Caves as Planetary Analogs for GPS Denied, Low-Light Mapping and Navigation in Rugged Environments

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Background: KNaCK (Kinematic Navigation and Cartography Knapsack) is a backpack-mounted mobile mapping system. It can map its surroundings in 3 dimensions and localize itself in space using a LiDAR (Light Detection and Ranging) sensor and SLAM (Simultaneous Localization and Mapping) algorithm (Fig. 1). **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.**

Caves as Planetary Analogs

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 (Fig. 5, 6, 7).

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, Alabama 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

Fig. 1. The KNaCK Instrument.

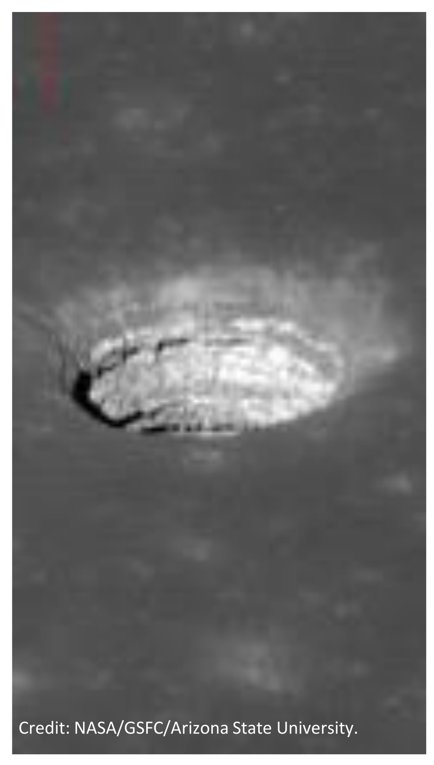

Fig. 2a. Mare Tranquilitatis Pit, Oceanus Procellarum, Moon.

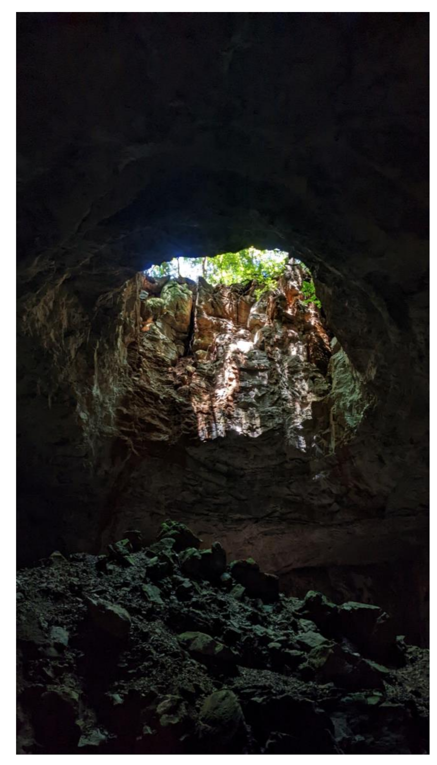

Fig. 2b. Skylight in Three Caves Quarry, Huntsville, AL. USA, Earth.

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

Field Work

Three Caves Quarry, Huntsville, Alabama (Fig. 4)
- *Data collected in 6.5min over a 370m traverse*
- *18.4M points after post processing*

Lava River Cave, Arizona (Fig. 5)
- *Data collected in 44min over 1100m scan*
- *44.8M points after post processing*

