EXPERIMENTAL RESEARCH ON THE USE OF THERMOGRAPHY TO LOCATE HEAT SIGNATURES FROM CAVES

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Abstract

Thermal differences between cave entrances and the surrounding landscape have long been known. Cavers traditionally ridge walked in cave-likely temperate regions in cold mid-winter with a falling barometer in order to visually detect “fog-plumes” of escaping subterranean air from crevices and unknown earth openings in order to locate caves. We are experimenting with a high-technology solution to this cave detection method by applying infrared thermography — a useful tool in fire detection, human body location, and other building examination — remote sensing to the surface of the earth. Early trials during the spring of 2005 with a Therma CAMTM B20 HSV infrared camera, even under foliage-filled and warm atmospheric conditions, resulted in promising results in initial trials in New Mexico and West Virginia. Further research is underway at Fisher Cave, Franklin County, Missouri.

This research began by documenting temperatures of cave openings and surrounding substrates. Atmospheric ambient conditions (temperature, relative humidity, specific humidity, and dew point) were recorded inside the cave, at the entrance, and at intervals up to 183 meters. Normal images were contrasted with thermograms which showed full temperature gradients of the openings. At 118 meters, the opening could no longer be seen with the naked eye. The thermograms showed distinct images of cave openings. Trials continued to 388 meters. In excess of 300 meters, thermograms showed the distinct cave opening of Fisher Cave. At 388 meters, the thermograms showed signatures that could be that of a cave entrance. The initial results indicate that individual cave entrances have separate and unique temperature gradients. Thus, individual cave thermograms are a “fingerprint” or signature of that cave. Thermograms can be used to isolate and identify caves entrances from surrounding terrain features. Once we have established standardized procedures, thermograms may become an important tool for cave location and exploration.

This work is in the experimental stages. The evidence of its success is presented in the matched infrared/visual images which follow.

Introduction

Thermography is a type of imaging. Thermographic cameras detect in the range of the and produce images of that radiation. Since infrared radiation is emitted by all objects at ambient temperature, thermography makes it possible to "see" one's environment with or without visible illumination. The amount of radiation emitted by an object increases with temperature, therefore thermography allows you to see variations in temperature, hence the name. With a thermographic camera warm objects stand out well against cooler backgrounds.

Thermographic technology has advanced considerably in the last few years. Several new generations have occurred, allowing us to use thermography in much broader applications. Current uses include building-energy audits, building diagnosis, medical applications, fire, military night vision, computer heat scans, industry, surveillance, and other utilitarian uses where heat production and dissipation are a factor.

We hypothesize that we can use this technology under the correct conditions to locate potential caves by photographing land masses such as hillsides and valleys while looking for heat signature changes in the images which would reveal cave openings, swallets, seeps, and other karst features.

Thermography could assist other scientific research such as geology, archeology, paleontology, bio-speleological discovery, and anthropology (such as studying the pigmentation signatures of petrocliffs) as it could assist in finding otherwise hidden openings in the earth. We believe it is currently underutilized, and are examining methods to remedy this.

Overview of Theoretic Thermography[1]

There are three methods by which heat flows from one object to another.

These are **radiation**, **convection** and **conduction**. IR viewers are primarily concerned with radiation effects, but the effects of the other two cannot be neglected.

CONDUCTION is heat movement in a solid by transferring thermal energy from molecule to molecule, heating up each adjacent area within the solid.

CONVECTION is defined as the way heat moves in a liquid or in a gas. In convection, the thermal energy uses a medium to carry it and actually develops a current in the medium to move it along more rapidly. Convection transfers heat more rapidly than conduction.

However, the most powerful effect is **RADIATION**. In radiation, electromagnetic energy is actually emitted by an object or gas.[2]

These three effects are not exclusive, but in most situations operate together towards a cumulative effect.

Contact-type heat measurement devices work by conduction. A thermometer in your mouth receives the heat energy from your body by conduction. A thermocouple attached to an instrument receives heat by conduction. All non-contact heat measurement devices use the radiation of an object to measure the temperature.

