Geophysical Aspects of Remote Sensing[1/]

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Introduction

Our ability to budget the natural resources of this planet will determine, in large measure, the course of future civilization. We must develop new resources for the needs of an expanding society and, at the same time, extract and use our current resources with greater concern for the damage that can be inflicted on our environment. Remote sensing techniques provide a means to explore for new resources and to identify the sources of environmental destruction.

The study of large regions of the Earth's surface is now feasible through the use of satellites. It is possible to observe how the surface reflects, stores, and reradiates solar energy. Techniques are also available to illuminate the ground, using controlled energy sources, and to record the reflected energy. Finally, we can remotely sense the interior of the Earth by measuring its gravitational and magnetic fields.

Remote sensing observations are made by using a variety of detectors ranging from simple photographic films to complex devices such as spectrometers, gravimeters, and multispectral scanners, all with the disarmingly simple goal of measuring electromagnetic energy or force fields. Techniques for data analysis are equally diverse, ranging from conventional photointerpretation to the use of a host of electro-optical devices and high-speed digital computers.

But the most important ingredient in the use of remote sensing to solve our resource problems must still remain our ability to interpret correctly new observations on the basis of previous experience. In mathematical theory this ability should be axiomatic, in the physicist's laboratory it may be a rational extension of physical laws, but in nature it is truly astonishing! When you consider the seemingly infinite variety of materials, natural settings, and climatic conditions it is difficult to believe that results obtained at one area under one set of conditions could have any application to a new area under a different set of conditions.

There are basically two different approaches to this problem. One can attempt to remotely sense many materials under many conditions and hence derive, by empirical relationships, a basis for interpreting remote sensing observations of a poorly known area. A number of statistical techniques can be applied to quantify the empirical relations and to automate some of the analysis procedure using computers to "recognize" similar relationships. In some cases, where well-defined problems and good observations occur, this approach has led to fundamental discoveries in physics. Examples include Newton's law of gravitational

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attraction which was derived from the empirical laws of Kepler describing planetary-motion observations and Planck's empirical formula derived to explain blackbody radiation. This led to his discovery of quantum physics.

But, when observations are made not to establish new physical laws but, rather, to discriminate and identify different materials it is more appropriate to base the approach on contemporary scientific principles than on empirical relations. In order to apply these principles in a systematic manner we must start with well-defined problems and a small number of variables, progressing logically to more complex situations. In science one of the most useful techniques to apply, in this kind of approach, is a "mathematical model." Model, in this context, refers to a simplified abstraction of a physical object.

For some purposes we might wish to model the Earth as a flat multilayered object, for others as a rigid sphere or as a point mass. The fact that these entirely different models are used to describe the same physical object does not mean that one is more precise than the other but rather that different physical processes are being studied. Thus a flat layered Earth model may be perfectly appropriate to study explosion seismology but quite inappropriate for satellite orbital mechanics. A rigid sphere might be quite useful to model lunar eclipses but utterly irrelevant to discussions of elastic wave propagation. Models provide a means to consider a problem with only a small number of key variables so that their importance can be evaluated for predicting other phenomena. In essence the test of a model is how well it can explain the observations.

One further question concerning models that bears consideration is: How complicated should a model be? The question is important, because it affects the complexity required in analysis and the type and precision of measurements which will have to be made. The most effective way to handle this problem is to develop an iterative model that is initially chosen to be very simple; that is, with only a few variables. In gravity analysis the initial model might be a point mass; in heat-flow analysis, a flat homogeneous solid heated by a regularly varying energy source. By starting with an elementary model which only grossly matches the preliminary observations and continually increasing its sophistication as new observations are made we can use a systematic approach in developing our iterative model. This technique also suggests the desirability of selecting the field test areas in the same manner as the iterative approach: starting with areas which are relatively simple and progressing to more complex areas which present a great diversity of problems.

In summary then, an effective approach in applying remote sensing techniques to resource studies is to start with observations of simple areas, analyze the results in terms of simple mathematical models which are based on scientific principles, and iteratively increase the complexity of the models and sites in a systematic manner. This approach, which I will call the "geophysical method", has been successfully applied in traditional geophysical studies of seismology, gravity, magnetism and electromagnetic induction. It should be equally appropriate to the latest remote sensing techniques involving the measurement of the reflection and emission of electromagnetic energy from terrain.

Problem Area

The long-range goal of the U.S. Geological Survey in remote sensing is to develop techniques which augment traditional field observations in order to provide a more complete understanding of the geologic resources of the United States. A new unit was established within the Geological Survey in 1968 to investigate remote sensing as a geophysical technique applied to geologic mapping and interpretation (Watson, 1971). Our initial approach has been to select field areas for remote sensing observation which display common rock types with good exposure and little vegetation cover. Through the use of mathematical models we then planned to evaluate the discrimination of these rock types and their structural and stratigraphic setting based on physical-property differences and also to evaluate the influence of some important variables associated with the atmosphere and the surface state. We then planned to extend the models to other common rock types and, in a systematic manner, to more complex rock types and geologic settings.

For the purpose of this discussion the results from our most intensively studied site, at Mill Creek, Oklahoma, are described in detail. Common rock units exposed in this area are relatively pure dolomite, limestone, sandstone, and granite (figure 1). A detailed study of the stratigraphic relations of the area (Ham, 1955) provided us with geologic information necessary in the analysis of remote sensing observations. In addition to conventional information recorded for geologic analysis it was necessary to observe the surface state of the geologic materials to a degree commonly ignored in conventional studies. Electromagnetic reflection and emission depends not only on conventional rock properties such as color, topographic expression, and composition, but also on surface roughness, lichen, plant, and tree cover as well as chemical and vegetative staining.

We planned to use remote sensing observations of the Mill Creek area to test whether we could measure differences between three common rock types that could be used to develop models for discrimination of rock types in unknown areas. We also wished to examine the application of remote sensing to structural and stratigraphic analysis and its potential for identification of rock types.

