Assessing Martian Cave Exploration for the Next Decadal Survey

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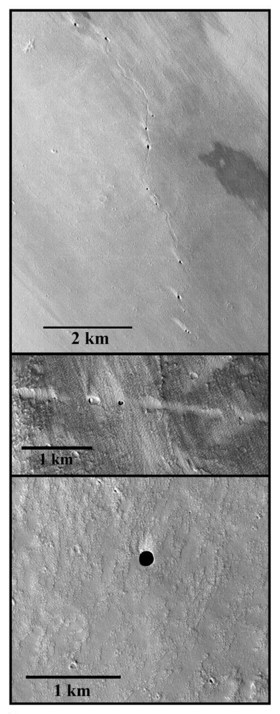
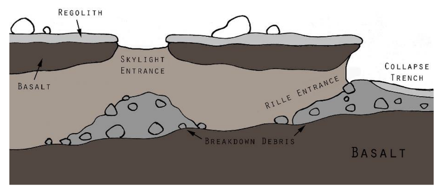
Introduction: Martian Caves

- Caves have been identified on Moon and Mars, usually associated with lava tubes (Wynne, 2016 and ref. therein)
- Cave represent unique environments and are high priority targets for exploration:
  - **Astrobiology** - provide stable environments, may trap volatiles, enhance secondary mineral and microbial growth, preserve biosignatures, provide record of past climate (e.g. Boston et al., 2001; Leveille & Datta, 2010; Northup et al., 2011)
  - **Volcanic processes** - petrology informs lava temperature and cooling history, give insight to magmatic processes (e.g. Ashley et al., 2011; Kerber et al., 2016)
  - **Human exploration** - Stable UV-shielding environment and possible volatile traps may provide ideal human habitats (e.g. Boston et al., 2007; Boston et al., 2010)



Candidate cave entrances on Mars. **Top**: Lava-tube rille with multiple skylight entrances (CTX: P17_007774_1757) **Center**: volcano-tectonic feature with skylight (HiRISE: ESP_014380_1775) **Bottom**: Atypical pit crater (HiRISE: PSP_003647_1745) From Cushing, 2010.



Cartoon cross-section of a lava tube cave. Credit: *Wikipedia*

A Mission to a Martian Cave Would Support MEPAG Goals

- (IB) to determine if environments with high potential for current habitability and expression of biosignatures contain evidence of extant life
- (IIIA) document geologic record preserved in the crust and interpret the processes that have created that record
- (IVB) obtain knowledge of Mars sufficient to design and implement a human mission to the Martian surface with acceptable cost, risk, and performance

Mission Objectives and Classes

- Building on previous studies, we identified a future mission **should provide initial reconnaissance** both for scientific and human exploration
- We consider how Sojourner-class rovers in a constellation architecture might offer a means to achieve science goals within a New Frontiers class mission *(Dubowsky et al., 2005; Kesner et al., 2007; Husain et al., 2013; Thangavelautham et al., 2017; Wyatt et al., 2018)*

A constellation of small rovers carrying instruments developed for small, cube-sat class satellites may provide a way to explore Martian caves in a New Frontier class mission cap

Science Goals and Payload

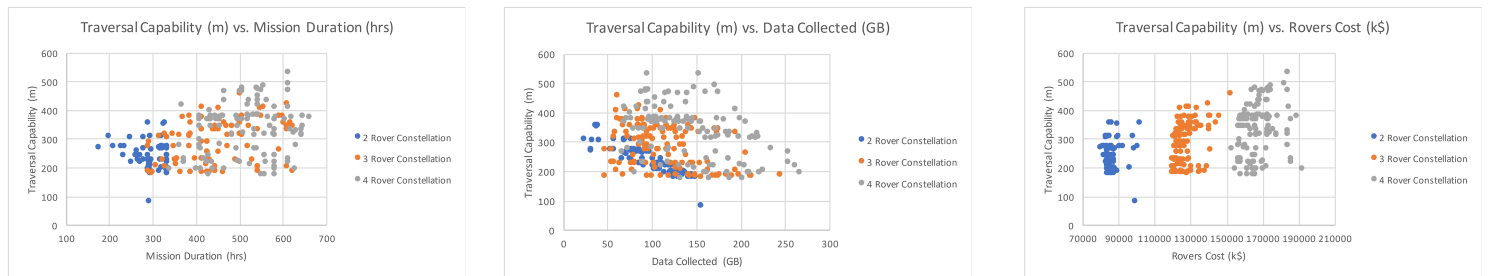
- Consider initial "pathfinding" concept with four objectives:
  - Map cave geometry
  - Map traverse obstacles
  - Document cave environment
  - Map compositional diversity
- Leverage miniaturized instruments developed for CubeSat-class missions, partially justified by mild radiation/thermal environment in cave