Infrared Imagers observe and measure heat without being in contact with the source and rely largely on radiation. The infrared camera used in this experiment generates a digital false-color image of the view being examined using IR sensors in the place of normal visual-range detectors.

The electromagnetic spectrum is divided arbitrarily into a number of wavelength regions, called bands, distinguished by the methods used to produce and detect the radiation. There is no fundamental difference between radiation in the different bands of electromagnetic spectrum. The same basic physics usually exemplified by radio waves governs all electromagnetic waves.

The Electromagnetic Spectrum Defined[3]

Thermography makes use of the infrared spectral band. At the short-wavelength end the boundary lies at the limit of visual perception, in the deep red. At the long-wavelength end it merges with the microwave radio wavelengths.

The unit relationship between the different wavelength measurements is: 10,000 Å = 1,000

1 Sierra Pacific Innovations. http://www.x20.org/thermal 2005.

2 FLIR™ Systems Handbook for the "Therma CAM B20 HSV Camera."

3 Campbell, C. Warren. "Application of Thermography to Karst Hydrology." *Journal of Cave and Karst Studies*. 58(3); 163-167.

nm = 1 μ = 1 μm.

The Infrared Spectrum

Every animate or inanimate body that exists emits infrared energy from its surface. This energy is emitted in the form of electromagnetic waves which travel with the velocity of light through a vacuum, air, or any other conductive medium. Whenever they fall on another body, which is not transparent to the eye, they are observed and their energy is reconverted into heat. The difference between a cold or hot body is the level at which it both emits and absorbs energy. If the body absorbs more energy than it radiates, it can be considered cold. If the body tends to emit more energy than it absorbs, it is considered hot. The state of being hot or cold is a dynamic state. If a body is allowed to come to equilibrium with its surroundings, the emission and absorption will become equal and the body will be neither hot nor cold.

History of Infrared Technology

Sir William Herschel, an astronomer, discovered infrared in 1800. He built his own telescopes and was therefore very familiar with lenses and mirrors. Knowing that sunlight was made up of all the colors of the spectrum, and that it was also a source of heat, Herschel wanted to find out which color(s) were responsible for heating objects. He devised an experiment using a prism, paperboard, and thermometers with blackened bulbs where he measured the temperatures of the different colors. Herschel observed an increase in temperature as he moved the thermometer from violet to red in the rainbow created by sunlight passing through the prism. He found that the hottest temperature was actually below red light. The radiation causing this heating was not visible; Herschel termed this invisible radiation "calorific rays." Today, we know it as infrared.

Measurement Principles

Infrared energy is emitted by all materials above 0°K. Infrared radiation is part of the electromagnetic spectrum and occupies frequencies between visible light and radio waves. The infrared part of the spectrum spans wavelengths from 0.7 micrometers to 1,000 micrometers (microns).Within this wave band, only frequencies of 0.7 microns to 20 microns are used for practical, everyday temperature measurement.

Though infrared radiation is not visible to the human eye, it is helpful to imagine it as being visible when dealing with the principles of measurement and when considering applications, because in many respects it behaves in the same way as visible light. Infrared energy travels in straight lines from the source and can be reflected and absorbed by material surfaces in its path. In the case of most solid objects which are opaque to the human eye, part of the infrared energy striking the object's surface will be absorbed and part will be reflected. Of the energy absorbed by the object, a proportion will be re-emitted and part will be reflected internally. This will also apply to materials which are transparent to the eye, such as glass; gases; and thin, clear plastics, but in addition, some of the infrared energy will also pass through the object. These phenomena collectively contributes to what is referred to as the **emissivity** of the object or material.

Materials which do not reflect or transmit any infrared energy are know as "blackbodies" and are not known to exist naturally. However, for the purpose of theoretical calculation, a true blackbody is given a value of 1.0. The closest approximation to a blackbody emissivity of 1.0 that can be achieved in real life is an infrared-opaque, spherical cavity with a small tubular entry. The inner surface of such a sphere will have an emissivity of 0.998.

