Airborne Infrared Thermal Detection of Caves and Crevasses*

Under certain conditions crevasses in Greenland and cave openings in Puerto Rico were detected with airborne infrared thermal scanners.

INTRODUCTION

As with many ventures, the thermal detection of subsurface voids is easier in principle than it is in practice. In order to use airborne infrared thermal sensing techniques on other than a trial and error basis, it is necessary to have information about the following items: the physical basis for the existence of a "detectable signal", its magnitude in the geometric sense as well as in terms of radiant energy, the dependence of this signal on other natural phenomena, and the variation of the signal with the passage of time.

ABSTRACT: Airborne infrared thermal scanners can be used to detect crevasses and cave openings, but only under certain conditions. First, the temperature inside the void must be significantly different from external conditions; and second, some mechanism must exist to bring this thermal difference to the surface where it can be detected by a scanner. Furthermore, it must be determined if other events influence this mechanism. In the case of crevasses, conduction and convection both play a role in altering the surface temperature of the snow bridge over a crevasse. For caves, convection is the mechanism that brings about the temperature alteration. Convection is linked to the breathing cycle which, in turn, is caused by changes in atmospheric pressure. From ground measurements of internal temperature, external temperature, and atmospheric pressure a flight time can be picked that will provide the most favorable circumstances. The cave signal is more of a problem because it is frequently surrounded by similar looking signals caused by other events. Results are given for a crevasse field in Greenland and for a cave system in Puerto Rico.

The results reported here are portions of two research projects: crevasse detection and cave detection.

The efforts in crevasse detection were done in the late 1950's and early 60's when the author was on the staff of the U. S. Army Snow, Ice and Permafrost Research Establishment (USASIPRE), Wilmette, Illinois. In the early 60's, this laboratory became part of the U. S. Army Cold Regions Research and Engineering Laboratory (USACRREL), Hanover, New Hampshire. The crevasse studies and airborne thermal sensing took place on the Greenland ice cap and were a joint effort between the group at USASIPRE/USACRREL and the Infrared Laboratory, Institute of Science and Technology, Hanover, New Hampshire.


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Technology, The University of Michigan. These early efforts in the use airborne infrared thermal sensing techniques for crevasse detection were first reported in the classified literature. Since then, the imagery has been declassified and is presented here as illustrative material associated with the general problem of detecting subsurface voids.

The cave detection results are from a portion of a research program concerned with remote sensing and environmental analysis within a study area in the Commonwealth of Puerto Rico. The field work and data collection were done in 1970, when the author was on the staff of USACRREL, Hanover, New Hampshire. The airborne thermal missions were done by the U. S. Air Force, Rome Air Development Center, under the jurisdiction of Mr. A. Stringham, Chief of the Reconnaissance and Mapping Branch. Although these two efforts may seem unrelated, they are, from the physical point of view, similar problems and are therefore combined in this presentation.

BASIS FOR DETECTION

All matter at a temperature above absolute zero (0° K or -273° C) emits electromagnetic energy. If the matter is hot enough, e.g., a red hot stove pipe, a tungsten light bulb, the sun, etc., it emits sufficient energy to influence the eye or a photographic emulsion. However, at normal earth surface temperatures, i.e., -50° C to +50° C, the amount of energy emitted is far below the threshold levels of either a photo emulsion or an eye. Thus, to detect such energy, special materials are used that are not only sensitive to infrared radiation but which have some property, such as electrical resistance, that changes rapidly and significantly with minute variations in the incoming signal. When working with energy levels associated with the temperature range of -50° C to +50° C, a detector most sensitive to infrared energy with wavelengths of 8 to 14 micra is normally used. This is so for two reasons: at such temperatures materials emit more energy at these wavelengths than at any others, and the atmosphere is relatively transparent to radiation of these wavelengths. The signal from the detector is amplified and then displayed on a cathode ray tube as well as recorded on magnetic tape, or directly on film via a modulated glow tube or a cathode ray tube trace. By convention, the gray tones are printed so that light tones indicate higher radiation levels, or warmer areas, and darker tones represent cooler areas.

