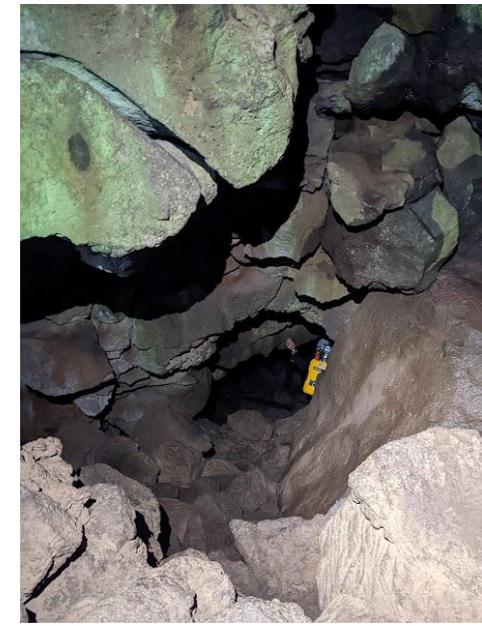
Fig. 3. Entering Three Caves Quarry (left), scanning borehole passage in Lava River Cave (middle), entering Lava River Cave (right).

Planetary Cave Applications:

- Assessing significance of features for science, ISRU (In-Situ Resource Utilization), or habitation
- Establishing the concepts of operation to enter and explore features on future robotic or manned missions
- Investigate geologic and morphologic history of subterranean spaces

Terrestrial Cave Applications:

- Enhanced studies of geomorphology, speleogenesis, hydrology, air circulation, habitat inventory, and other environmental and geologic studies



Three Caves Quarry, Huntsville, Alabama (Fig. 4)

- *Data collected in 6.5min over a 370m traverse*
- *18.4M points after post processing*
- *Centimeter-scale resolution*

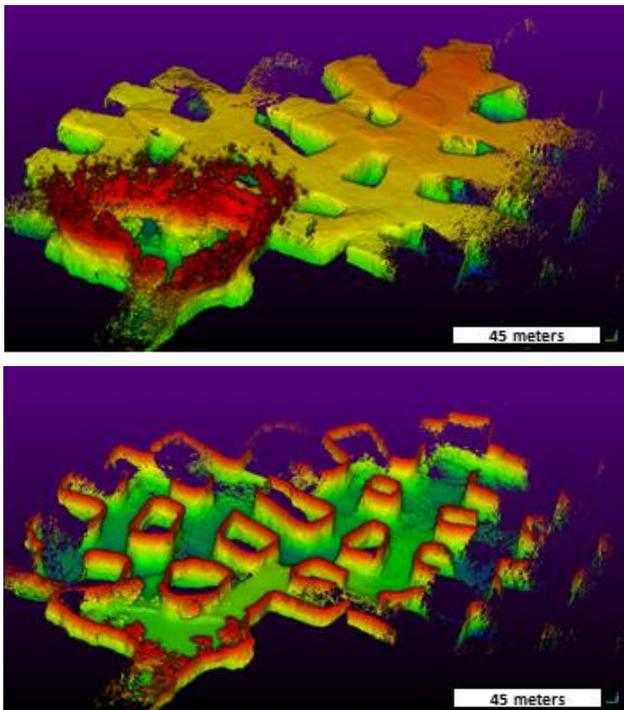


Fig. 4. Three Caves Quarry, Huntsville, AL: (top) full point cloud, (bottom) cross-section exposing the interior volume.

Lava River Cave, Arizona (Fig. 5)

- *Data collected in 44min over 1100m scan*
- *44.8M points after post processing*
- *Centimeter-scale resolution*