Different kinds of materials and gases have different emissivities, and will therefore emit infrared at different intensities for a given temperature.

Theoretical Basis for IR Temperature Measurement

The formulas upon which infrared temperature measurement is based are old, established, and well proven.[2]

Verbal summations of the important physics formulas are as follows:

1. ***Kirchoff's Law:*** When an object is at thermal equilibrium, the amount of absorption will equal the amount of emission.

2. ***Stephan Boltzmann Law:*** The hotter an object becomes the more infrared energy it emits.

3. ***Wien's Displacement Law:*** The wavelength

at which the maximum amount of energy is emitted becomes shorter as the temperature increases.

4. ***Planck's Equation:*** Describes the relationship between spectral emissivity, temperature, and radiant energy.

Thermography (infrared, thermal scans) uses specially designed infrared video or still cameras to make images (called **thermograms**) that show surface heat variations. This technology has a number of applications.

Speleology and Thermography

Speleology comes from the Greek words *spelaion*, meaning cave and *logos*, meaning study.[4] According to George W. Moore and G. Nicholas Sullivan in *Speleology: The Study of Caves:*

> Speleology is no longer a highly specialized pastime in which we are incidentally studying unusual but relatively unimportant facets of nature. As caves have been better known we have realized that they can broaden our understanding of the interaction of certain biologic and geologic processes that have been shaping our planet and its inhabitants for hundreds of millions of years. Thus, the study of caves is an important means of understanding our world.[4]

The natural meteorological conditions of temperate caves make infrared thermographic investigation possible. Differences in temperature and humidity make cave entrances discrete from the surface, and visible to thermography. As the inside of the cave maintains a constant temperature and the outside ambient temperature fluctuates with the seasons the cave entrance temperatures are normally different than the ambient outside conditions. It is this premise that this research is based on.

Moore and Sullivan put this most succinctly:

> The air in most caves is nearly saturated with water vapor — in other words, the relative humidity is close to 100 percent. This is so because seeping water moistens the ceilings, wall, and floor and that the air must pass by as it moves slowly through the cave. The constant temperature of the inner part of the cave permits this high humidity to be maintained indefinitely.
>
> Near the entrances to caves, however the humidity may be lower, partly because the outside humidity is usually lower, and partly because the cave temperature differs from the outside temperature.
>
> In the summer, warm air entering a cool cave soon becomes saturated without absorbing water from the cave walls. In the winter the air becomes warmer as it enters the cave, and for a short distance its relative humidity falls.[4]

Research assumptions:

- Finding caves and studying them is desirable.
- Cave entrance substrate temperatures are normally different from other outside substrate temperatures. The air blowing from a cave or into a cave is at a different temperature and humidity level than the outside ambient temperature and humidity.
- Cave humidity causes a different degree of moisture on the cave entrance substrates than on other surface substrates.
- An infrared camera measures and images the emitted infrared radiation from an object. The fact that radiation is a function of object surface temperature makes it possible for the camera to calculate and display this temperature.
- Cave entrances can have their surface temperatures displayed by a thermo-imaging infrared camera.

Experimental Design

Materials

The camera used for this research is the Therma CAM™ B20 HSV, which is the most sophisticated of the Infrared thermo-graphic image cameras made by the FLIR Company.

Nikon D1X Camera and lenses.

A steady tripod was necessary to get accurate signatures.

4 Sullivan, G.N. and G.W. Moore. *Speleology: The Study of Caves.* Cave Books, St. Louis, MO 1978, 150 p.

Delmhorst HT 3000 A Thermo Hygrometer and Dickson TH 550 Thermo Hygrometer to measure temperature, humidity, and dew point at cave entrances and distances from the entrance.

Data Log Recorders (HOBO-timed temp, dew point, relative humidity, and specific humidity at prescribed intervals and distances from the entrance.)

Fluke 52 II Thermometer and Thermocoupler to measure temperature readings of the substrates at cave entrances.