In order to detect a given object, it must have a radiation characteristic that differs from its surroundings, i.e., a different temperature or a different emissivity, or some combination of the two. The term emissivity describes the level at which a given material absorbs and emits energy at any selected temperature for the wavelength of interest. Materials emit energy at those wavelengths at which they absorb. A material with an emissivity of unity is a perfect absorber, reflecting none of the radiation striking its surface; it emits more energy than a material with a lesser emissivity at the same physical temperature. Emissivity is a function of the molecular species, its temperature, and the portion of the electromagnetic spectrum being considered. For example, snow appears very bright in the visible part of the spectrum which means that it has a high reflectivity and a low emissivity. However, for infrared radiation in the 8 to 14 micra range, it is nearly a perfect absorber, reflecting but little of such energy striking its surface.

In order to decide how to detect any given object, it must first be determined if the object ever shows a thermal difference from its background. A subsurface void, such as a cave in the ground or a crevasse in an ice field, can be detected only if an opening can be found that has a temperature different from that of the adjacent background, or if thermal conduction, or convection, in the overburden has brought the surface above the void to a temperature different from those of adjacent surfaces. The latter, although of applicability in crevasse detection, has little practical bearing on cave studies.

A crevasse is a crack in the ice of the upper portion of a glacier and is formed in response to stress induced by movement of the glacier over different slopes of bedrock. Because of the weight of the overburden, the bottom of the glacier is plastic and it conforms to the surfaces over which the glacier moves. The top portion of ice is brittle rather than plastic, and consequently can snap and form a crack as the glacier bends. This crack, which can get wider with time, usually bridges over with snow during the winter months, which effectively obscures the underlying crack. Figure 1 is an interior view of a crevasse. During the winter, the internal temperature of the crevasse can be many degrees warmer than the outside air and exposed snow surfaces. In fact, if a hole develops in the bridge over the crevasse, the relatively warm inter-

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nal air can rise as a plume of steam visible for some distance. In many places the bridge is permeable to air and if the atmospheric pressure drops, the relatively warm internal air can warm the bridge as it passes through, thus bringing the surface of the bridge to a temperature different from the surface of the adjacent firn. The bridge can also alter its temperature by conduction. Field measurements revealed these differences and set the basis for trying thermal detection techniques.

With respect to caves, the problem is only slightly different, for the mantle of material (soil and rock) over a cave is nonpermeable, and is usually of such a thickness that thermal conduction processes cannot establish a reliable and persistent surface thermal pattern. For detection purposes, this leaves the openings or, more correctly, the mass of air in the openings, as well as the material around the openings or lining them. As do crevasses, caves breathe in and out as the atmospheric pressure changes, and if the temperature of the air inside the cave differs enough from that of the outside air, soil, and vegetation, there is the possibility that it will thermally alter the immediate environment in and around the opening as it passes over it during the "exhaling" part of the "breathing cycle". In order to determine the sequence and extent of such events, it is necessary to monitor them for several days by placing suitable recording instruments in the cave as well as on the ground surface near a cave opening. In addition, a variety of day and night ground measurements should be made during the study period. Primarily these would be radiation and contact temperature measurements of surfaces of interest, e.g., soil, rock, roads, vegetation, etc, and frequent incoming radiation measurements of the sky at zenith. With these data in hand, one can determine if it is possible to detect the opening and the proper time at which to do so.

RESULTS

CREVASSES

In addition to measurements on crevasses in the Greenland ice sheet, an undersnow target was set up at the SIPRE field station near Houghton, Michigan, to serve as a means for evaluating airborne techniques. The target was a refrigerated device in the shape of a large letter Z. The surface of the snow over the cold target was kept at a somewhat lower temperature than the surface of the snow adjacent, which was warmed by the flow of heat from the unfrozen mass of ground below. Figure 2 shows the results of a flight over the Z target and over a compacted snow target. The compacted snow, having a greater density, conducted heat from the ground to the surface at a higher rate than the uncompacted snow. Consequently, that surface is portrayed as a relatively warm area. Field measurements in Greenland showed that indeed the surface of the snow bridge over a crevasse could have a temperature different from the adjacent firn and that this difference arose from both conductive and convective processes.