Perhaps I should explain what I mean by identification versus discrimination of rock types and why this represents an important concept in remote sensing. Discrimination means recognizing the difference among rock types, i.e., one unit, A, is different from another unit, B. Identification means labeling the rock type, i.e., unit A is granite and unit B limestone. The actual process is really one of degree of confidence, with identification and discrimination representing the end members. The recognition of rock types from remote sensing observations is a complicated process which is performed at a number of different confidence levels. This approach is a familiar one in conventional geologic studies. Rock types can be identified directly from standard petrographic analysis; indirectly, from infrared spectroscopy by relating molecular resonance to crystal species; inferentially, from physical property measurements of, for example, density, thermal inertia, and dielectric constant; or presumptively, from topographic expression or vegetative cover. Thus as the level of confidence in the approach decreases, identification of rock types requires a greater understanding of the limitations of the methods and more detailed knowledge of the geologic environment.

Because our initial interest at Mill Creek was to discriminate rock types, we chose as our prime experiment the observation of ground thermal emission by means of an infrared scanner. We hoped to be able to see temperature differences among the rock types that would be attributable to differences in their thermal properties. We also planned to observe the reflection of solar radiation in the visible and near infrared, the spectral emission in the infrared and microwave, and the reflection of radar energy. These observations, which are dependent on other physical properties, would then provide a consistent framework for development of additional models. It would then be possible to examine a variety of remote sensing techniques under controlled conditions and in a systematic way. Thus we would develop a group of models which can be used individually to discriminate rock types and define their stratigraphic and structural settings, collectively as a potential tool for rock-type identification, and which could be extended to other areas of geologic interest.

Mission Objectives and Results

Because the initial remote sensing flights of the Mill Creek area (Mission 84) were to be flown as part of the larger overall objectives of the NASA Earth Resources Aircraft Program which include many disciplines, the mission flight parameters had to be planned several months in advance of the actual overflight. We decided to limit this initial flight to survey coverage with primary emphasis on photographic and thermal infrared scanner data. Several flight lines were selected over key areas so that images would have contiguous edges but virtually no overlap. A flight altitude of 1800 m above mean terrain was selected to insure reasonable useful resolution on the infrared data. Flight times were selected that seemed a reasonable compromise to obtain maximum utility from thermal and photographic data during the daytime and optimum thermal contrast at night: midmorning, midafternoon, and predawn.

In addition images, multiband photographs, and microwave line scan data were requested. This information was considered useful for examining the application of spectral reflectivity to characterize rock types and for determining albedo which would be necessary in the thermal analysis (albedo of a surface is a number equal to the fraction of incident sunlight which it reflects), and for comparing microwave and infrared temperatures over a diurnal cycle. Instrument operational problems during the flight and lack of data analyses facilities were later to restrict severly the use of these data.

In support of the overflight measurements we also planned a number of ground observations to calibrate the aircraft data and to measure additional parameters for thermal modeling. Later data analysis illustrated some of the limitations of this initial ground data recording, including the need to investigate more fully the density of "point" ground measurements, the difficulty of comparing measurements made at different scales, and the need to monitor continuously the relevant atmospheric parameters for several days before the actual overflights.

Despite the preliminary nature of the initial overflights, the results were extremely promising (Rowan and others, 1970). The infrared data in particular contained significant stratigraphic and structural information. The relatively pure limestone and dolomite of the test area can be differentiated in the predawn infrared images, and facies changes between them can be detected along and across strike (see figure 2). The daytime images display much stratigraphic and structural detail (see figure 3). Small-scale bedding detail is enhanced in the morning images of areas of low elevation difference, and contrasts of alternating formations that form ridges and valleys are enhanced in the afternoon images of areas of high elevation differences. The difference in features displayed in morning and afternoon images appears to be a function of the insolation (solar flux at the ground) on sunward and shadowed slopes of differing scale. Fault or fracture zones are best displayed in the predawn image; they appear cooler than surrounding ground, because of greater water content and concomitant evaporation. The abundance and throughgoing nature of lineaments (which coincide for the most part with joint systems) are more obvious in the infrared images than in aerial photographs. Lineaments striking northwest are preferentially enhanced in the morning images and lineaments striking northeast are preferentially shown in the afternoon images.

Data Analysis

The interpretation of remote sensing observations obtained to study Earth resources is complicated by both the number and the magnitude of factors which affect the signal received by the detectors. The use of simple mathematical models, which are based on scientific principles, is essential in the application of the "geophysical method" to these observations. Correlations between selected variables can be found, assumptions about suspected major factors can be tested, and unsuspected factors can be discovered and analyzed. To illustrate this point more fully a case history example is presented describing the modeling of thermal emission data obtained at the Mill Creek, Oklahoma, test site (Watson, 1971).

A simple initial model which describes the diurnal heating and cooling of the ground can be selected in the following manner. Let us consider the sinusoidal heating of a semi-infinite solid with homogeneous thermal properties. Then the flux into the ground F can be written as

$$F = F_0 \cos wt$$

where F_0 is the flux at time $t = 0$ for a periodic function with a time periodicity $T = 2\pi/w$. The time $t = 0$ will correspond to the time of maximum heating, local noon, and the period T is 1 day. The surface temperature V for this periodic flux (Carslaw and Jaeger, 1959, p. 68) can be derived from the equation of heat conduction and is

$$V = \frac{F_0}{K} \sqrt{\frac{k}{w}} \cos (wt - \pi/4)$$

where k is the thermal diffusivity and K the thermal conductivity of the homogeneous solid. For convenience we shall introduce a parameter, P, called the thermal $P = K / \sqrt{k}$. Using a single quantity is clearly more convenient than the ratio of two quantities. Thus, we can write

$$V = \frac{F_o}{P\sqrt{w}} \cos (wt - \pi/4).$$

From this simple model we recognize an important parameter in characterizing terrain: the thermal inertia. The model also implies that materials with high thermal inertia have a smaller amplitude and hence they heat and cool less than materials with low thermal inertia. This behavior illustrates why P is called the thermal inertia.