Methods

The radiation measured by the camera does not only depend on the temperature of the object but is also a function of the emissivity. Radiation also originates from the surroundings and is reflected in the object. The radiation from the object and the reflected radiation will also be influenced by the adsorption of the atmosphere. Our methodology was informed by the work of C. Warren Campbell.[5]

To measure temperature accurately, it is therefore necessary to compensate for the effects of a number of different radiation sources. This is done electronically and automatically by camera. The following parameters must, however, be supplied for the camera:

- The emissivity of the object
- The reflected temperature
- The distance between the object and the camera
- The relative humidity

These parameters were established for the camera with the use of handheld thermo hygrometers at the cave entrances. The data loggers were then set up to ensure accurate monitoring during the photography, and to provide data for the FLIR camera manufacturer, which is in process of establishing standard emissivity tables for limestone based on this research.

Results

Measurements at the entrances of known caves for temperature, relative humidity, and dew point were taken at different distances from the entrance for the caves and locations reported in Table 1. The data was used to calibrate the B20 HSV. A tripod was required for steady images as the B20 HSV does not have a fast "shutter speed."[6]

We found that taking the thermograms was easier if the remote control was removed from the camera and used to adjust the setting and take the shots, as it helped reduced camera shake

We recorded our atmospheric readings in Table 1. The resulting thermograms and corresponding visual images are reproduced and correlated to data in Table 1 via photo caption information

We found we will need to compensate for the following conditions in future trials:

- Shooting thermograms through tree foliage will pick up reflective signatures off the leaves.
- Shadows on hills do not show the same temperature gradient as actual cave openings.
- Images without a tripod are susceptible to camera shake thereby altering the image result.

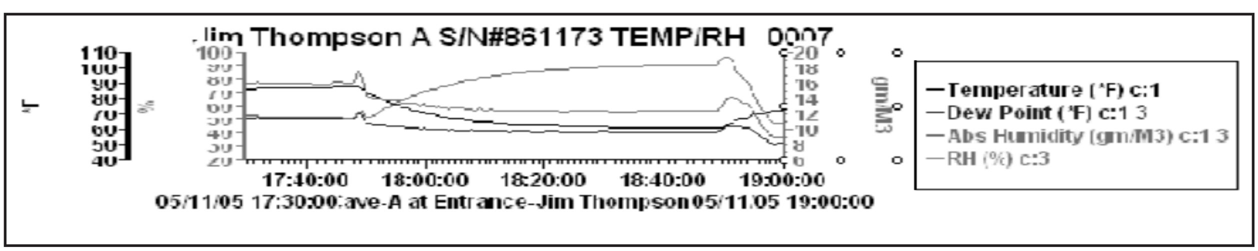
Data logger Graphs for Fisher Cave Control Location

Data Log Recordings (HOBO) measuring Temperature, Dew Point, Absolute Humidity, and Relative Humidity at Fisher Cave were placed approximately 17:50 May 11, 2005, and removed near 18:50 May 11, 2005.

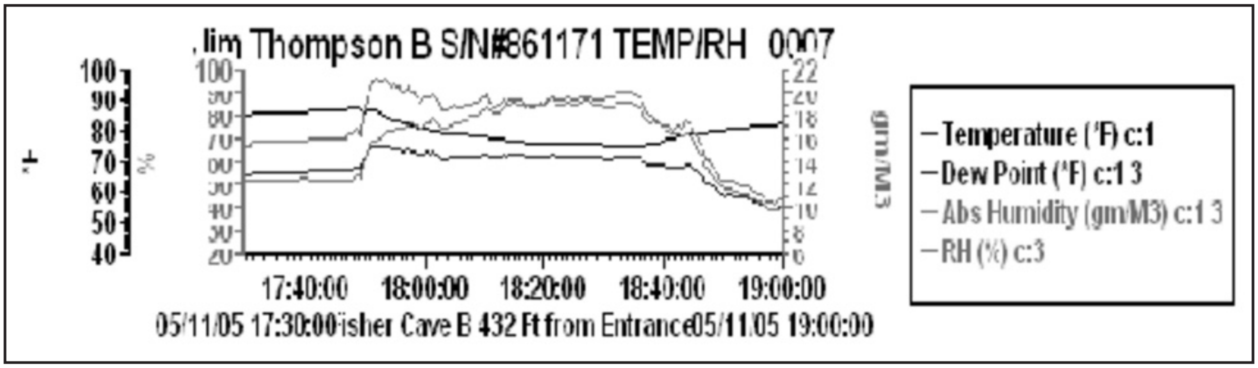
5 Campbell, C. Warren. "Application of Thermography to Karst Hydrology." *Journal of Cave and Karst Studies*. 58(3); 163-167.