Figure 3 is a comparison of photo imagery to infrared thermal imagery over a crevasse field on the Greenland ice cap, not far from Thule Air Base. The light streaks in the thermal image, which indicate relatively warm signals, mark the locations of crevasses. Specifically, they mark portions of the bridge porous enough, or thin enough, to be markedly altered by the volume of warmth below. The air temperature inside one of these crevasses was in the range of $-8^\circ C$ to $-12^\circ C$ while the
FIG. 2. Airborne nighttime infrared thermal images of special targets for studying thermal patterns in snow. The undersnow target, designed to simulate a crevasse (left image), was made by connecting a series of hollow panels together to form a large letter Z (265 feet on the diagonal and 136 feet along each end) which rested on an insulating layer at ground level. Chilled trichloroethylene was circulated through the panels, and by conduction the surface of the snow above the target could be maintained at a temperature lower than that of the adjacent snow surface. In this image the temperature difference between surficial snow over the target and the snow adjacent was 3°C. By convection, thermal imagery is usually printed so that lighter tones indicate relatively warmer signals. Thus, the colder snow over the Z target shows as a dark streak. To the right is the image of a compacted snow area (100 feet by 100 feet) created by driving tracked vehicles over the surface. The denser, compacted snow ($d = 0.452$), can conduct heat from the ground up to the surface faster than the loose, uncompacted snow, and thus shows as a relatively hot signal (3°C warmer in this case). In the daytime when the sun shines on the surfaces, the compacted area can conduct surficial heat downward at a greater rate than the uncompacted snow, and thereby maintains its surface at a lower temperature. Thus, in daytime this signal can be reversed, and the compacted snow show as a darker gray tone. A surface wind can degrade, and even erase these signals.

outside air was closer to $-35^\circ$C. The interior view shown in Figure 1 is of one of the crevasses in this group.

Figure 5 shows thermal imagery of another crevasse field in the same general region of the ice cap. In addition to the warm traces of thin areas in the bridges over the crevasses, the imagery also depicts the compacted snow trails and the campsite. The emissivity of snow is relatively high, 0.90 to 0.95 for fresh snow, which means that the material is a very good absorber. The thermal energy detected by the scanner comes not from any depth, but from the surface. Since this signal is primarily a surface phenomenon, it is influenced by atmospheric events from above as well as conductive and convective events from below. A wind blowing over the snow surface can erase the signal imposed by subsurface vents, and inscribe thereon the marks of its own passing. Figure 6, of the same area as in Figure 4 (upper), shows the influence of wind on the surface thermal pattern.

CAVES

A more familiar form of subsurface void is a cave and, with the exception of conductive events, the physical basis for detecting such a feature is analogous to that associated with the crevasses. Figure 7 shows the approximate location of the study area within the island of Puerto Rico.

This particular cave system, which exists in massive beds of heavily fractured and severely eroded limestone, is associated with the underground passage of the Camuy River. The river flows north in a deep narrow valley until it disappears at the base of a steep face. From this point, it continues north via underground channels for several kilometers before emerging to resume its course as a surface stream. The location of much of the underground system was unknown, and the infrared thermal scanner flights were made in the hope of finding additional sinkholes that were directly connected to the underground channels and voids.
Limestone is slightly soluble in acidic ground water and, over long periods of time, slowly dissolves along fractures and cracks, constantly enlarging them. Systems of these interconnected and enlarged fractures can eventually capture a surface stream and cause it to flow through the underground channels, further increasing the rate of dissolution and erosion. Eventually some of the voids and channels become so large that the overlying material is too weak to support the span and it fails, falling to the bottom. Figure 8 is a stereo pair of air photos that portrays the ruggedness of this karst terrain and shows some of the sinkholes associated with the cave. Collapse structures are prominent in this image and two such features have been labeled, i.e., the sinkholes Tres Pueblos and Empalme which connect directly to the cave system. Figure 9 is a set of oblique aerial photos of some of the sinks and cave openings. Tres Pueblos Sink is about 600 feet in diameter and some 450 feet deep. The Camuy River flows along the bottom of this sink and is easily seen from the surface. Empalme Sink also descends directly to the river 416 feet below the opening.