But the model has some obvious limitations. It assumes that all materials are heated in the same manner, ignoring the fact that dark materials which have low albedos absorb more solar energy than light materials which have high albedos. In order to treat this phase of the problem more precisely we must first examine the insolation. If atmospheric transmission effects are ignored, the insolation, I, is proportional to the cosine of the sun's zenith angle, Z, which is the angle between the sun and the zenith.

$$I = I_o \cos Z$$

where I_o = Solar Constant

A simple formula describes the change of sun's zenith angle with time for different latitudes and seasons (sun's declination).

$$\cos Z = \cos \lambda \cos \delta (\cos wt + \tan \lambda \tan \delta)$$

where λ = local latitude

δ = sun's declination

Our new model for the flux absorbed by the ground during the daytime is expressed as

$$I = I_o (1 - A) \cos Z$$

where A is the ground albedo and hence (1 - A) is the fraction of the insolation which is absorbed. During the day and night the ground loses heat primarily by radiation and this term can be approximated by the Stefan-Boltzmann law which states that the total radiative flux is proportional to the fourth power of the temperature.

Thus, our simple flux boundary condition $F = F_o \cos wt$ is now replaced by one of greater utility but more complexity:

$$F = I_o (1 - A) \cos Z - \sigma V^4 \qquad \text{daytime}$$

$$F = - \sigma V^4 \qquad \text{nighttime}$$

Where σ is the Stefan-Boltzmann constant.

Two mathematical techniques exist to solve the equation of heat conduction, subject to the flux boundary conditions described above: the method of harmonic analysis (Carslaw and Jaeger, 1959, p. 64-68; Jaeger and Johnson, 1953) and the method of Laplace transforms (Carslaw and Jaeger, 1959, p. 399-402; Jaeger, 1953). Both methods require an iterative approach (i.e., repetitively improved solutions based on an initial guess) to handle the nonlinear term V^4 in the flux equation. Suffice it to say that the problem can be solved numerically using digital computers, provided that sufficient care is taken in the analysis to avoid convergence problems.

This revised model can now be applied to interpret the Mill Creek thermal observations. Values for the thermal inertia of limestone, dolomite, and granite are obtained from published data (Clark, 1966; National Research Council, 1933). Albedo values are selected partly on the basis of field measurements and partly from qualitative examination of the photographic film data. The insolation is computed for the site latitude (34.5°) and the appropriate sun's declination (-23.3°) for the December flight. The computed surface temperature variation with time for a single diurnal hearing cycle is then determined for the three materials (see figure 4). The model is then evaluated by comparing its results with the thermal images obtained at three times during the diurnal cycle. During both daytime flights no obvious contrast is apparent among the three rock types; however, the predawn contrast is striking between the warmer dolomite and the cooler limestone and granite. These observations are consistent with results predicted by the thermal model.

Several additional improvements in the model have been made to include the effects of atmospheric transmission as a function of sun's altitude, cloud cover, atmospheric heating, and topographic slope.

Some generalized conclusions can be drawn from the model results. Predawn is the most appropriate time for flights in order to show maximum thermal inertia differences because then the thermal contrast is high (see figure 5) and the insolation effects are least (see figure 6). The pronounced influence of atmospheric heating effects on the diurnal temperature range is illustrated in figures 7 and 8. As expected, the greatest temperature contrast--and hence the greatest response to the rock parameters (albedo, thermal inertia), excluding vegetation and water content effects--occurs when the insolation is great (i.e., sun's declination is equal to the site latitude and clear-sky conditions) and the sky radiation is low (i.e., low day and night effective air temperatures). To examine this obvious consequence of the model a comprehensive overflight program was performed in June 1970 at Mill Creek, Oklahoma, through the auspices of the NASA Earth Resource Aircraft Office. Although some of the features of the limestone-dolomite contrast were observed, clearly (see figure 9) the most striking features of the predawn images are the relatively warm granite outcrops. This result is not consistent with the model results using the same thermal inertia and albedo values as in the initial study for the winter flight (see figure 10). It is tempting to speculate that the differences are due solely to the insolation changes. However our reliance on physical principles restricts us to the obvious conclusion that either the thermal inertia and albedos of the rock types have changed seasonally or some transient heating event occurred. Added credence is given to the latter explanation by the observation at the overflight time of a warm airmass moving into the area. A simple model of transient heating was constructed. If we assume, for discussion purposes, that the granite has a lower thermal inertia than the limestone, the model predicts that at predawn the granite would be warmer than both the dolomite and the limestone (see figure 11). The presence of a significant lichen cover over the granite outcrops is supporting evidence for a low thermal inertia for this granite.

Summary

Remote sensing techniques provide a means to explore for new resources and to identify the sources of environmental destruction. An extensive variety of platforms, detectors, and data analysis techniques is available but the most important ingredient is the ability to apply previous experience in the correct interpretation of new observations. An effective approach to this problem is the geophysical method which relies on observation of simple areas, analyzed in terms of simple mathematical models based on scientific principles. Increasingly complex models and sites can thus be examined in a systematic manner.

Results obtained through the NASA Earth Resources Aircraft Program at Mill Creek, Oklahoma, provide a case history example of the application of remote sensing to the identification of geologic rock units. Thermal-infrared images are interpreted by means of a sequence of models of increasing complexity. The roles of various parameters are examined: rock properties (thermal inertia, albedo, emissivity), site location (latitude), season (sun's declination), atmospheric effects (cloud cover, transmission, air temperature), and topographic orientation (slope, azimuth).

The results obtained at this site also illustrate the development of an important application of remote sensing in geologic identification. Relatively pure limestones and dolomites of the Mill Creek test area can be differentiated in nighttime infrared images, and facies changes between them can be detected along and across strike. The predominance on the Earth's surface of sedimentary rocks, of which limestone and dolomite are major members, indicates the importance of this discrimination.

References

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Figure 1. An aerial photograph of the Mill Creek test site showing the major rock units; L-limestone, D-dolomite, G-granite. The Regan fault and a minor fault to the south are indicated with an F. North is at the top of the photograph.

