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Ground Temperature and Thermal Infrared

The change in minimum resolvable temperature difference with target temperature depends on the type of detector in the system.

Introduction

Infrared line-scan imagery has become increasingly important because of its ability to provide information not readily available through other remote sensing techniques. Thermal data derivable from such imagery have been used, not only for the detection and measurement of such obviously temperature-related phenomena as coal refuse pile fires,[1] thermal water pollution,[2] and active geologic processes,[3] but also for structural geologic mapping,[4] ecological studies,[5] and archeological studies.[6] In many instances, the imagery obtained during a particular data collection flight is usable for the intended purpose almost by chance. Experience has provided almost the only basis for selecting the equipment to be used and the operating procedures for many of the present uses.[7] This paper is intended to provide a basis on which equipment selections and operating procedures can be made to provide the maximum usable information for the intended purposes and with the given ground situation. The primary area of concern is the effect that the average ground temperature has on the appearance of and the information contained in the infrared imagery.

Abstract: *Infrared imagery displays the apparent temperature differences occurring in the surface being imaged. The magnitude of detectable temperature depends not only on system parameters, but also on the temperature of the surface being imaged. Theoretical relations between minimum detectable temperature difference and the target (ground) temperature show the loss of sensitivity to temperature change as target temperature decreases. Indium antimonide detectors are more susceptible to this change than are mercury-doped germanium detectors. The effects are illustrated in infrared imagery.*

Imaging System Theory

Signal Generation

Line-scan imaging systems have been described in previous papers.[8,9] The only characteristic of importance here is the manner in which thermal information is obtained by, and processed through, the system. In a few instances, the system output depends on the total radiant energy input. However, because of the small amount of radiant energy collected from the target, and the generally large amount of thermal energy added to the detector from other sources, this measuring of total energy is rarely used. Rather, the *change* of input energy is the quantity detected and provided as output data from the system. Processing and system circuitry are designed to eliminate that data associated with changes in the input energy from sources other than the ground target being scanned.

The derivation of a signal representing a change in energy, and the fixing of the zero level from which the change is measured, are functions of the system design. In a radiometer, or an imaging system which measures the target radiation temperature, the output indication is derived by measuring the differ-

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ence-signal generated as the detector alternately sees the target and a standard blackbody radiator whose temperature is known. For most line-scan systems, the output signal for a particular spot in the imagery depends on the difference between the energy received from the corresponding spot on the ground and the energy which represents the zero, or background, level in the imagery. In general, signals may be either positive or negative with respect to the set zero level.

The zero level may be derived either from some long-term (several scan times) average of the energy variations or by fixing it as the level generated when the detector sees some reproducible target such as a temperature-regulated blackbody, or the interior of the scanner unit. The effect in the display of zero level choice may be clarified by an example. If the ground area being imaged has a gradual change in apparent temperature, the signal levels in the two systems would differ. For the system which derives the zero level by averaging the signal for a number of scan times, there would be no drift in the zero level regardless of the apparent average ground temperature drift provided the variations around that average stayed constant. For the system which clamps the output zero or background level to the signal generated by a fixed-temperature source in the scanner, the average signal level about which variations occur will drift with the average apparent ground temperature. Signal variations about that average will stay approximately constant for equal ground temperature changes provided the average temperature does not change drastically.

ΔT DEFINITION

The variation obtained in the output signal depends on the change in the energy input and on the gain setting of the imaging system. When the thermal information sought consists of large energy differences, little difficulty is encountered in adjusting the system to produce a usable output.

In many instances however, the imagery is intended to depict very small thermal differences. These small differences are occasionally found superimposed on large thermal differences. Special techniques for displaying these are required. But whether the small differences occur in a reasonably constant background, or in a background with large temperature differences, the minimum resolvable apparent temperature change is an important parameter of the system. This minimum detectable temperature difference, ΔT, depends on both the imaging system parameters, and on the ground target temperature.