6 "Digital photography: the complete course." New York Institute of Photography Unit 2 Lesson Five "How to Use a Digital Camera."

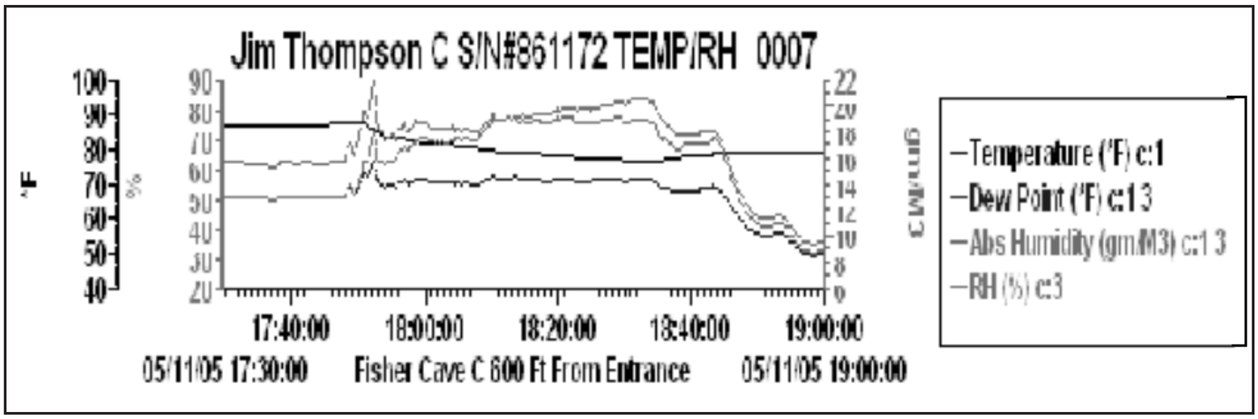
1. Data at Fisher Cave Entrance;