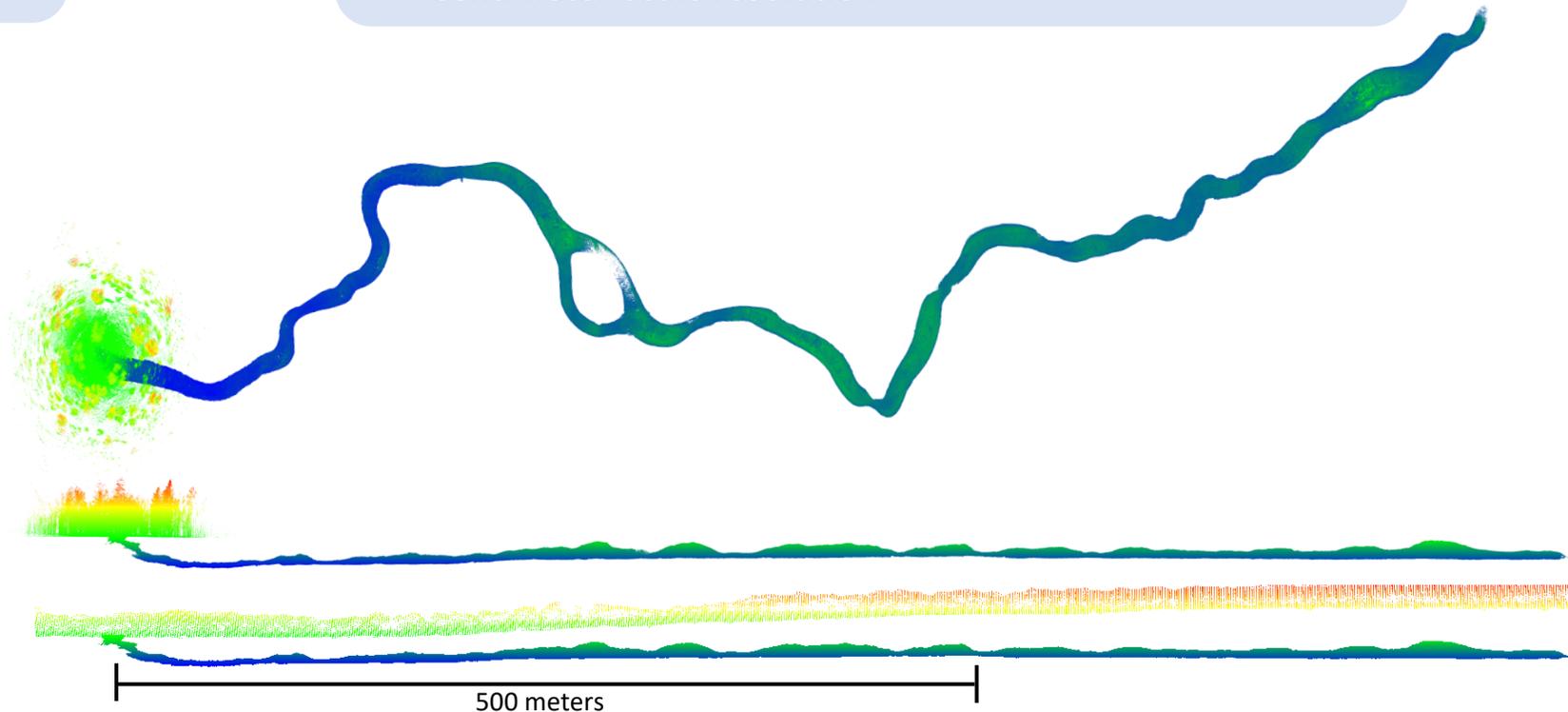
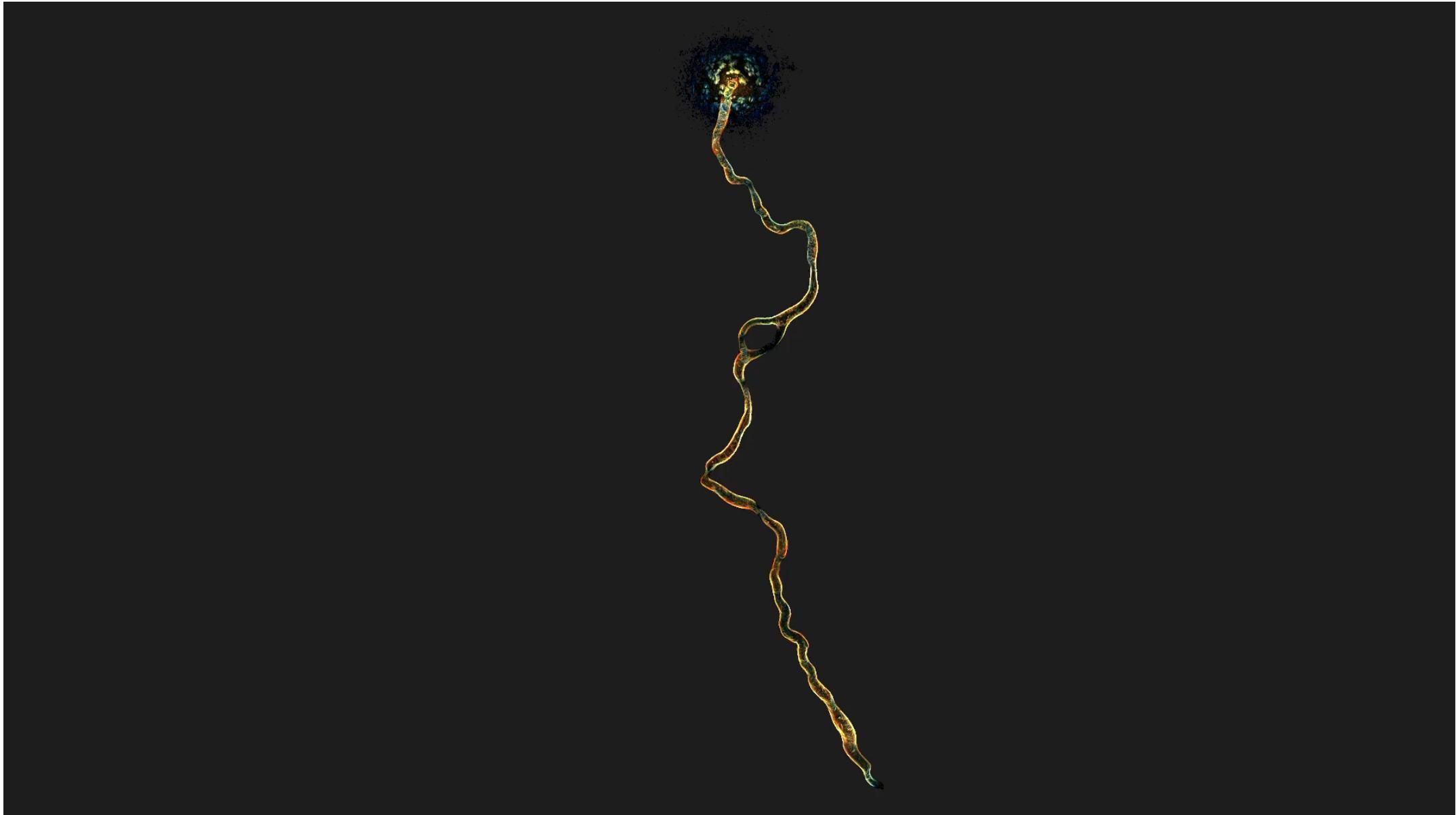


Fig. 5. Lava River Cave, San Francisco Volcanic Field, Arizona: (top) LiDAR map overlaid with traditional cave map, (middle) profile view of LiDAR map, (bottom) NAIP Point Cloud DEM overlaid with LiDAR map.