In every line-scan system, some minimum level of noise exists. This noise may be generated by a number of sources in the system. For ultimate performance, the system is generally designed so that the noise generated by the detector is the limiting factor. This noise, and any other in the system which can be so related, is expressed as the Noise Equivalent Power (NEP) of the detector. The NEP is the change in energy input to the detector, expressed in watts, which will produce a signal level change equal to the noise signal level. For a given imaging system, the NEP can be expressed in terms of a Noise Equivalent Input (NEI). This NEI is the change in power density, in watts per square centimeter, at the input optical aperture which will produce the NEP at the detector. The limiting thermal resolution, ΔT, of the system is the temperature difference in the scanned area which will produce a power density change at the scanner equal to the NEI.

If for a one-degree change in target temperature the energy density at the optical aperture would change the same amount regardless of the target temperature, the ΔT for the system could be specified just as is the NEI, and would depend only on system characteristics. However, the energy change produced by a one-degree change in target temperature depends greatly on the original target temperature. Thus, the ΔT of the system can be expressed only if a target temperature is given as well. In most instances the system ΔT is specified for a 300°K or 500°K target temperature.

Theoretical ΔT Dependence on Temperature

To investigate the manner in which the ΔT changes with target temperature, let us begin with the Planck radiation equation which relates the power radiated by a blackbody and the wavelength at which particular intensities are produced. A series of curves for this equation are plotted in Figure 1 where the temperature of the radiating body is the varying parameter. As most line-scan imagery is made over ground targets whose temperature extremes are not great, the limits of 313°K and 243°K are used for these curves.

Generally two spectral regions occur where detectors are employed for infrared line-scan imagery. These are the approximately 3 to 5-micrometer region where indium antimonide (InSb) is sensitive, and the 8- to 14-micrometer region where mercury-doped germanium (Ge:Hg) is used. These two spectral regions are delineated in the graph of Figure 1. The area under each curve within the spectral limits for the detectors is a measure of the amount of energy available at the input to the collecting aperture of the imaging system for that particular target temperature. The differences in those energies for various temperatures is a measure of the signal generated for a corresponding target temperature change.

The rate of change of input energy with temperature may be shown by plotting the derivatives with temperature of the curves of Figure 1. In Figure 2 are a series of parametric curves showing the rate of change of energy with the temperature and wavelength for each of the temperatures of Figure 1. The curves are similar in shape to the energy distribution curves of Figure 1 but the wavelength at which the maximum change of energy occurs for any given temperature is lower than that at which the maximum radiation intensity occurs for the same target temperatures. The effect of this shift is to make the InSb detector somewhat more useful or sensitive to energy changes as compared to the Ge:Hg detector than might be expected on the basis of total energy comparison. Further, the separation of the curves with temperature is greater at the InSb band than at higher wavelengths suggesting that the lower wavelength band will provide emphasis of targets which are warmer than the average target temperature. Thus *hot spot* detection is better with InSb than it is with Ge:Hg.

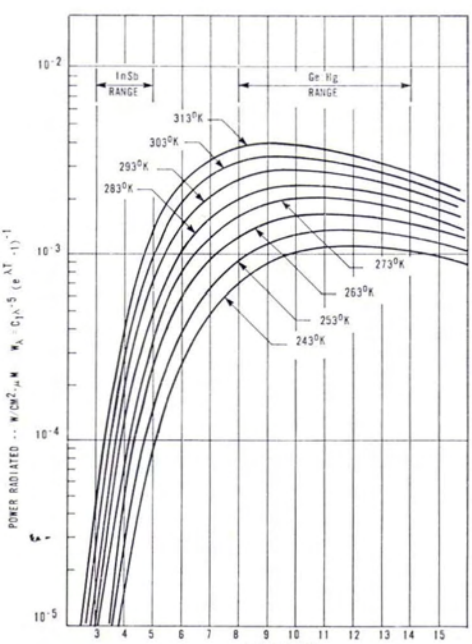

FIG. 1. Blackbody radiation curve.