Figure 2. A predawn thermal infrared image of the Mill Creek test site (Dec. 1968). It can be directly compared with the aerial photograph of the same area shown in figure 1. Geometric distortions at the sides of the image are due to the perspective of a line scanner. Note that the dolomite is warmer than the limestone and that the granite is somewhat intermediate.

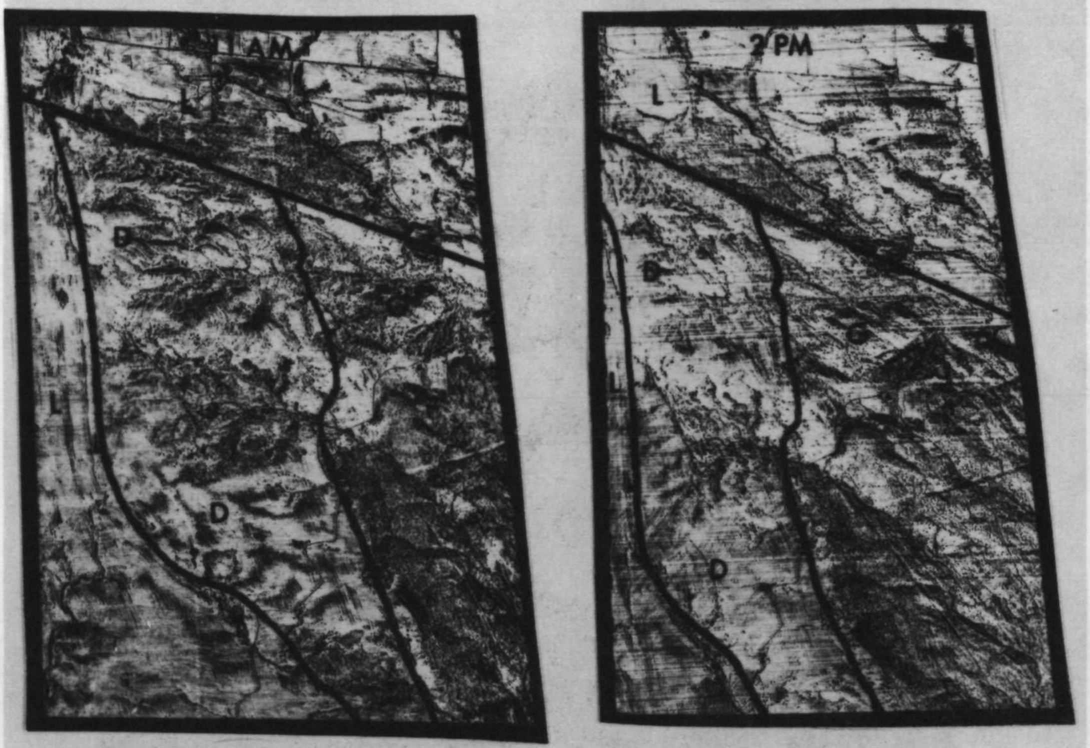

Figure 3. Two daytime thermal infrared images of the Mill Creek test site obtained at 11:00 A.M. (left) and 2:00 P.M. (right). Comparison with figure 2 illustrates that the limestone and dolomite are indistinguishable from each other. Lineaments (which coincide for the most part with joint systems) are more obvious in the infrared images than in aerial photographs. Lineaments striking northwest are preferentially enhanced in the 11:00 A.M. image (see region near left-hand L) and lineaments striking northeast are preferentially shown in 2:00 P.M. image (see region near bottom D).

