ANNUAL THERMAL AMPLITUDES AND THERMAL DETECTION OF SOUTHWESTERN U.S. CAVES: ADDITIONAL INSIGHTS FOR REMOTE SENSING OF CAVES ON EARTH AND MARS.

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Introduction: Recent research has demonstrated that cave-like features can be detected in the thermal infrared on both Earth and Mars [1,2]. Caves are optimally detectable when the temperature contrast is greatest between surface and cave entrance [1].

Our understanding of thermal behavior and thermal detection of caves is still in its infancy [1,3]. Resolvability of caves via thermography is influenced by several factors including cave volume, horizontal length, depth from surface, percentage of rock obstructing the entrance, slope, aspect, geographic location, elevation, topographic roughness, and geologic substrate [1]. Currently, effects of these variables on the thermal behavior of caves (and thus their detectability) are not well understood. Detectability of caves is also influenced by (*i*) the size of cave entrance vs. the sensor's spatial resolution, (*ii*) the precision of the thermal measurements vs. the strength of the thermal signal associated with the cave entrance, and (*iii*) the viewing angle of the platform relative to the slope trajectory of the cave entrance [1]. Consequently, some caves are more easily detectable than others, some will be detectable only at specific times of day, while other caves may not be detectable at any time [1,3].

Potential Importance of Martian Caves. (A) Caves may be important in detecting evidence of extraterrestrial life [4-6] because they offer protection from low surface temperatures, unfiltered ultraviolet radiation [4,5] and violent windstorms, which may degrade and decompose organic materials. (B) A manned mission to Mars will require access to significant H_2O deposits for drinking water, oxygen and liquid hydrogen fuel. If water deposits exist, caves may provide the best access to these resources [7]. (C) Future human exploration and possible establishment of a permanent settlement on Mars will require construction of living areas sheltered from harsh surface conditions. Caves with a protective rock ceiling would provide an ideal environment where these shelters may be built [8].

The purpose of the work reported here is to further our understanding of terrestrial cave thermal behavior, particularly as it relates to detecting these features using thermal remote sensing.

Results: We used thermistors to collect hourly temperature measurements for at least one year at the ground surface, entrance, and deep cave (dark zone) of nine caves in the southwestern United States (seven lava tube caves in western New Mexico and two limestone caves in northern Arizona). For each cave, we modeled temperature trends using Fourier analysis to characterize thermal behavior, and line graphs to display temperature data to identify optimal times of detection in the thermal infrared.

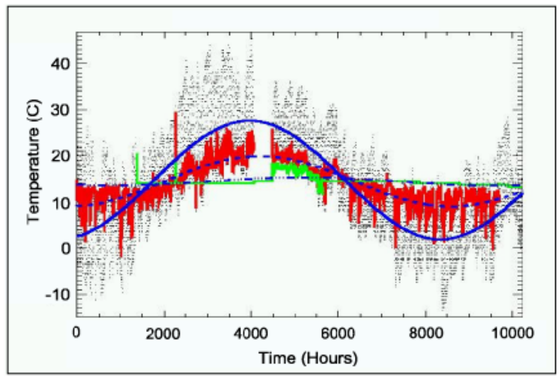

Figure 1: Temperature variation at Cathedral Cave, Arizona with temperature trends over ~16 month period showing surface (black dots), entrance (red line) and dark zone (green line) temperatures and best-fit sine waves of surface (solid blue line), entrance (blue dashed line) and dark zone (blue dot-dashed line) are plotted.

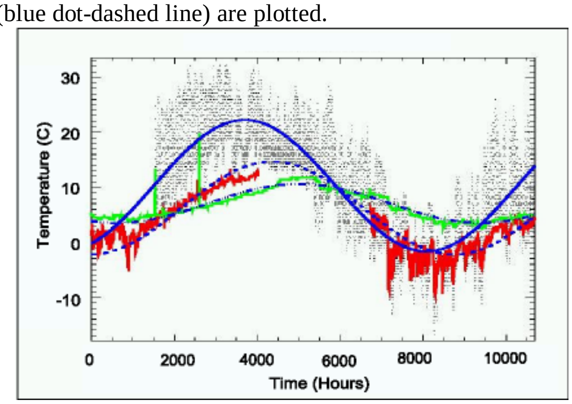

Figure 2: Temperature variation at Braided Cave, New Mexico with temperature data over ~14 month period. Color schemes for temperature and best-fit sine waves are the same as for Figure 1.