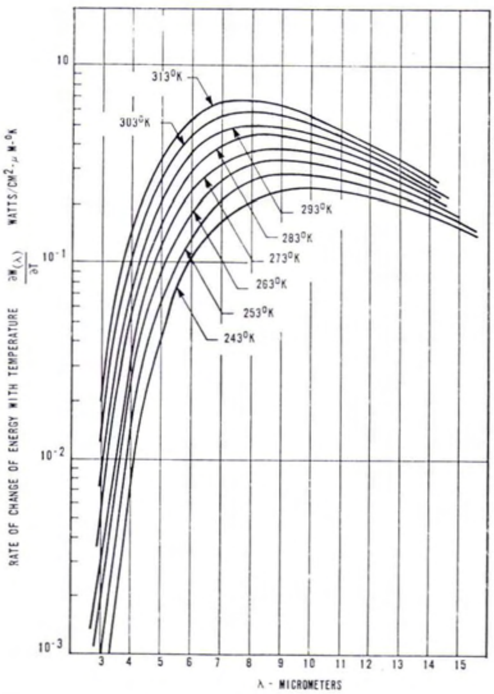

FIG. 2. Rate of change of radiated energy with temperature.

The curves of Figures 1 and 2 for theoretical blackbody radiators give indications of what may happen to the ΔT of the system as the target temperature changes. Other factors must also be considered before any numerical estimates of the ΔT changes can be obtained. The two major factors are the variation of detector response with wavelength, and the effect of atmospheric absorption on the energy available to the detectors. Typical response curves for InSb and Ge:Hg detectors are shown in Figure 3. The relative response at a given wavelength is used in the calculations since total system response, including true detector sensitivity, is accommodated in the NEP determination. Atmospheric absorption depends somewhat on the amount of water vapor and other gases, but a typical curve for transmission through 1,000 feet of air at sea level over open water was used in these calculations.

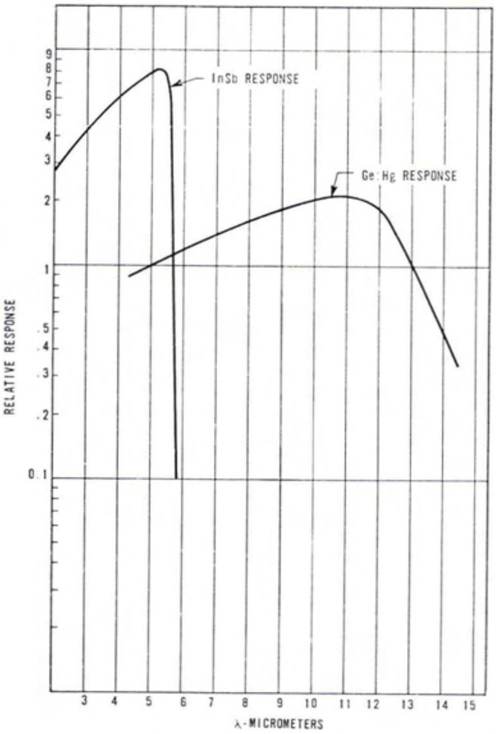

FIG. 3. Typical detector response.

The two effects of transmission and detector response were applied to the theoretical radiation curves of Figure 1. The resultant effective radiation curve which shows the energy available to elicit response in the detector is shown in Figure 4. Only the curve for 313°K (40°C) is shown in the Figure. Similar calculations were made for each temperature in Figure 1. To obtain a measure of the rate of change of energy with temperature for the real case, the areas under the effective radiation curves were integrated and the total effective ground radiation vs. temperature was plotted for each detector. Figure 5 shows the InSb detector band, and Figure 6 shows the Ge:Hg detector band. The slope of the curve at any given temperature is the factor of primary interest since it shows the rate of change of effective energy into the system for a one-degree change in target temperature. The slope of each curve was calculated graphically and plotted as a function of temperature in Figures 7A and 7B. These curves show what occurs to the minimum resolvable temperature difference, ΔT, as the ground temperature changes.