1. Data 432 feet (133 meters) from Fisher Cave Entrance;



1. Data 600 feet (185 meters) from Fisher Cave Entrance;

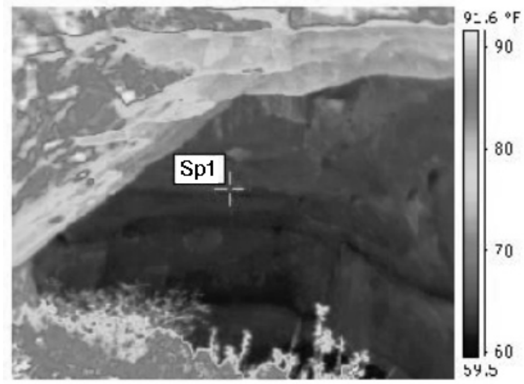
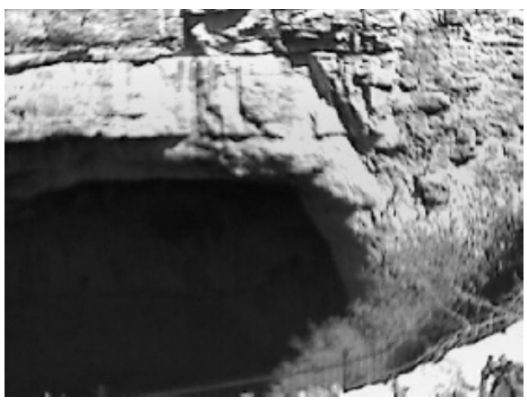
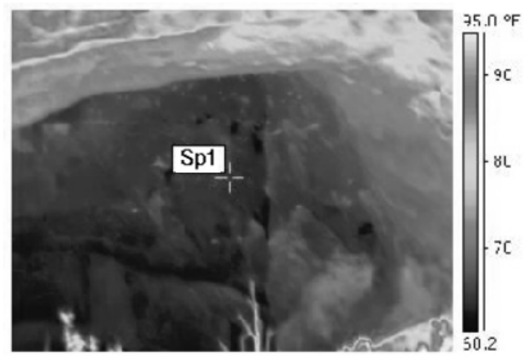
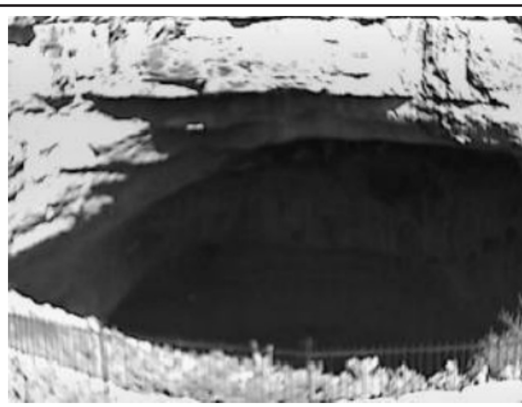
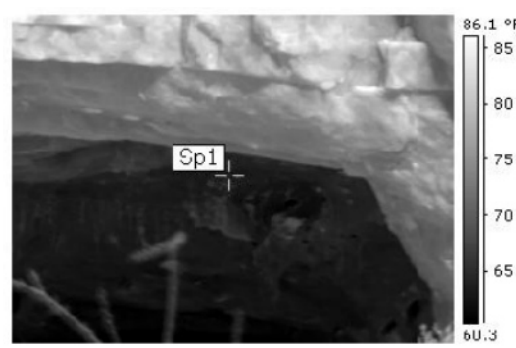


1. Table 1. Field work in support of the viability of using Thermography

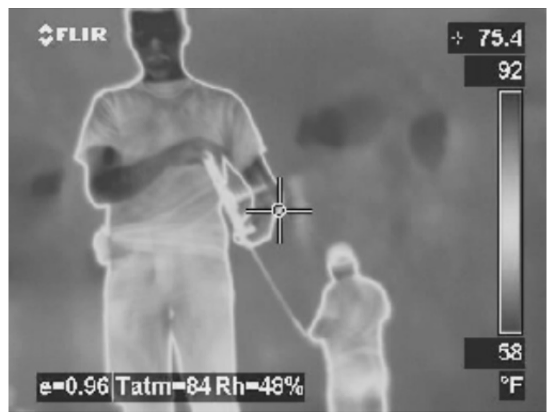
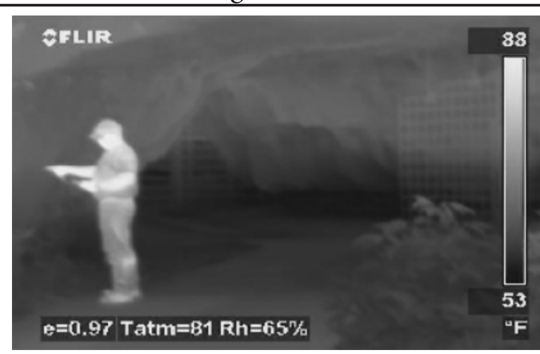
Cave and Location	Date	Ambient air temp °F and weather	Temp °F at cave entrance Humidity and Dew Point	Distance to Cave entrance in feet	Thermogram's Number (See images)
Carlsbad Caverns, N.M.	4-9-2005	90± Clear 32.2°C		±75 ft ±22.9 m	1, 2, 3, 4, 5, & 6
N038° 12.84' W091° 07.87' Hwy 185 Mo.	5-11-2005	Slight Rain 85.8°F 29.9°C RH 58.4% 69 DP°F 9.4 DP°C	Rock 75°F 23.9°C Emissitivity set .96	51 ft 15.6 m	7 & 8
Lone Hill Onyx, Mo.	4-12-2005	56.1°F 13.4°C Recent rain	52.9°F 11.6°C 92% RH 49.8 DP°F 9.4 DP°C	50 ft 15.2 m	9 & 10