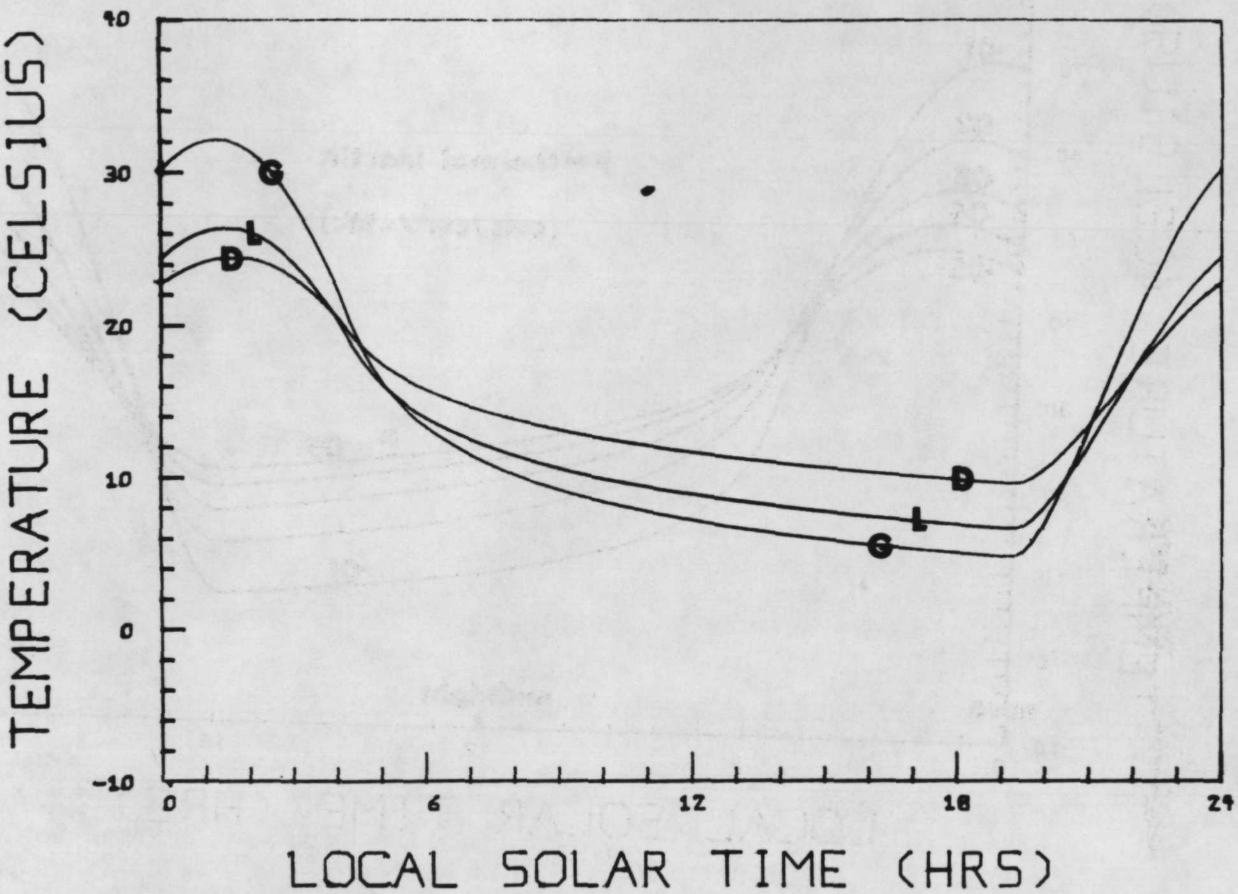

Figure 4. The computed surface temperature variation with time for a single diurnal heating cycle in December for three materials; L-limestone, D-dolomite, G-granite. Values for the thermal inertia and albedo were determined from published data, field measurements, and qualitative examination of the photographs. The model results are in qualitative agreement with the thermal images shown in figures 2 and 3. Noon is at 0 hours and midnight is at 12 hours local solar time.

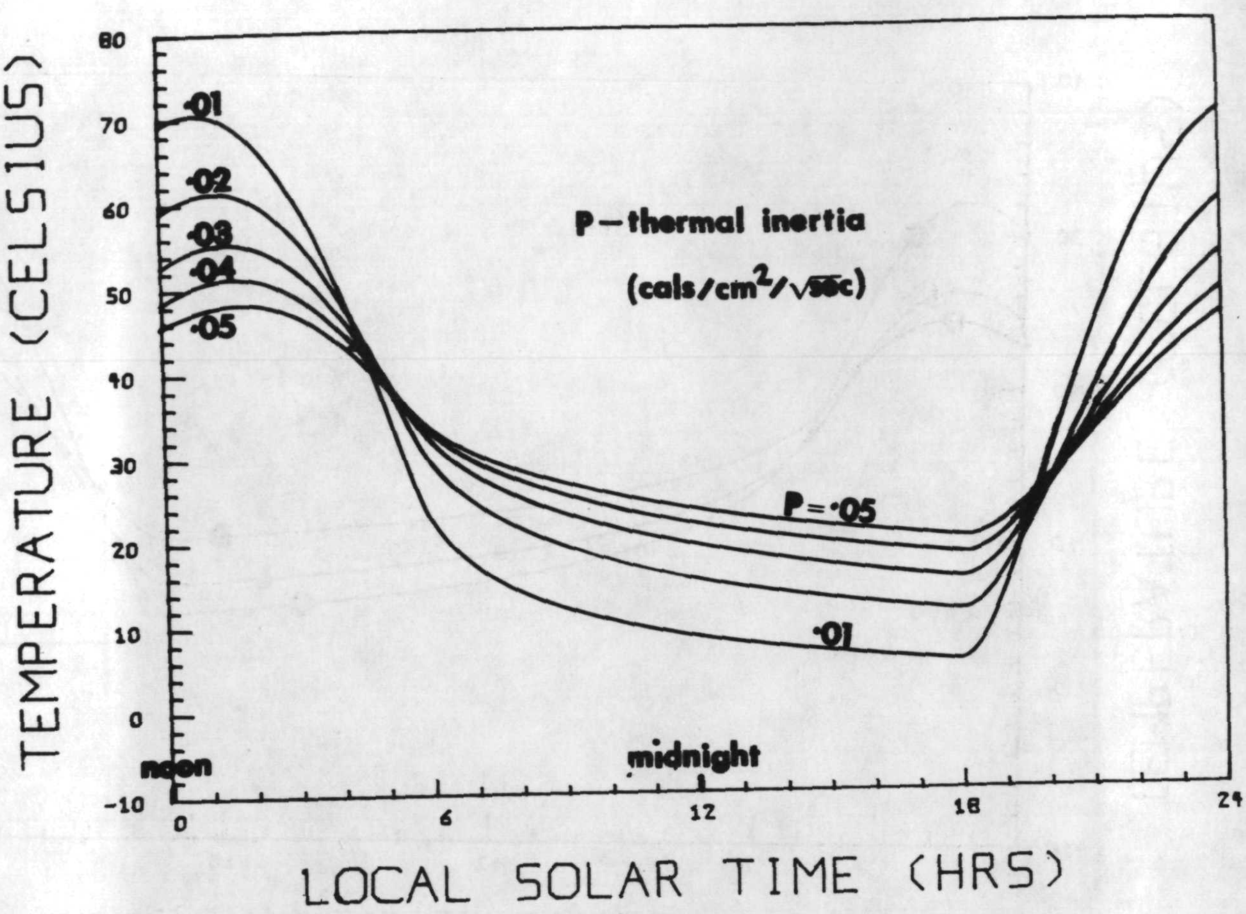

Figure 5. The computed surface temperature variation with time for materials with various thermal inertias. Note that materials with high thermal inertias go through a smaller temperature change from day to night than materials with low thermal inertias.