The ΔT is inversely proportional to the target temperature. That is, as the ground temperature is lowered, the minimum temperature variation discernible in the imagery becomes larger. For example, for a given system with an InSb detector producing imagery of the ground at 303°K (30°C) the minimum apparent temperature change discernible might be about 0.1°K. From the curve of Figure 7A, a 1° change in temperature would produce a change in input energy of approximately 0.17×10^{-4} watts/cm.^{2}°K. A ΔT of 0.1°K means that 0.017×10^{-4} watts/cm.^{2} is the minimum energy change to which this particular system will respond. With that same system and detector, but a ground temperature of about 283°K (10°C) the same minimum signal change represents a ΔT of the target of 0.2°K. That is, at 283°K, the energy change per degree is 0.085×10^{-4} watts/cm.^{2}°K. The same minimum detectable energy change, 0.017×10^{-4} watts/cm^2, is produced by a temperature change of 0.2°K at this temperature. On the other hand, if a Ge:Hg detector is used in the same system and the same ΔT of 0.1°K at 303°K prevails, then at 283°K the ΔT is about 0.12°K. The thermal detail available in the imagery produced by this detector is degraded very little by the ground temperature change. These effects can be predicted from the shapes of the curves in Figures 7A and 7B. The perfor-

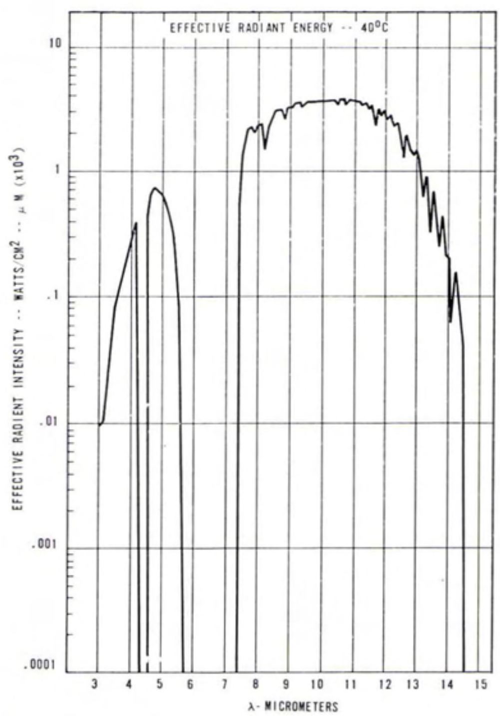

FIG. 4. Effective radiation versus wavelength.

mance of the Ge:Hg detector will begin to degrade more rapidly at colder temperatures as indicated by the steeper slope of the curve there.

For very cold (compared to usual ambient temperature) ground targets, the ΔT will be quite large. If a system is set to produce discernible differences in the imagery gray level for apparent ground temperature differences of one or two degrees when the ambient level is 293°K to 303°K, no details will be evident in the imagery at all for ambient temperatures at 263°K to 253°K. This is the case even when the average background or zero level has been adjusted to accommodate the lower ground temperature. The cold area will appear to be essentially featureless to the infrared system. If enough sensitivity or additional gain were available in the imaging system, some detail might be made available. However, the minimum resolvable apparent temperature difference would be a larger increment than that possible at higher target temperatures.

A technique used to emphasize small temperature differences superimposed on large changes is that of printing a differentiated signal rather than the usual imagery signal. As this is essentially the energy change signal with a very short *memory* time for the zero level determination, the imagery appears to be primarily edges at which energy change takes place. This technique is valuable to depict small energy changes over the entire imaged area even though there are large energy changes as well. Normally, on undifferentiated imagery, if the dynamic range is set to accommodate the large energy changes, small variations in signal level will not be discernible in the imagery. If the settings are changed so that the imagery shows small variations at one ground temperature, large changes in ground temperature will exceed the dynamic range of the recording medium, and all information at those ground temperatures is lost. Differentiation allows small variations of temperature to be recorded. However, the same ΔT-effect is present when the signal is differentiated. That is, the change in signal level caused by a given temperature difference is much larger for a warm target than it is for a cold target.