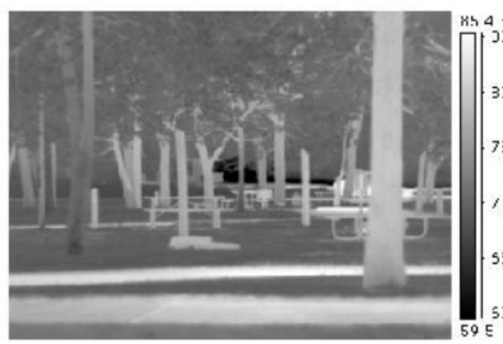
Cave and Location	Date	Ambient air temp °F and weather	Temp °F at cave entrance Humidity and Dew Point	Distance to Cave entrance in feet	Thermogram's Number (See images)
Powder Mill Spring Cave, Mo.	5-13-2005	Few clouds 82.2°F 27.9°C 47.9% RH	62.8°F 17.1°C 74.1% RH Stream 56.5°F 13.6°C	222 ft 67.7 m	11 & 12
Round Spring Cavern, Mo.	5-13-2005	71.4°F 21.9°C 64.5% RH	71.2°F 21.8°C 61.4% RH	150–175 ft 45.7–53.3 m	13, 14, & 15
Fisher Cave Meramec S.P., Mo.	5-11-2005	60.1°F 15.6°C 62.4% RH 47.2 DP°F 8.3 DP°C Recent rain	61.6°F 16.4°C 66.8% RH 50.2 DP°F 10 DP°C Rock 66.5°F 19.2°C	50 ft 15.2 m	16 & 17
Fisher Cave Meramec S.P., Mo.	5-11-2005			388 ft 118.3 m	18 & 19
Fisher Cave Meramec S.P., Mo.	5-11-2005		79.5°F 26.4°C 64.6% RH 68 DP°F 20 DP°C	600 ft 182.9 m	20 & 21
Fisher Cave Meramec S.P., Mo.	5-11-2005			1,000 ft 304.8 m	22 & 23
Fisher Cave Meramec S.P., Mo.	5-11-2005			1,275 ft 388.9 m	24 & 25
Fisher Cave Meramec S.P., Mo. Hill next to Fisher Cave	5-11-2005		THIS WAS A CONTROL SHOT WITH NO CAVE- FROM SAME POINT	1,275 ft 388.6 m	26

1. Table 2. Table of Normal and Thermographic Images

Number from Table #1	**Normal Image**	**Thermogram**
1 & 2	 Carlsbad Caverns, N.M. ±75 ft ±22.9 m	 Carlsbad Caverns, N.M. ±75 ft ±22.9 m
3 & 4	 Carlsbad Caverns, N.M. ±75 ft ±22.9 m	 Carlsbad Caverns, N.M. ±75 ft ±22.9 m
5 & 6	 Carlsbad Caverns, N.M. ±75 ft ±22.9 m	 Carlsbad Caverns, N.M. ±75 ft ±22.9 m

Number from Table #1	**Normal Image**	**Thermogram**
7 & 8	 N38°12.84' W091°07.87' Hwy 185 Mo. 51ft 15.5 m	 N38°12.84' W091°07.87' Hwy 185 Mo. 51ft 15.5 m
9 & 10	 Lone Hill Onyx, Mo. 50 ft 15.2 m	 Lone Hill Onyx, Mo. 50 ft 15.2 m
11 & 12	 Powder Mill Spring Cave, Mo. 222 ft 67.7m	 Powder Mill Spring Cave, Mo. 222 ft 67.7m