	LiDAR	Environmental Sensor Suite	NIR Point Spectrometer	Color Camera
Type example	GRSSLi, in development GSFC	REMS (MSL), MARA (MASCOT), LET (Biosentinel)	BIRCHES, or in dev. At JPL, see Blacksberg et al. this conf.	EECAM (Mars 2020)
Mass	~1kg	~0.6kg	~1.5 - 3 kg	~0.5kg
Power Usage	~10W	~2W	~3W – 10W	~5W
Data volume/image	~500 Mb	Very small	Small	~240 Mb

Example of low mass, low power instruments that could achieve science goals

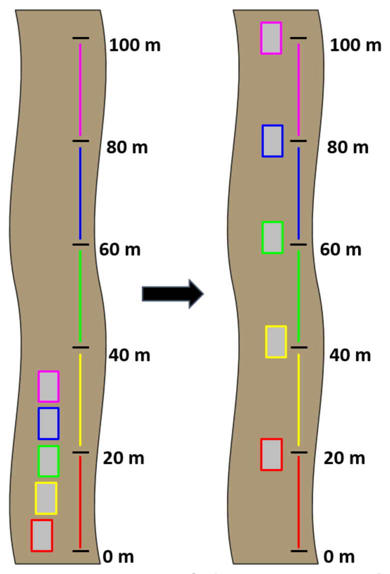
System Design and Trade Optimization

- Model 2-4 rovers ~25 kg each and explore tradeoffs between rover configuration and number of assets as they affect cost, data volume return, traverse distance
- Results demonstrate this technique can be used to analyze trade space decisions



Example plots from trade optimization studies exploring multiple possible rover configurations and assets. Models utilize instrument specifications in table listed above, and traverse distance and mission duration limited by battery lifetimes. The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

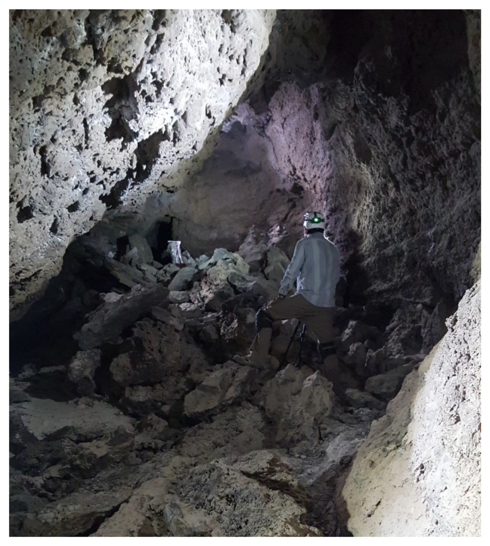
Autonomous Operations



Cartoon representation of dynamic zonal coverage

- Autonomous ops offers the best chance to explore caves because of limited mission duration and comm. link opportunities
- Simulated multiple autonomous exploration approaches using 3D models of terrestrial caves:
  - Dynamic zonal coverage - Rovers maintain spacing using low data rate pings, rovers deepest in cave wait for shallower rover to make further progress before proceeding to maintain communications relay. Algorithm adjusts in event of rover loss.
  - Scout (Heterogeneous architecture) - Scout rovers identify science targets, more capable science rover then visits identified targets
  - Simulation scoring - Cave wall imaging/LiDAR coverage simulated, assessed in 3D model