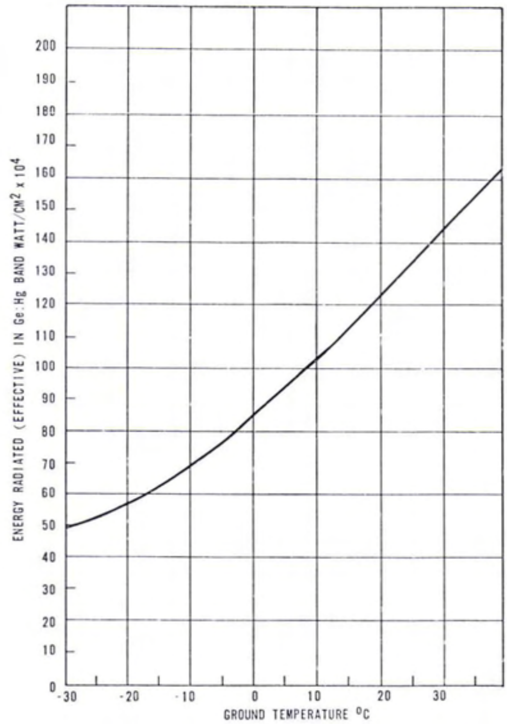

FIG. 6. Effective radiated energy into Ge:Hg detector as a function of ground temperature.

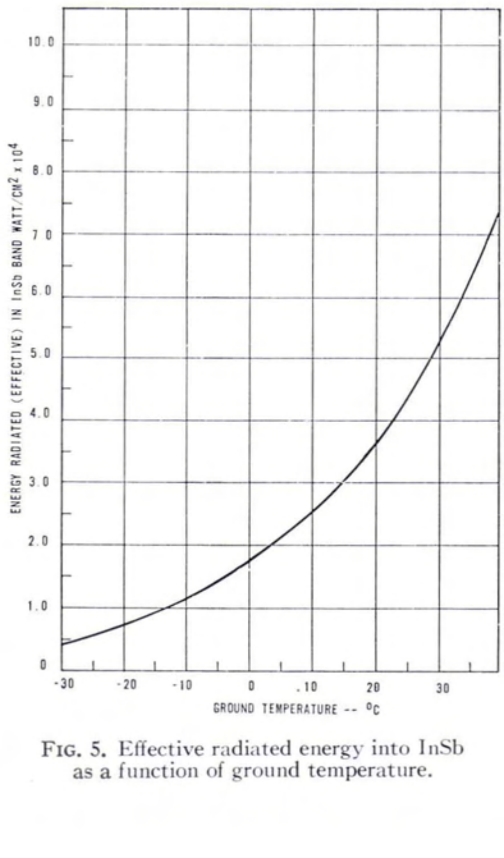

FIG. 5. Effective radiated energy into InSb as a function of ground temperature.

IMAGERY EXAMPLES

A few examples of imagery are included here to illustrate the effects of ground temperature on thermal resolution. Apparent

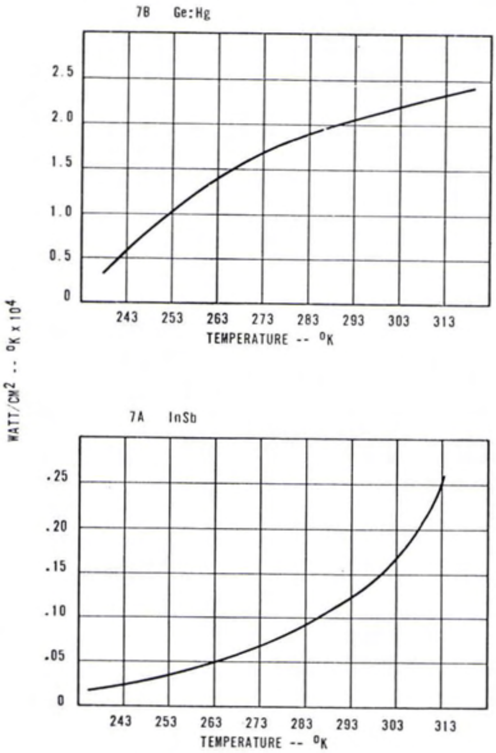

FIG. 7. Signal generated by a temperature change of one degree.