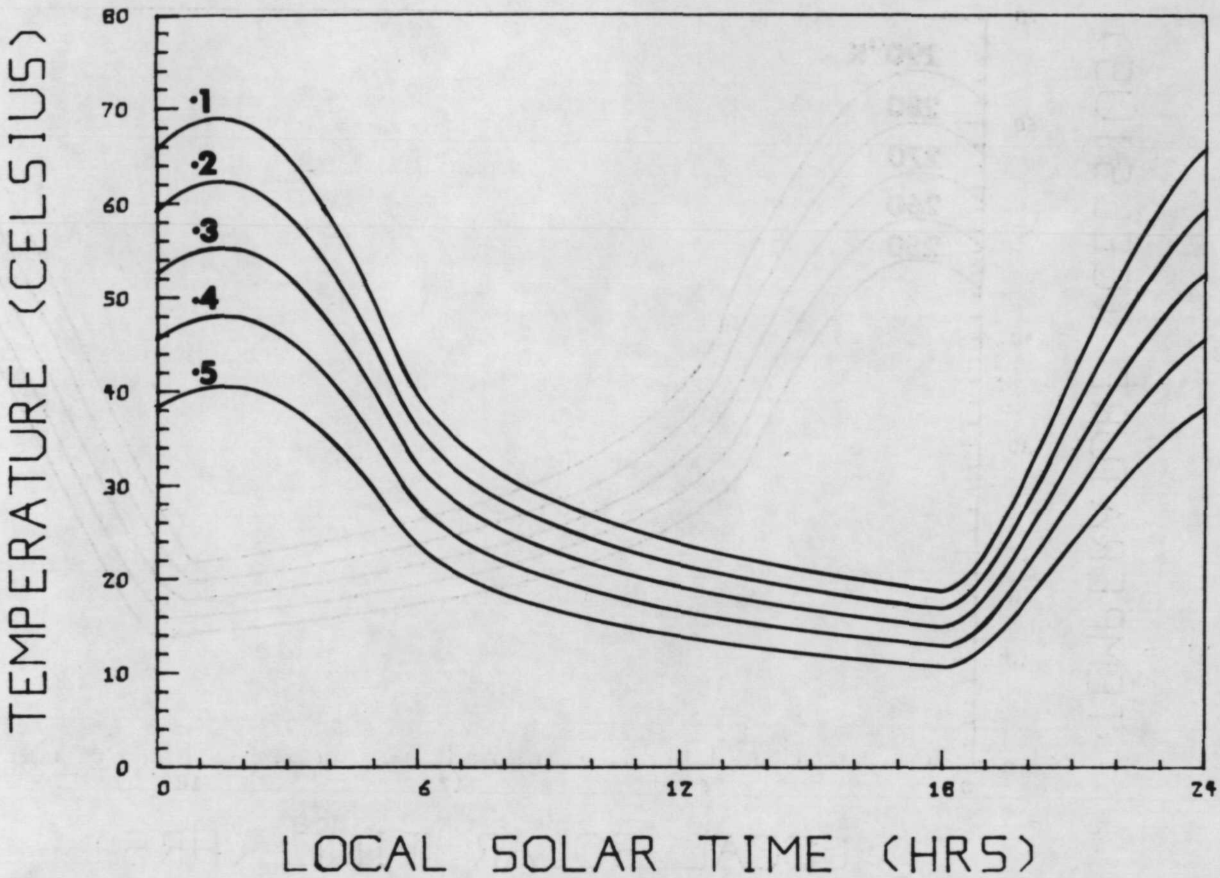

Figure 6. The computed surface temperature variation with time for materials with various albedos. Note that the temperature contrast between materials of different albedos is greatest during the daytime and least at dawn. Noon and midnight are as shown in figure 5.

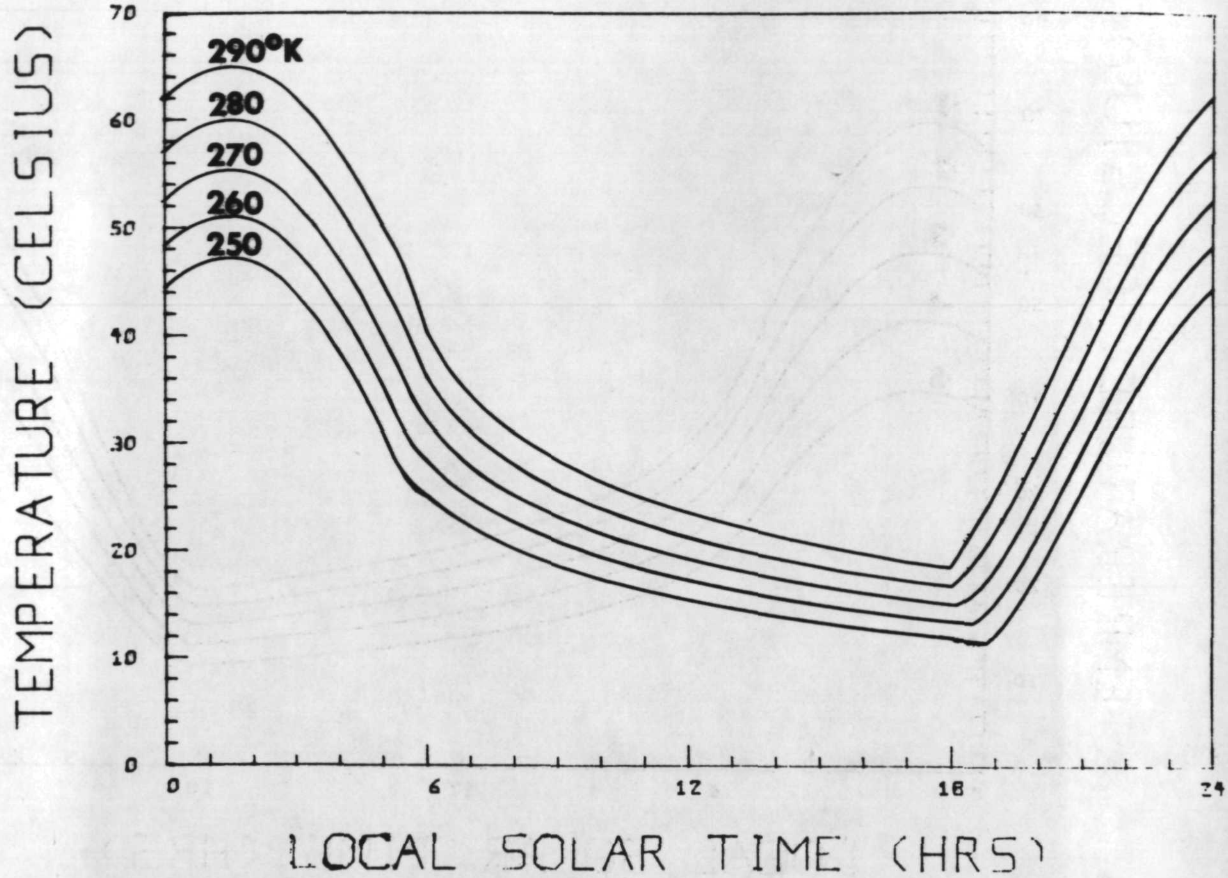

Figure 7. The computed surface temperature variation with time for daytime atmospheric heating of the ground.