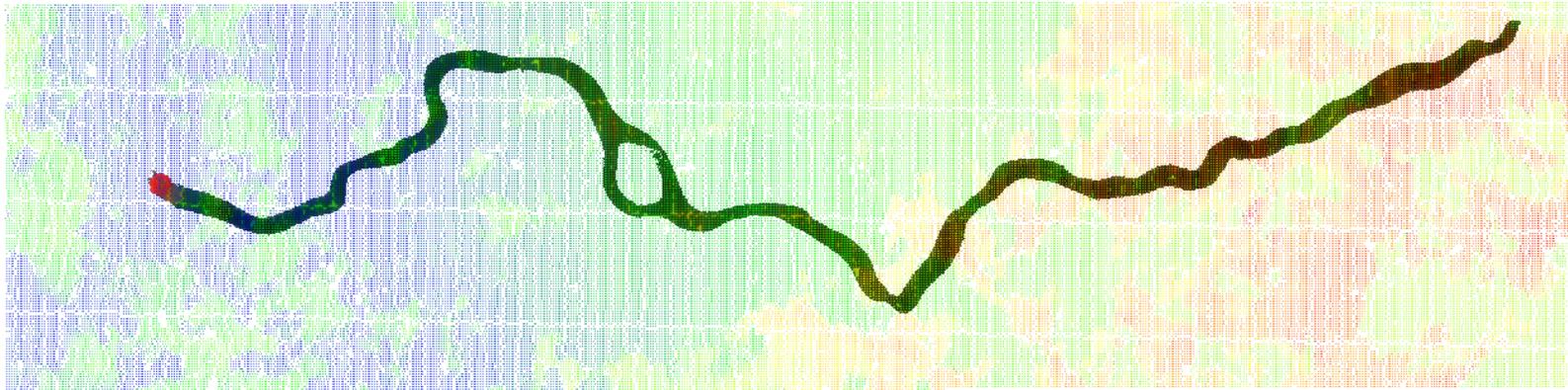
Lava River Cave



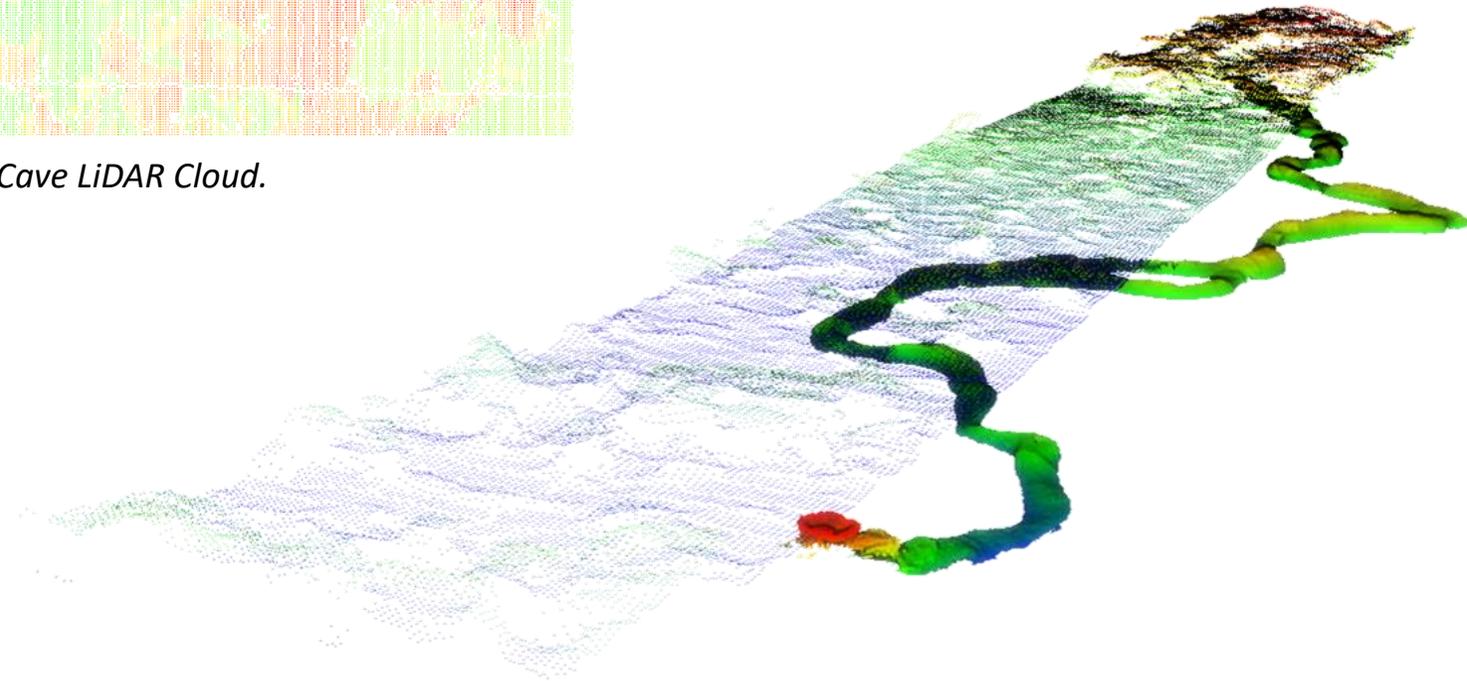
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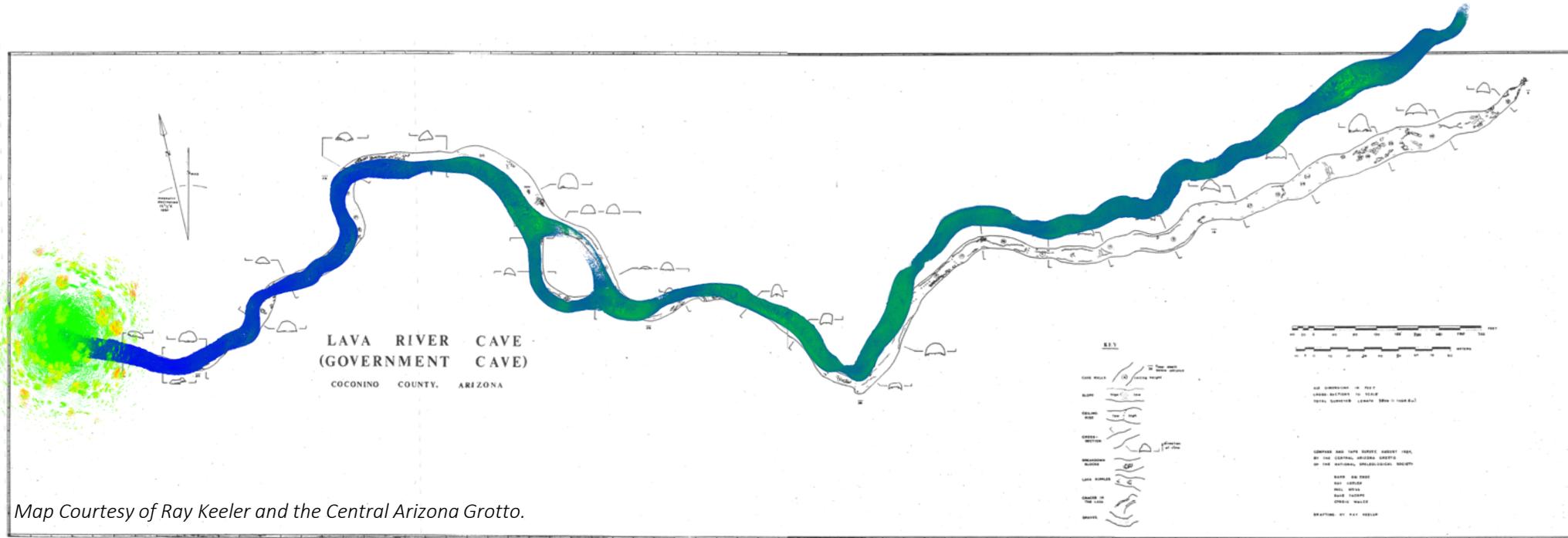
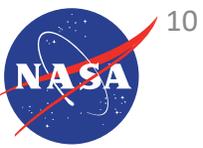