temperature differences on the ground may be caused by changes in emissivity as well as by actual temperature change. Basically the emissivity of a surface relates the power radiated by a surface to that which would be radiated by a black-body surface at the same temperature. Since temperature differences are detected as emitted power differences, a lowered emissivity gives the appearance of a colder temperature to the target surface. Along with the lower apparent temperature goes the increase in the minimum resolvable temperature difference.

The first imagery example, Figure 8, shows this emissivity effect. The imagery was flown near dusk on a winter day. There may be some snow in patches, but generally the lower temperature areas are cooler valleys. A radiometer was flown with the infrared scanner, and the ground trace of the radiometer is shown by the thin line near the center of the imagery. Interruptions in the line are used to correlate the radiometer signal recording with the imagery. The HRB-Singer, Inc. RECONOFAX* IV scanner and the AR-2 radiometer were used to obtain this imagery and temperature recording. An InSb detector was used in the scanner.

The chart recorder trace of the radiometer signal has been annotated in conjunction with the imagery. Of particular interest are the two points where the temperature indication on the chart has gone completely off the bottom edge. These two spots are identified as metal-roofed buildings on the ground. The actual temperature of these buildings is not 20°K or more below ambient, but the low emissivity of the metal roof makes them appear to be so. Any thermal detail on the roof is completely lost, although both radiometer and scanner response times are fast enough to record any if it were available.

The imagery also shows loss of detail in colder ground areas even though the radiometer recording shows such detail to be present. The detail is available in the radiometer recording both because the system has been calibrated to produce detail, and also because a Ge:Hg detector is used in the radiometer. Some of this loss of detail in the imagery may occur because the signal is below the dynamic range of the film, although the change in thermal sensitivity with ground temperature is a contributing factor.

The imagery of Figure 9 illustrates the ground temperature effect much more clearly. The two film strips were made four days apart in January using InSb detectors. The only difference between the conditions for the two images was the temperature. Ground temperature for the imagery in Figure 9A was 260°K, for the imagery in 9B, the ground temperature was 282°K. As there were no major temperature changes to be accommodated in the area on a given flight, the gain was set to produce good thermal resolution. The imagery in Figure 9A shows much less thermal detail than does that of 9B. Although some effect may be caused by rhododendron leaves being curled tightly in the cold and uncurled on the warmer evening, the primary cause of the *flat* imagery is the cold ground temperature. The water appears warmer than the ground, and is, even though the stream was completely frozen over during the first flight. On the second flight when the ground temperature was 282°K, the ground and water were almost the same temperature. Imagery, not available for publication, was made at the same time with Ge:Hg detectors in another RECONOFAX system. Some difference occurs between the two dates in the amount of thermal detail shown but, as predicted by the theory, much less dif-