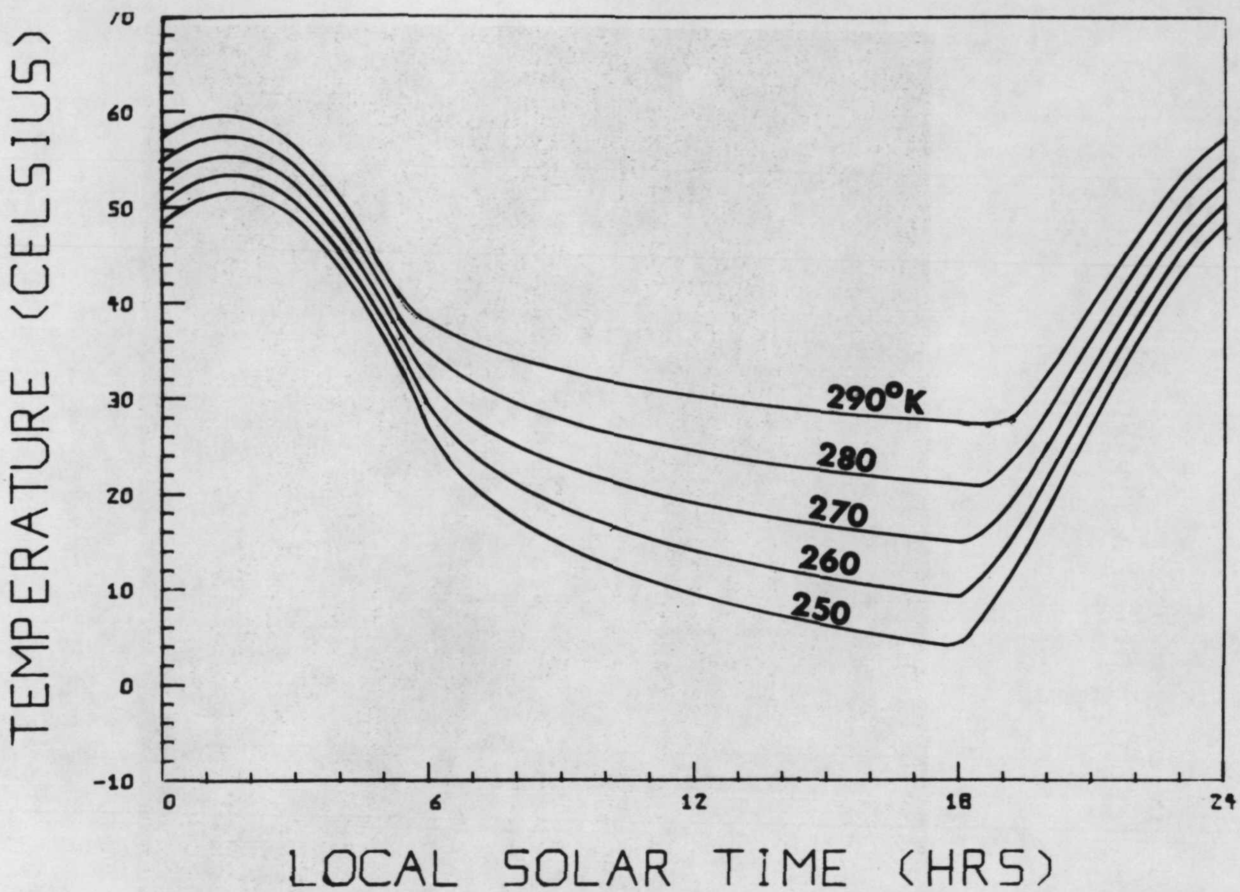

Figure 8. The computed surface temperature variation with time for nighttime atmospheric heating of the ground.

Figure 9. A predawn thermal infrared image of the Mill Creek test site (June, 1970). Contrast with the Dec. 8, 1968, results in figure 2. The most striking features are the relatively warm granite outcrops (G) in the June image. L, limestone; D, dolomite.