Integrating with existing surface elevation models allows unique and intuitive representations of the relationship between surface and subsurface topography.



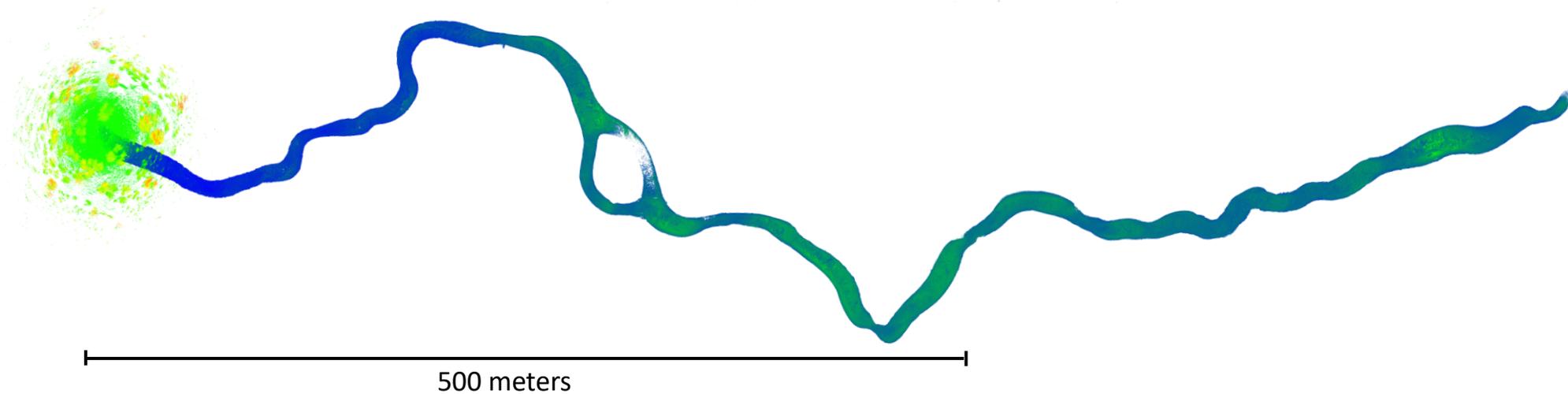
NAIP Point Cloud (2017) overlaid on Lava River Cave LiDAR Cloud.