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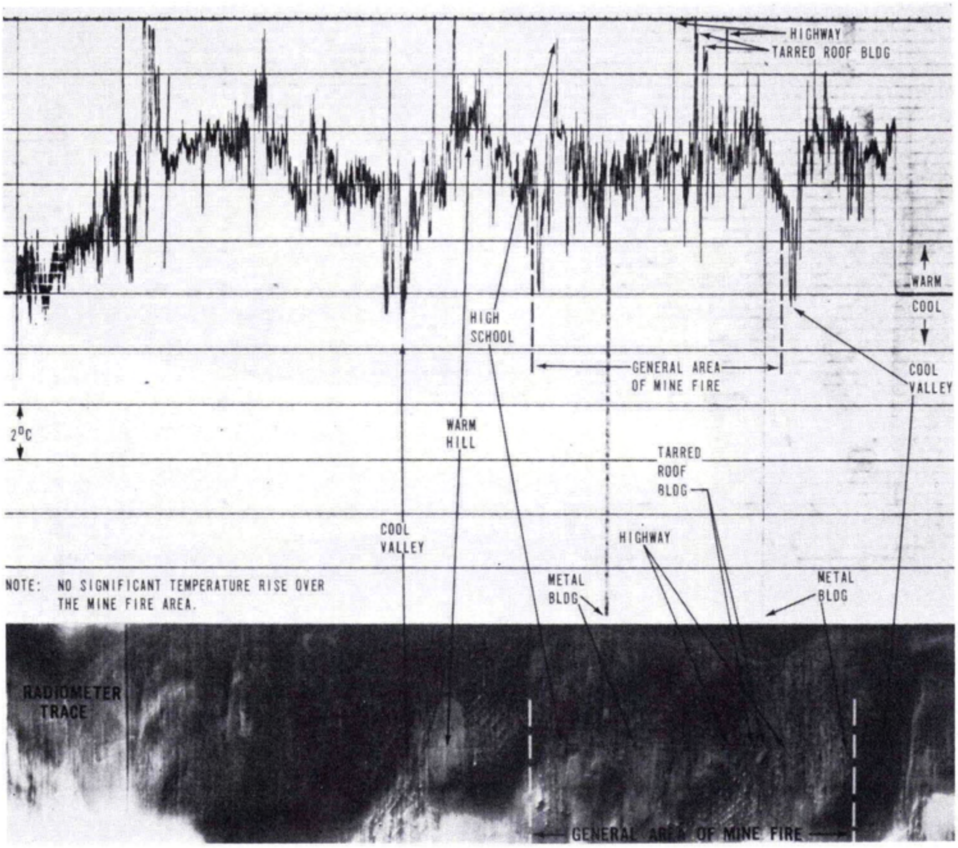

FIG. 8. Radiometric profile across Connellsville, Pennsylvania.

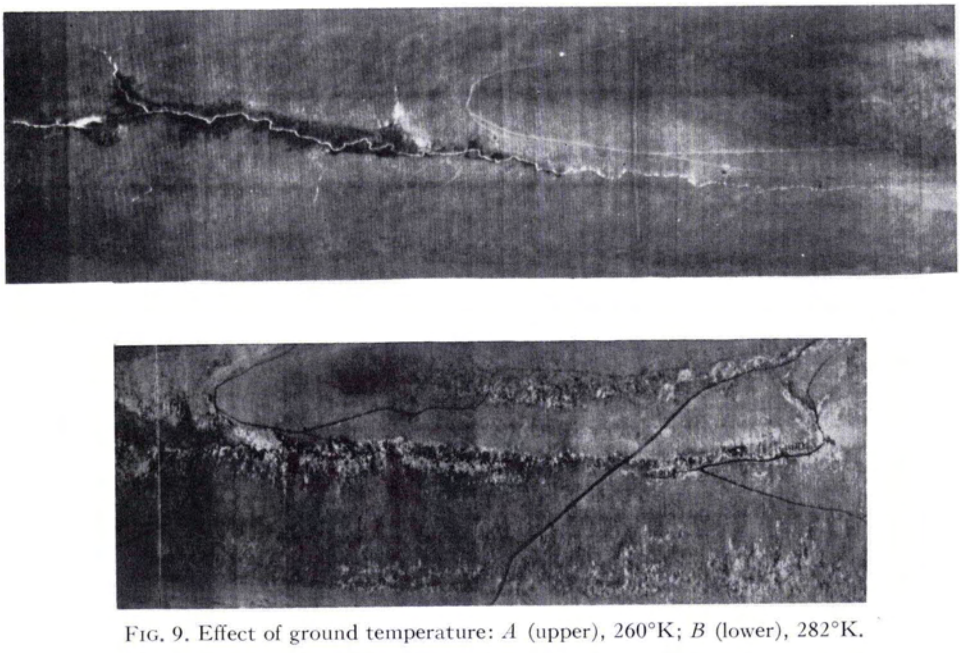

FIG. 9. Effect of ground temperature: *A* (upper), 260°K; *B* (lower), 282°K.