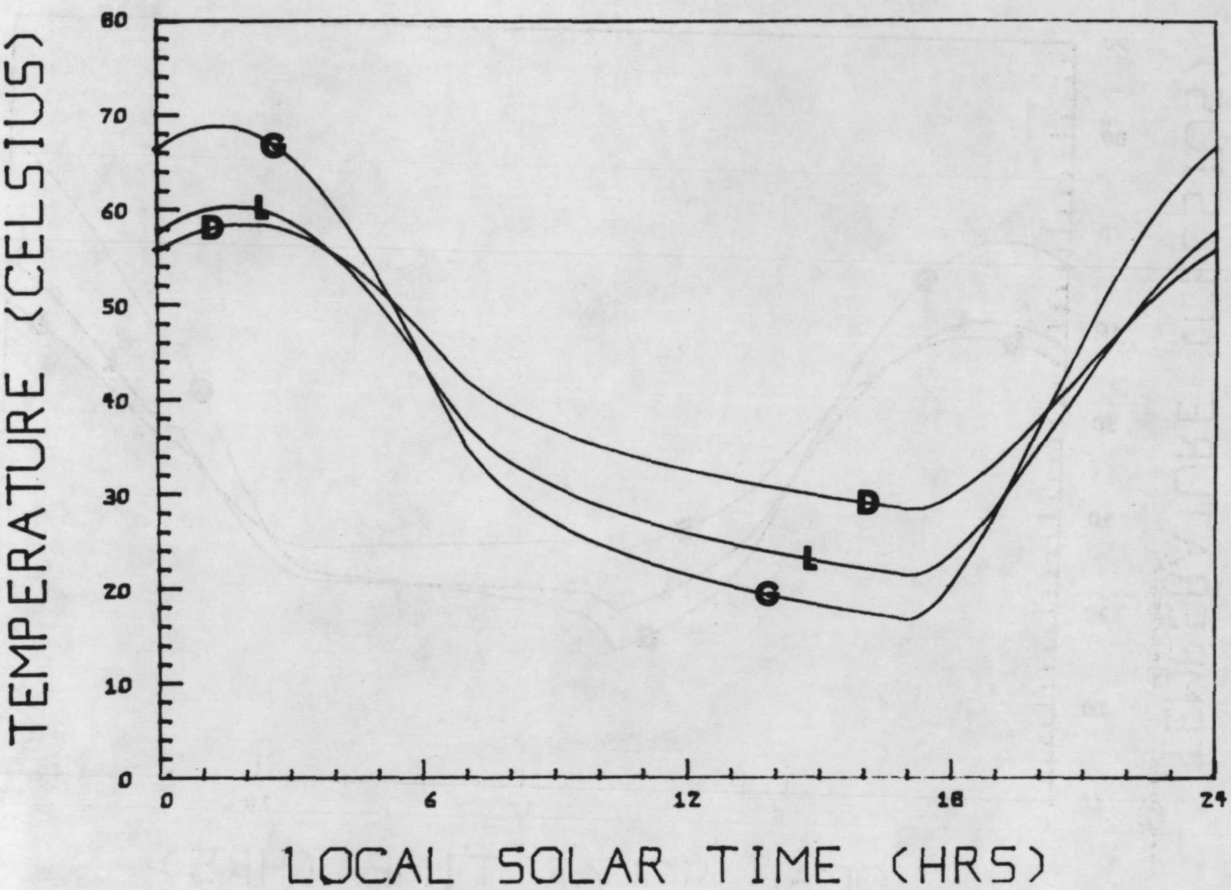

Figure 10. The computed surface temperature variation with time for a single diurnal heating cycle in June for the three materials: L, limestone; D, dolomite; G, granite. Compare with figure 4 to see the effects of the increased insolation during the summer flight.

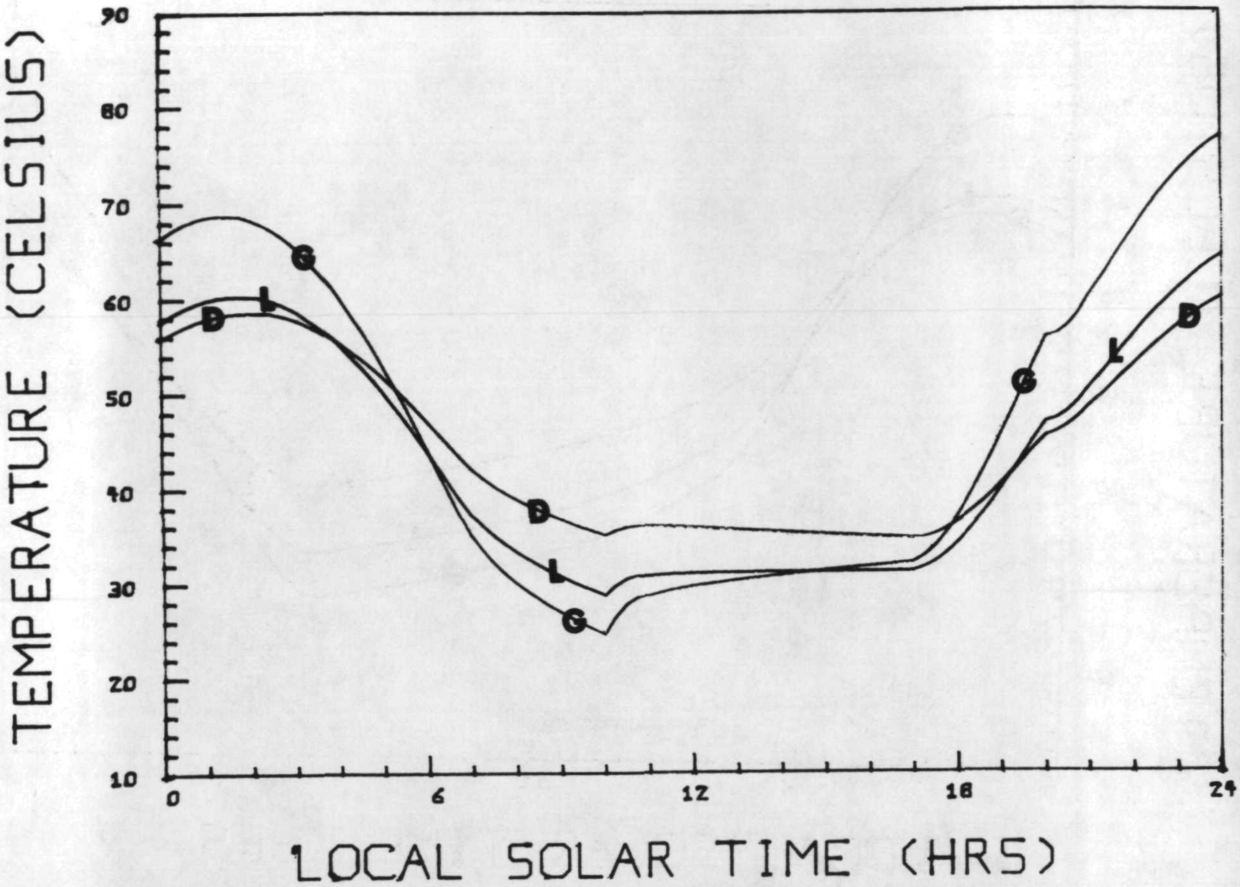

Figure 11. The computed surface temperature variation with time as in figure 10 but modified for impulsive heating at 10 hours local solar time which coincides approximately with the entry of warm air into the test site. Note that near dawn the granite (G), because of its low thermal inertia, is warmer than the dolomite (D) and limestone (L).