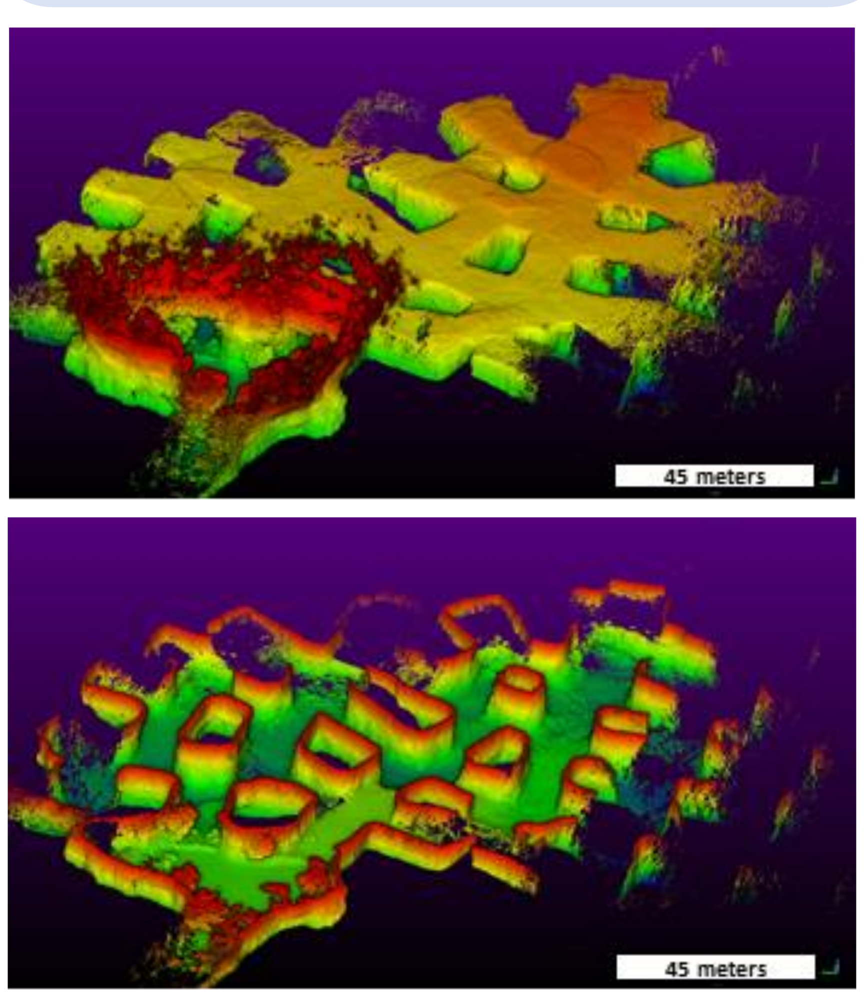

Fig. 4. Three Caves Quarry, Huntsville, AL: (top) full point cloud, (bottom) cross-section exposing the interior volume.