Recording hygrothermographs were placed in parts of the cave system and at a surface station, along with a recording barograph. Within the cave the air temperature was fairly constant, about 70°F, while the outside air showed a typical diurnal variation ranging from the high 60's to the low 80's. A portion of this information is shown on the graph in March of 1962.
FIG. 5. Infrared thermal imagery of a crevasse field in northwest Greenland (1420 hrs., March 1962). This area is a glacial feed to the Moltke Glacier that flows into Wolstenholm Fiord. The well-defined light streaks are portions of crevasse bridges that are relatively thin. The dark streaks associated with them are massive portions of the bridge composed more of ice than of snow. Where the bridge has iced up, it is relatively impermeable to air and maintains a cooler temperature. The large light area in the upper left part of the image is a campsite. Leading out from it, as well as in other parts of the images, are vehicle trails which show as a warmer signal. Since this is winter, the snow surface is relatively cold. Each centimeter below the surface the temperature is a little warmer until it reaches a maximum that represents the previous summer; with further depth, the temperature decreases to a minimum established by the previous winter. This cyclic variation of temperature repeats itself with each cycle becoming less evident until, at some depth, a relatively stable temperature is reached. At this time of year (late winter) the compacted snow of the trails conducts the stored heat to the surface and thus shows as a warm signal, as compared to the adjacent uncompacted snow. This imagery was taken with an InSb detector at an altitude of about 2,000 feet.

Figure 10 which combines data from both temperature recorders. In the early morning hours, the interior of the cave is warmer than the outside ground air by as much as four or five degrees, and this was coincident with a small decrease in atmospheric pressure. Thus, at this point on the cycle, the cave should be "exhaling" slightly, and the warm interior air might be detectable either as a mass inside the sink or as a result of warming the adjacent soil and vegetation surfaces. For most types of infrared thermal missions it is preferable to fly at night to avoid the complicating factor of intense solar heating with its high levels of radiation and large radiation differences. Although flights were frequently scheduled over the Camuy region during the airborne program, weather and clouds usually prevented them.

Some flights were made during the early morning of 11 June 1970, under a relatively clear sky with little surface wind. Increasing cloud cover prevented additional passes. Some of these results are shown in Figures 11 and 12.

The only two sinkholes or openings known to connect with the cave that were consistently registered in the image were Tres Pueblos and Empalme. Also these are the only ones that open directly, in a vertical sense, to the river. Other sinks connect to the interior, but do so by inclined, somewhat twisted, and longer paths. Careful comparison to stereo aerial photography did not reveal additional "detected openings."

In Figure 12, Run 6, there is a row of three small hot spots labeled as firepots. These are pails of burning charcoal used to mark known locations. In regions that are well endowed with distinct and easily seen ground patterns, i.e., roads, rivers, ponds, structures, plowed fields, etc., it is not difficult to verify the presence or absence of some desired signal associated with a known cause. However, in
unknown regions, or where corroborative pattern detail does not exist and the looked for signal cannot be found, one does not know if the signal was not recorded because it did not exist, or because the aircraft did not fly over the proper spot at the proper time. As an aid to this problem, small firepots can be placed in a well defined pattern at or around the area of interest. If the image records these markers, at least it is known that the aircraft passed over the site in question.

A second problem associated with many detection procedures is that of sorting out the signal being sought from amidst a clutter of similar looking signals. It is relatively simple, in the sense of physics, to determine if it is possible to detect a given signal and under what conditions, but in real situations, it is

Fig. 6. Effect of wind on the surface thermal pattern. In these infrared thermal images of the same area as in the upper illustration of Figure 4, a surface wind is cooling the snow surface. Areas protected from the wind by vehicles, buildings, snowdrifts, etc., were radiating at a higher energy level. Although the wind streaks are evident in the lower image, the wind not strong enough to erase the thermal pattern of the crevasses. In the upper image, the wind speed was such that it greatly subdued the surface thermal pattern established by the crevasses although the compacted trails show. This is usually the result when winds across the surface exceed 8 to 10 knots.