Comparing to the 1984 Survey

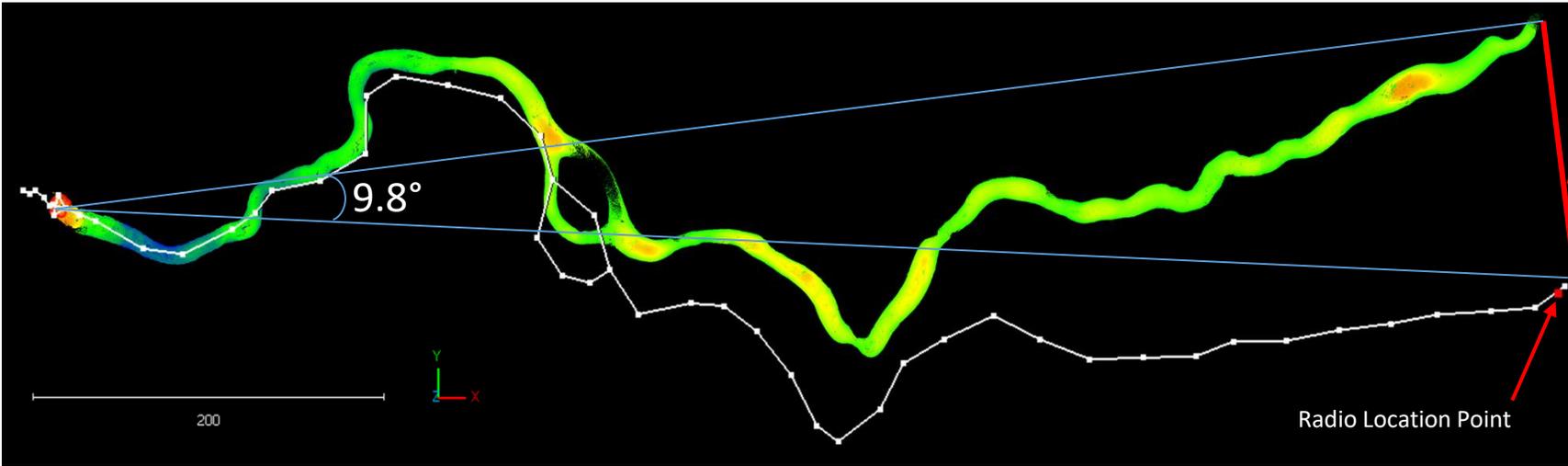


Map Courtesy of Ray Keeler and the Central Arizona Grotto.