Study sites fell into three thermal behavior categories. *Classic* thermal behavior occurs when a cave is in thermal equilibrium with the surface, and the deep cave temperature is approximately equal to the annual mean surface temperature. In *pseudo-classic* caves, the mean annual temperature decreases from surface to entrance and then levels off at the deep zone. *Ice* cave behavior is consistent with a cave made of ice. The annual mean temperature of the cave is near freezing and the cave displays significant diurnal temperature variations when the outside surface is snow or ice covered.

Short-term data from two Chilean caves [1] provided insight into optimal times of day for detecting these features in the thermal infrared. These longer term data sets of southwestern U.S. caves enabled us to identify broader windows for detection (i.e., seasons and/or multiple times of day).

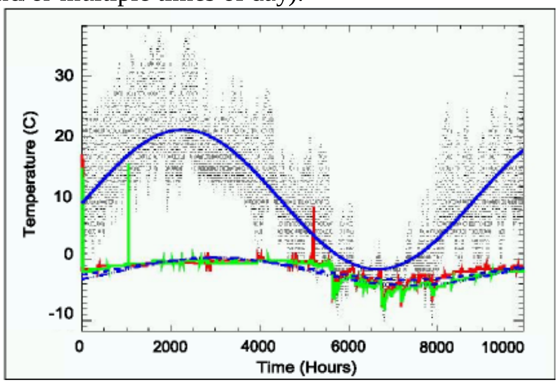

Figure 3: Temperature variation at Ice Cave, New Mexico with temperature data over a ~13 month period. Color schemes for temperature and best-fit sine waves are the same as for Figure 1.

Discussion: Temperature data from these nine caves provide much richer information on diurnal and seasonal variation in cave and ground surface temperatures. Analysis of the temperature patterns of these caves contribute to a better understanding of cave thermal behavior under a variety of conditions, and how this behavior influences detectability of the caves.

All of the New Mexico caves occurred within a ~20 km radius resulting in a high correlation of surface temperatures across study sites. Differences in surface temperature were related to the thermal inertia of the surface material in which the data logger was placed. Thermistors placed on solid rock surfaces showed smaller diurnal and annual amplitudes while sensors placed on unconsolidated soil showed larger amplitudes. Temperatures measured at cave entrances did not correspond well to physical characteristics of either the cave or the surface, suggesting cave entrance data may reflect sensor placement within the entrance rather than the actual thermal behavior of the entrance.

Sensors placed within the dark zone provided temperatures more representative of the cave interior. This provided us with perhaps some of the best insights into cave thermal behavior.

Classic thermal behavior occurs when the mean deep cave temperature is approximately equal to the annual mean surface temperature. We defined this category as "classic" because previous research [e.g., 9,10] suggests this is how caves behave thermally. Only one of nine caves studied exhibited this behavior suggesting this end member may be an outlier rather than *classic* thermal behavior.

All caves had mean interior temperatures at least 10°C cooler than the surface mean. Four of the New Mexico *ice* caves contained ice during most of the year. This suggests these features may be in thermal contact with a heat sink, such as large underground ice deposits.

While this research lends additional support to the viability of thermal detection of caves on both Earth and Mars, it underscores there is still much to be learned regarding cave thermal behavior. Our understanding of cave thermal behavior may be further improved by (*a*) placing multiple sensors on the surface, as well as within each cave entrance so that more accurate thermal gradients from surface to dark zone can be modeled, and (*b*) monitoring a larger number of caves in different geographic and geologic regions to better capture cave structure variability. These data may then be used to develop thermal behavior simulation models for Martian caves. This will ultimately enable us to identify the range of conditions under which caves are detectable in the thermal infrared, thus improving our detection capabilities of caves on both Earth and Mars.

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