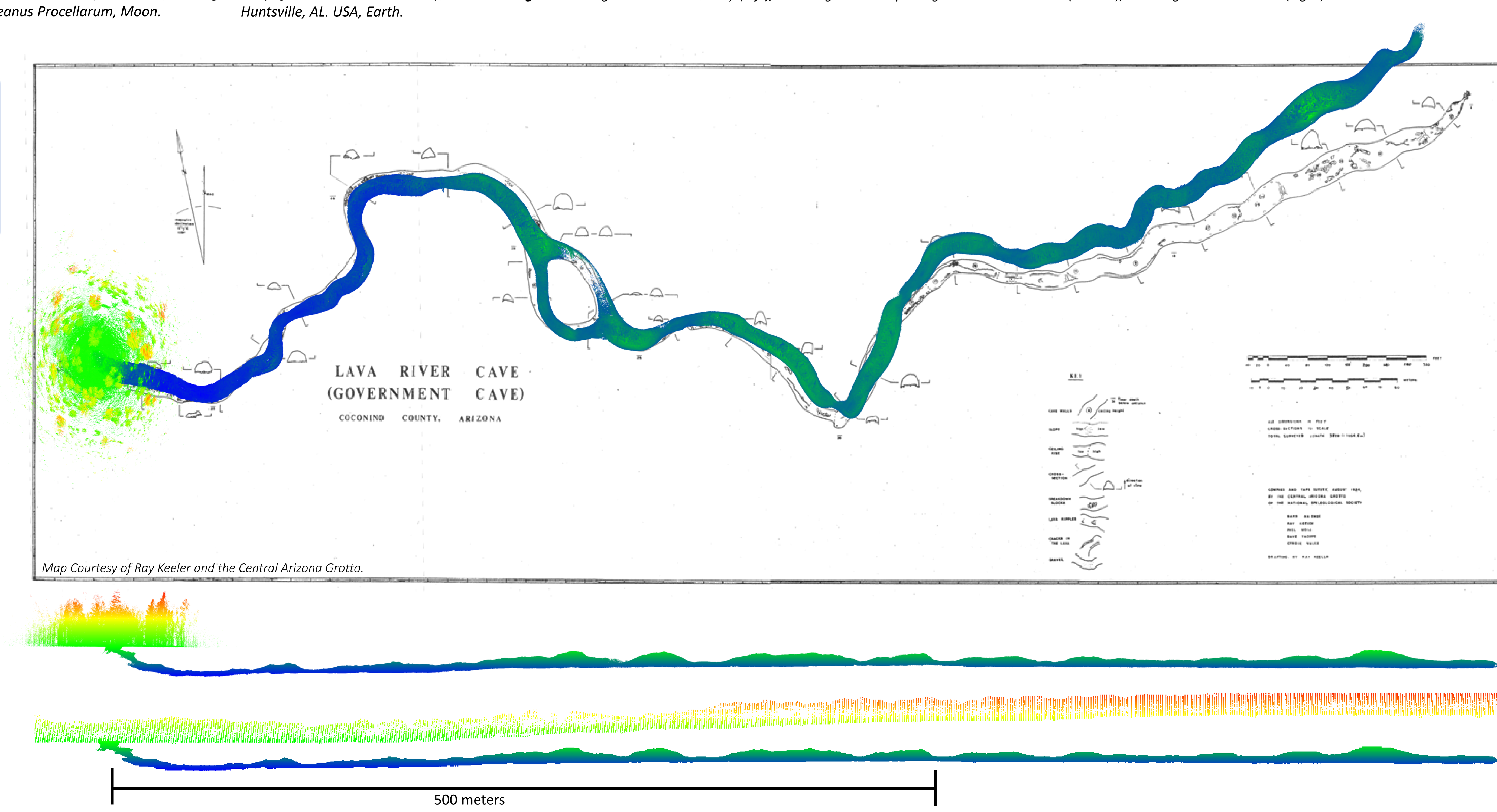

Fig. 5. Lava River Cave, San Francisco Volcanic Field, Arizona: (top) LiDAR map overlaid with traditional cave map, (middle) profile view of LiDAR map, (bottom) NAIP Point Cloud DEM overlaid with LiDAR map.

Results

- Maps produced are highly accurate at local scale, recording the morphology of the caves in detail (Fig. 6).
- Dead reckoning error introduces notable drift from ground truth at global scale (Fig. 7).
- Continued testing in cave environments offers the opportunity to tune SLAM parameters and experiment with constraining solutions with other data sets (such as survey data or radio location stations).