Fig. 7. The general location of the cave study is shown on this outline map of Puerto Rico. The Camuy Cave is located in massive beds of limestone that dip gently to the north. The Camuy River flows through this region as a subsurface stream over 400 feet below the terrain envelope.
FIG. 8. Portions of a stereo pair of air photos over the study area (USGS photography, 1951, scale 1:15,000). Collapse structures are very evident. Of these, the large sinkholes, Tres Pueblos and Empalme, connect directly to the underground channel of the Camuy River. Tres Pueblos Sink is about 600 feet in diameter and 450 feet deep.

FIG. 9. A closer view of the collapse structures marked in Figure 7. Empalme Sink, to the left, provides a drop of 416 feet to the surface of the Camuy River. Tres Pueblos Sink, to the right, is about 600 feet across and some 450 feet deep. The Camuy River flows along the bottom at the right hand edge. Photos by Dave Atwood of the U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.
frequently difficult to identify a particular signal even though it was recorded. For example, consider the imagery of any single run in Figure 11. It is known from ground experience that Empalme Sink is located at the intersection of two roads, that these roads have a unique pattern, and that they will be visible in the thermal image. The imagery

![Graph showing temperature and atmospheric pressure readings.](image)

**Fig. 10.** The upper graph shows the combined temperature records from instruments on the surface and within Espiral Sink, not far from the Empalme site. The lower graph shows the variation in atmospheric pressure during the same period of time. The mission was flown in the early hours of 11 June 1970, at a time when the cave was warmer than the outside and "exhaling" (note small dash and arrow above pressure trace).

![Infrared thermal images of the Camuy Cave area.](image)

**Fig. 11.** Infrared thermal images of the Camuy Cave area. The two sinkhole connections that were consistently detected, Empalme and Tres Pueblos, are marked. In the flyover at 0117 hours (Run 3), the cave was in the early phase of its exhaling cycle and Empalme Sink is barely discernible as a warmish mass. By 0129 hours (Run 6), Empalme Sink has developed into a very strong signal. Figure 12 shows portions of two of these runs at an enlarged scale. Note the background confusion of signals that make it difficult without auxiliary information to identify the particular signal being sought. The other signals are caused by small ponds, bare rock outcrops, houses, etc.
FIG. 12. Enlargements of portions of the thermal images from Runs 3 and 6, shown in Figure 11. In Run 3 the opening of Empalme Sink is not discernible, although there is a warmish area in the general vicinity of the opening that marks the beginning of the warming trend brought about by exhalation of the warm interior air. Twelve minutes later (Run 6) the trend has proceeded to the stage where the sink opening itself can be detected. The charcoal firepots used for site identification are apparent in Run 6. They were not ignited until just after the flyover of Run 3.

can then be examined for the pattern of the proper road and road intersection to see if there is some sort of signal that might represent the hole that is known to be there. However, if one knew nothing of this region, was handed imagery of one of these runs, and asked to comment on the presence or absence of cave openings, silence would probably ensue, for there are too many similar looking signals arising from other causes such as small ponds, bare rock outcrops, etc. If the thermal image could be compared to stereo aerial photography or if, as in this case, a sequence of thermal images was taken to pick up changes in a given signal, there would be a basis for noting areas of suspicion. The absence of the desired signal can also pose a problem. Suppose this imagery did not record any thermal variation that could be associated with cave openings? It cannot be concluded from this alone that infrared thermal techniques cannot detect cave openings, for perhaps the flights were made at the wrong time of day or under the wrong meteorological conditions. Thus, it is important to examine the physical basis of a problem and to collect ground data associated with the important parameters of that problem before coming to firm conclusions about choice of detector, times for flying, altitude, and weather restrictions. At times, factors beyond the investigators control determine the choice of sensor system and times for flying. Even so, this basic information is of help in analyzing whatever imagery does result from the missions.