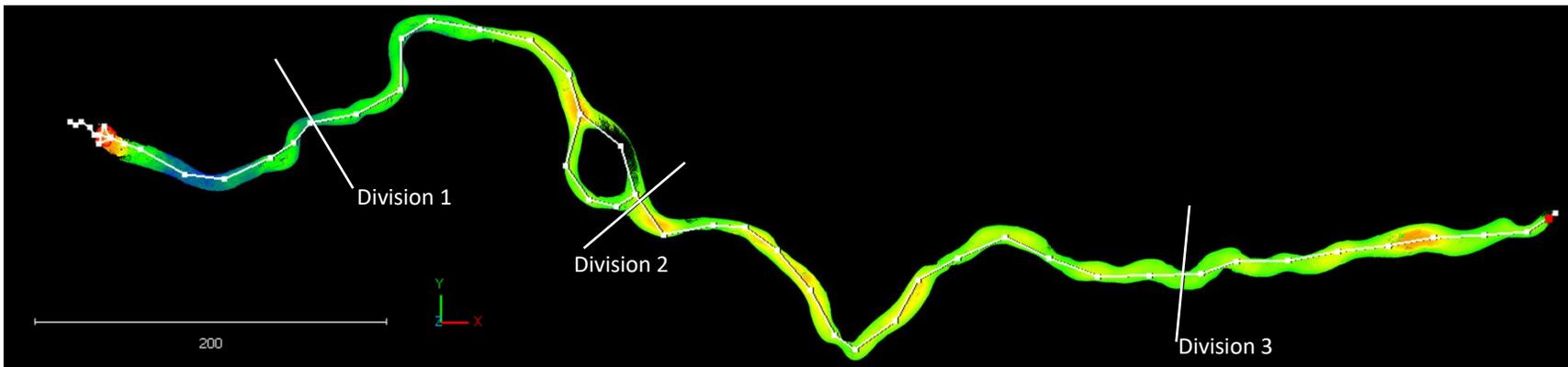


Comparing to the 1984 Survey



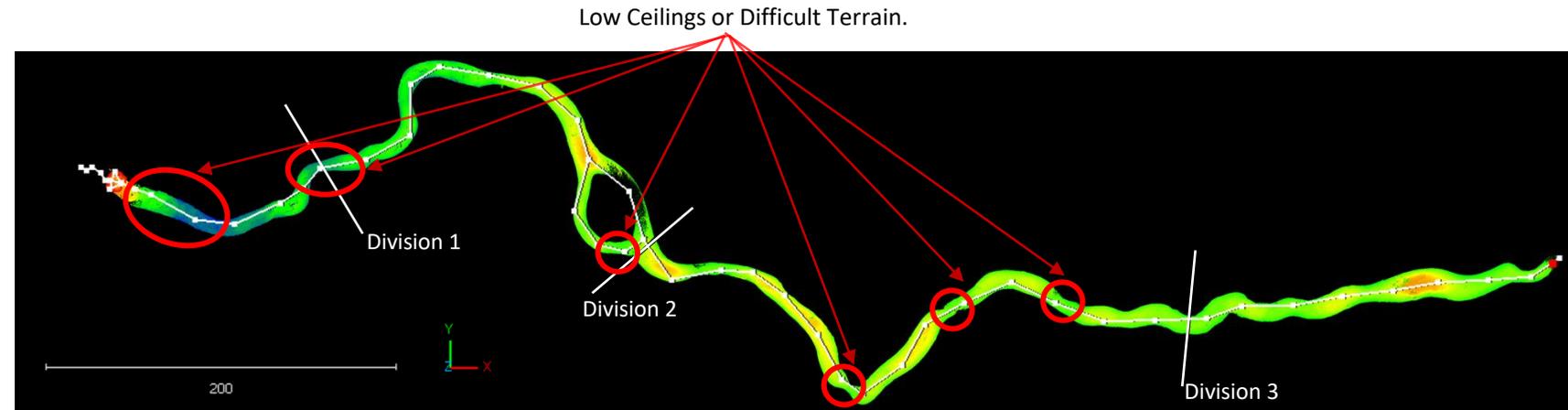
Distance: 144.463273			
ΔX	12.283630	ΔXY	144.462143
ΔY	-143.938965	ΔXZ	12.296812
ΔZ	0.569216	ΔZY	143.940094

- Alignment based on probable station locations and plausible shots into the cave. Original station placement unknown
- Radio location point indicates accuracy of the 1984 survey
- <10 degrees of total deviation between the point cloud and survey line plot
- Large portions of the point cloud are highly consistent with survey
- Division and manual alignment yields a map with both local and global accuracy



Survey data (line plot) courtesy of Ray Keeler and the Central Arizona Grotto. Radio location data courtesy of Paul Jorgenson.

- Small dead reckoning errors accumulate
- Error likely higher in narrow and difficult to traverse sections
- Large number of people moving in the cave may have interfered with scan matching
- Opportunities for enhancement:
 - Processing of complete dataset (out and back)
 - Tuning SLAM parameters
 - Constrain solution with other data (survey data or radio location stations)



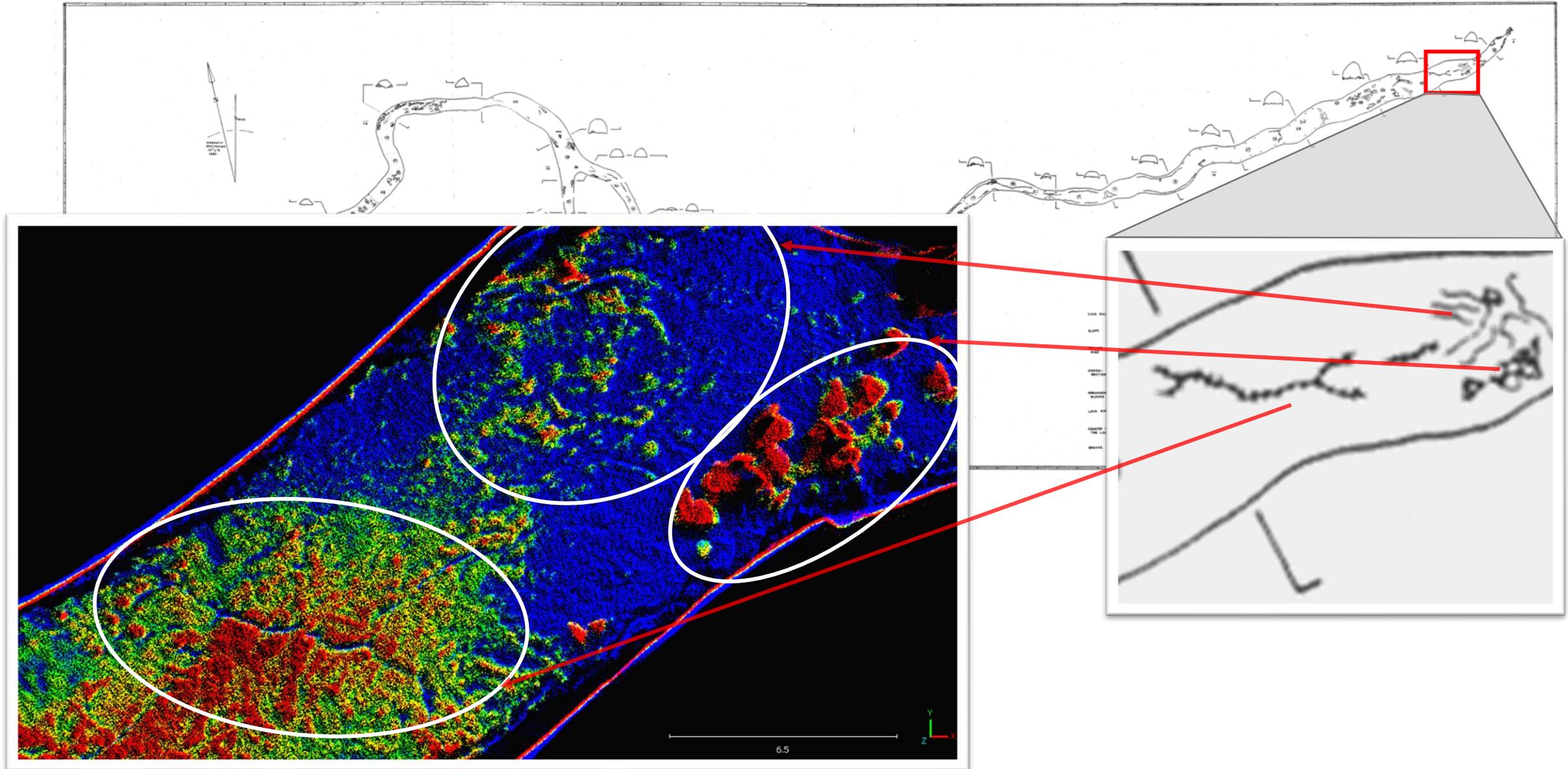
Survey data (line plot) courtesy of Ray Keeler and the Central Arizona Grotto. Radio location data courtesy of Paul Jorgenson.