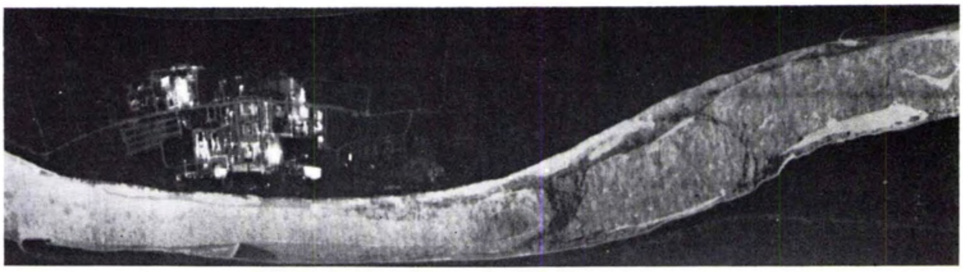

FIG. 10. Hot-spot enhancement.

ference exists in the Ge:Hg imagery than in that made with the InSb detector.

The imagery of Figure 10 shows the hot-spot enhancement effect of InSb detectors. This imagery was made on the same flight as that of Figure 9A. Ground temperatures were not measured at this point, but it is assumed they are approximately 260°K, the same as the imagery of Figure 9A. The background level was adjusted to exhibit detail in the river. The ice floes are quite apparent. The surrounding area is cold so that the detail is not very apparent. The roads, and particularly the buildings, stand out sharply in the industrial area. In the colder areas some detail can be discerned, but small temperature differences do not cause the change in signal level that are evident in the warmer areas of the buildings.

SUMMARY

Infrared line-scan imagery is generated as the record of apparent temperature difference from some background or zero level. That level may be determined by clamping it to some reference temperature source or by providing an average of the signal variations over some relatively long term integration. The minimum resolvable temperature difference is a function of system parameters, but also is a function of the apparent temperature of the target being scanned. The minimum energy difference which can be presented by the imaging system as a discernible change in the imagery represents a much larger temperature change in a cold target than it does in a warm target. Or, stated another way, the same temperature difference in the ground target will produce a much larger signal when the ground is warm than when it is cold.

The change in minimum resolvable temperature difference with target temperature depends on the type of detector in the system. An InSb detector exhibits much more effect than occurs with a Ge:Hg detector. This results not from any inherent sensitivity of the detectors, but rather because of the radiant energy distribution with wavelength and the spectral bands in which the detectors are sensitive. If the average target temperature changes 70°K, e.g., 313°K for one set of imagery, and 243°K on another, a 10-to-1 change in the ΔT occurs, for the same system, for an InSb detector, but less than 5-to-1 change for a Ge:Hg detector. Further, the largest portion of the change for the Ge:Hg detector occurs for ground (target) temperatures of 273°K and below. The major change for InSb detectors occurs in the temperature region above 283°K. These changes are shown in the two curves of Figure 7.

For thermal resolution stability in the imagery, a Ge:Hg detector should be used. Similarly, if minor thermal detail is sought in an area which may be cooler than its surroundings, the Ge:Hg is required. In general, the Ge:Hg detector should be used if detail is required in cold target areas. On the other hand, if the purpose of the imagery is to detect *warmer* spots in an ambient background, an InSb detector will provide the best imagery. If the target temperature is quite cold, e.g., 250°K to 240°K, neither detector will provide much sensitivity to small temperature changes in the imaged area. A system which produces discernible changes in the imagery for an apparent temperature change of 0.5° where the target temperature is 310°K will produce the same kind of change in the imagery only if the temperature change in the target is at least 3° to 5° when the target temperature is 240°K. For imagery of cold areas, special systems designed for that purpose will be required if thermal sensitivities comparable to those available currently on normal (summer) ambient ground temper atures are to be obtained.

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