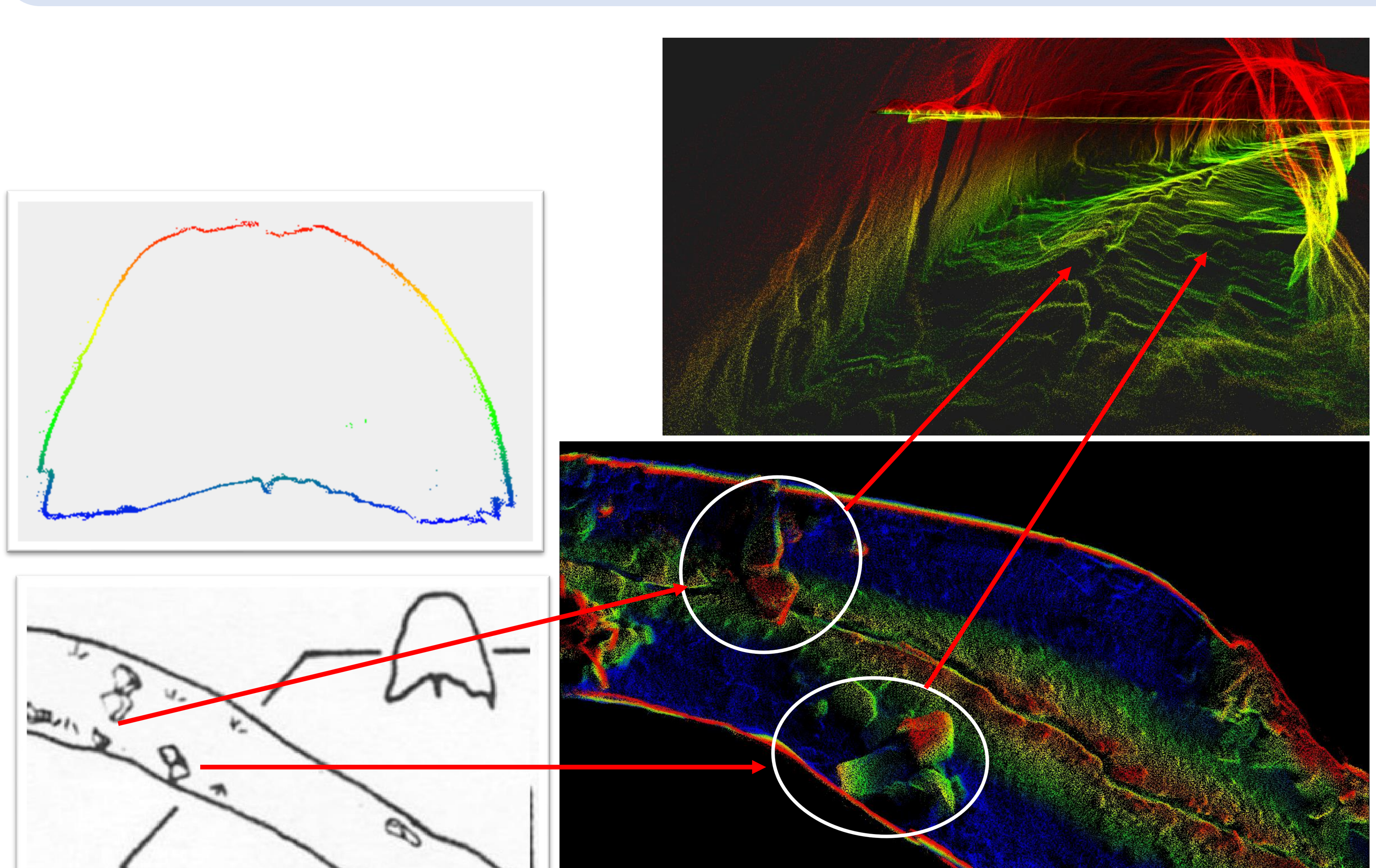

Fig. 6. SLAM LiDAR captures every detail at cm-scale. (lower left) Paper cave map excerpt. (lower right) LiDAR shows corresponding features and additional detail not included in the paper map. (upper right) Features can look very different from other perspectives. (upper left) Cross-section of passage derived from the LiDAR point cloud.