Additional Challenges

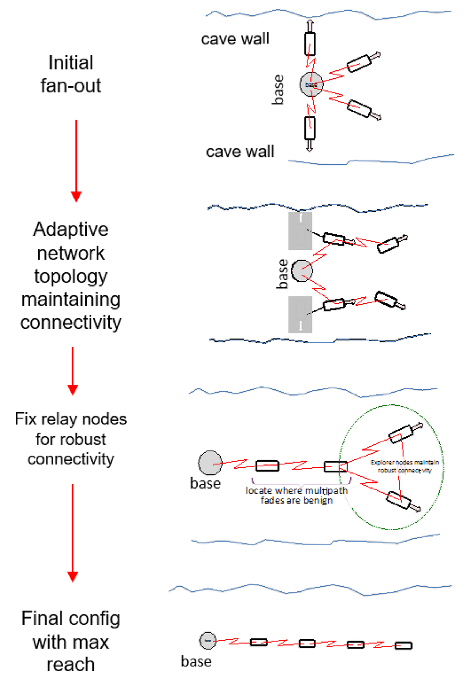


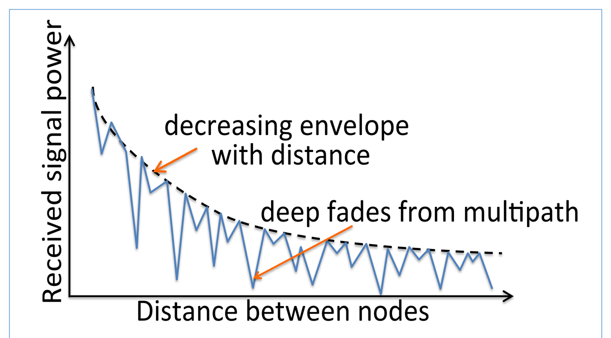
- Mobility
- Pinpoint landing near cave entrance, many of which are found at high elevations on volcanic flanks

Doug explores a very rocky Glove Cave at Pisgah Lava Field, CA and uses all four limbs to assist in mobility.

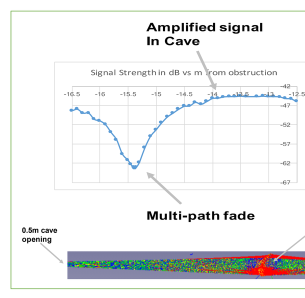
Communications

- Goal to reach ~100m into a cave requires daisy chain operation
- Multipath environment can generate unpredictable link qualities
- Initial tests with COTS hardware in terrestrial basaltic lava tube showed complication cave geometry allow high rate communication
- Undertaking RF signal propagation experiments and theoretical modeling to explore impact on link quality due to cave geometry, obstructions, and to understand/mitigate uncertainties





Cartoon of signal propagation



3D modeling of signal propagation

Testing COTs hardware in Glove Cave, Pisgah, CA

Timeline

- If this pathfinding mission can be achieved with a New Frontiers class mission, then could occur in parallel with MSR
- However, there are significant challenges associated with this mission, and continued advanced concept studies similar to the work presented here will be important to continue in the next decade

Synthesis: Information for next Decadal Survey to consider

- Martian caves are compelling targets for future exploration.
- Initial cave reconnaissance should occur before complex science oriented mission, and pathfinding mission may be possible by a New Frontiers class mission that leverages constellation architecture with small, Sojourner-class rovers
- However, considerable study is still needed to design this challenging mission and should continue in the next decade; such studies have the potential to not only benefit future cave exploration but also demonstrate how constellation architecture could be affordable and enable improved science for *in situ* missions at sites across the planet.

References and acknowledgements: *Wynne, J. "The Scientific Importance of Caves in Our Solar System: Highlights of the 2nd International Planetary Caves Conference, Flagstaff, Arizona," NSS News. Ashley et al., 2011, 1st Planetary Cave Workshop; Boston, et al., 2001, Astrobiology, 1(1):25-55; Boston et al., 2007, Gravitational & Space Research, 16, 2; Boston, 2010, Journal of Cosmology, 12, 3957-3979; Dubowsky et al., 2004, IEEE Transactions on Robotics, 20, 5 ; Husain et al., 2013, IEEE Aerospace Conference; Kerber et al., 2016, LEAG meeting; Kesner et al., 2007, IEEE Robotics & Automation; Leveille & Datta, 2010, PSS, 58, 4; Northup et al., 2011, Astrobiology, 11, 7; Thangavelautham et al., 2017, 2nd Intertional Workshop on Planetary Missions; Wynne, et al., 2016, Eos, 97.*
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