Fine Scale Features



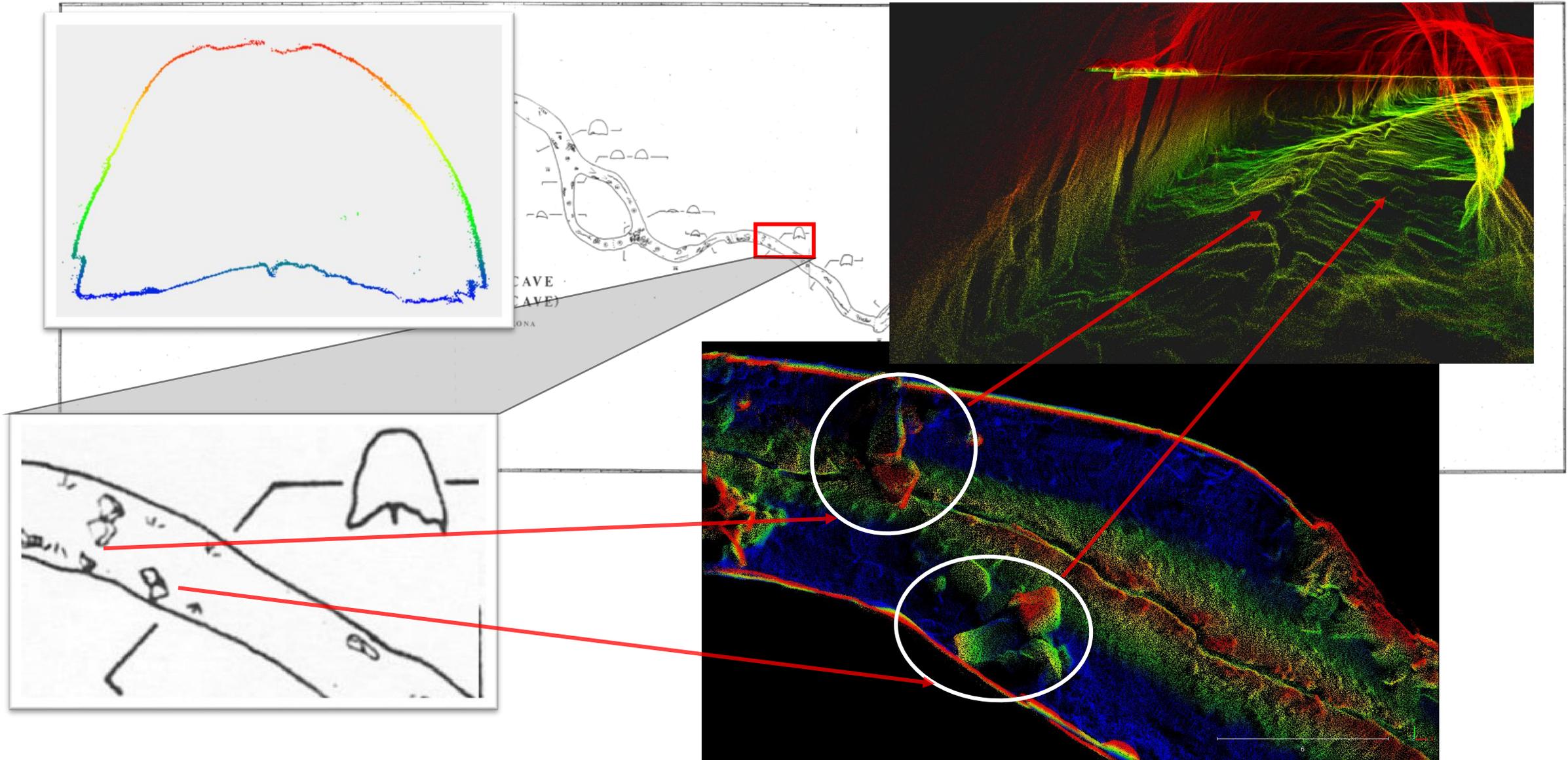
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Moving Forward