Number from Table #1	**Normal Image**	**Thermogram**
13 & 14	 Round Spring Cavern, Mo. 150–175 ft 45-7–53.3 m	 Round Spring Cavern, Mo. 150–175 ft 45-7–53.3 m
15	This next section demonstrates the images shot at different distances from Fisher Cave, Mo.	 Measuring at cave entrance.
16 & 17	 Fisher Cave entrance, Mo. 50 ft 15.2 m	 Fisher Cave entrance, Mo. 50 ft 15.2 m

Number from Table #1	**Normal Image**	**Thermogram**
18 & 19	 Fisher Cave, Meramec SP, Mo. 388 ft 118.3 m	 Fisher Cave, Meramec SP, Mo. 388 ft 118.3 m
20 & 21	 Fisher Cave, Meramec SP, Mo. 600 ft 182.9 m	 Fisher Cave, Meramec SP, Mo. 600 ft 182.9 m
22 & 23	 Fisher Cave, Meramec SP, Mo. 1,000 ft 304.8 m	 Fisher Cave, Meramec SP, Mo. 1,000 ft 304.8 m

Number from Table #1	Normal Image	Thermogram
24 & 25	 Fisher Cave, Meramec SP, Mo. 1,275 ft 388.6 m	 Fisher Cave, Meramec SP, Mo. 1,275 ft 388.6 m

Analysis of the Results

We believe thermography shows great promise as a cave entrance location method, as evidenced by the photographs taken. It seems like a viable solution to expediting field work in locating cave sites for a variety of scientific endeavors, especially in temperate climates, where the mean annual temperature (and therefore the temperature of the cave air) is stable but local surface atmospheric conditions reflect wide seasonal variation. The ability of a thermogram to penetrate vegetative cover (once we learn to norm for reflective signatures) may turn ridge walking into a year round activity, not one confined to late fall through early spring as it is currently. The importance of recording cave entrance meteorological data as it relates to monitoring trogloxene and troglophile species is another possible application of thermographic imaging.

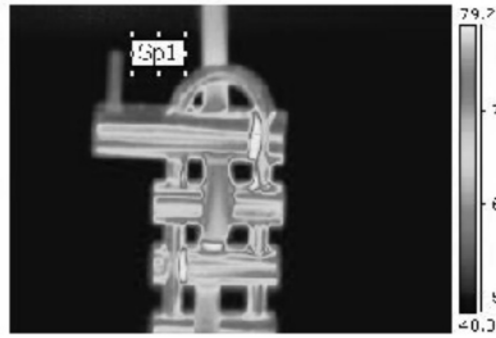
Research Potential

The application of using thermography can be expanded to include the discovery of unknown caves by photographing larger land mass areas such as hillsides and aerial perspectives. This paper documents fundamental field-research that was done to demonstrate that this technology is a viable tool to assist scientists from many disciplines in finding caves, sinkholes, swallets, seeps and other karst features.

As this technology continues to improve and the applications of field utilization improve, much expense and time to scientists will be saved. This field work is an ongoing project which will invariably set standards for various uses.

Thermography is currently being used in a safety research study of the heat dissipation sig-

Normal Image and Thermogram	Thermogram
 Lost World Caverns, W, Va. 120-ft rappel	 Thermogram showing effects of heat on rappel rack and rope.

Normal Image and Thermogram	Thermogram
	

natures of rappelling equipment used in speleology with a goal of finding data that can be used in establishing safer methods and equipment. See ilustrations above.

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Advice and Guidance

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Barbara am Ende PhD - author of *Beyond The Deep. The Deadly Decent Into The World's Most Treacherous Cave.*

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Participation in Field Research

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Scott Watson - Jim Thompson & Co. Inc.

Justin Blankenship - Jim Thompson & Co. Inc.

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Christina Ann Thompson: Daughter and NSS member