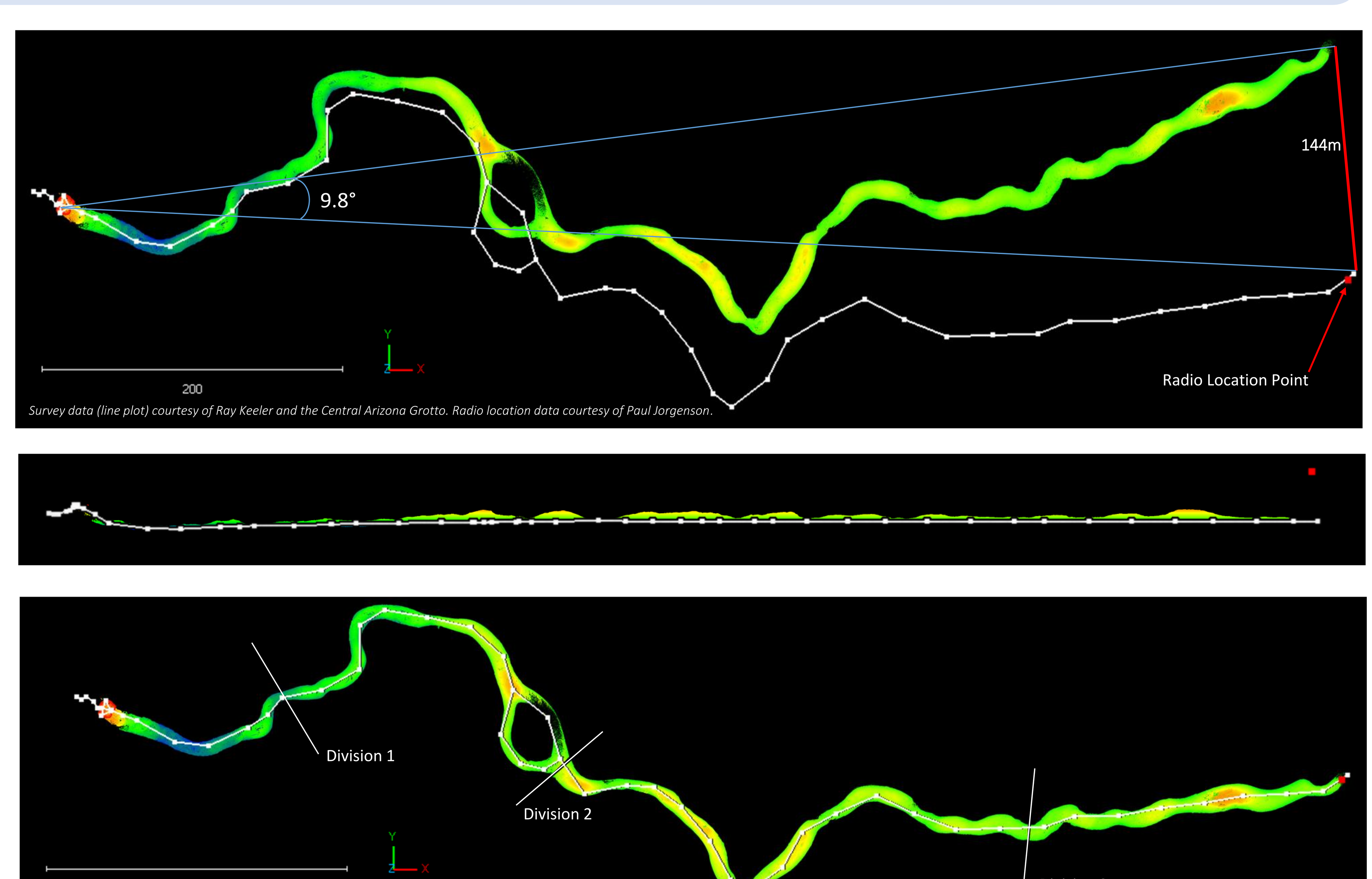

Fig. 7. Comparison to the 1984 survey data. LiDAR cloud and survey data were aligned based on probable station locations and plausible shots into the cave. Radio location point verifies the accuracy of the 1984 survey. (top) ~10 degrees of total deviation between the point cloud and survey line plot, equivalent to 144m of drift at the farthest point in the cave. (middle) Drift in the vertical direction was minimal— ~0.5 meters at the farthest point in the cave. (bottom) Large portions of the point cloud are highly consistent with survey. Division and manual alignment yields a map with both local and global accuracy.

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