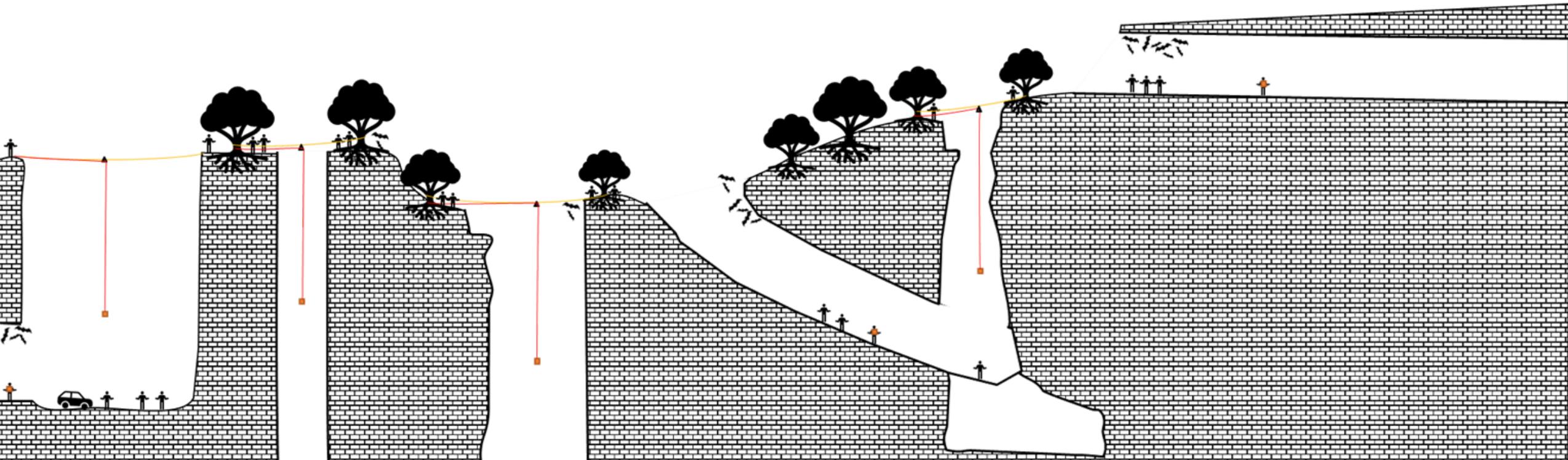


Ongoing Work:

- Repackage KNaCK to be more compact, robust, and tolerant of harsh environments
- Conduct vertical scans of pit caves as analogs for exploration of lunar skylights

Future Work:

- Constrain SLAM solutions with other data sets (survey stations, radio location stations, etc.)

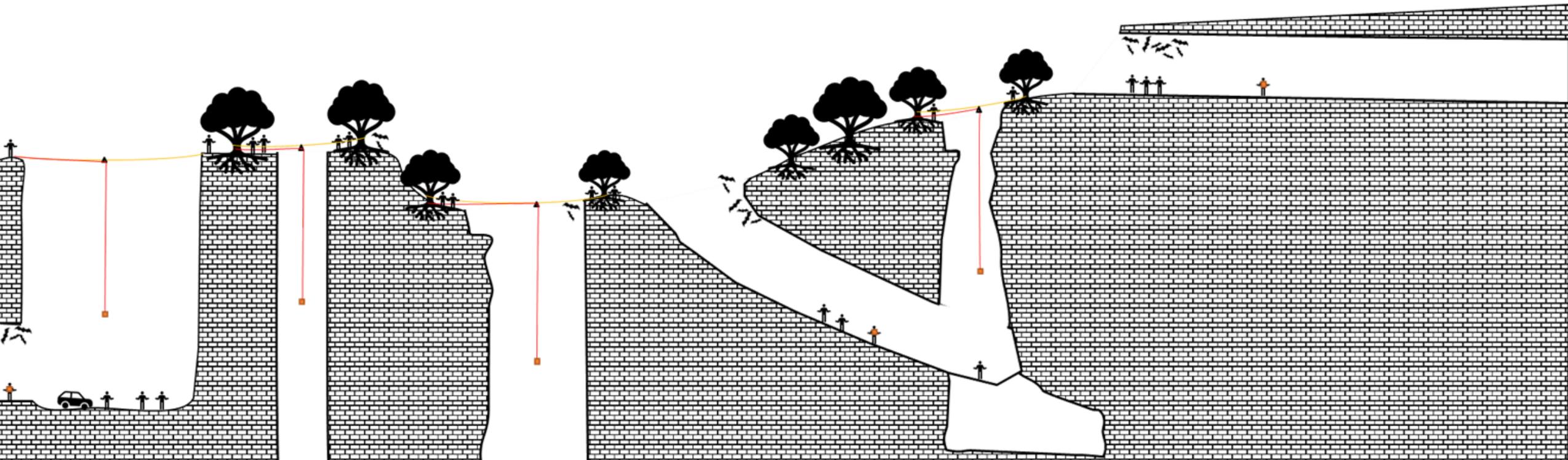


Summary



The KNaCK team is leveraging caves as a proving ground to refine technology for mapping and navigation on other worlds while simultaneously advancing the State of the Art for terrestrial cave exploration and study.

- Mobile LiDAR is easy to operate, sees beyond the cast of visible light, can operate without GPS, and produces rapid and very detailed surveys.
- Maps produced are highly accurate at local scale. There is currently notable drift from ground truth at global scale.
- Both Alabama and the Arizona have thriving space science communities. The responsible use of cave environments as terrestrial analogs can advance technology development, space science, and speleology.



Acknowledgements



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