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TERRAIN THERMAL MODELING FOR CAMOUFLAGE AND TARGET ACQUISITION, (U)
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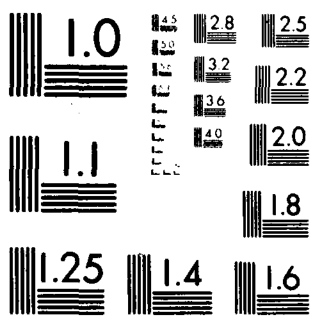

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TERRAIN THERMAL MODELING FOR CAMOUFLAGE AND TARGET ACQUISITION

JUN 1980

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INTRODUCTION

Camouflage and target acquisition have opposing functions, one to hide and the other to seek. They have a common denominator, however, in that the features that surround the target to be camouflaged or identified (sometimes called the background) are critical in both the hide and seek role. An equally intimate knowledge is needed of the characteristics of both the target and the background. In essence, making something match the background and discriminating something from the background are inverse problems that require the same technology.

In the past decade thermal infrared (IR) technology has come of age providing sensors with new capabilities for target acquisition and presenting a new threat for camouflage. Optimizing IR sensors for target acquisition or optimizing camouflage measures to defeat such sensors requires a quantitative understanding of the thermal IR signatures of both targets and backgrounds.

The Army-Wide Ground Target Signature Program (AWGTSP) is addressing the need for a target-background design data base for sensor design and evaluation through a three-part program: development of a battlefield IR signature model that will allow extrapolations of target and background signatures to varying environmental, climatic, and seasonal conditions throughout the world; updating a tactical signature library to fill critical gaps in the existing empirical signature data base; and susceptibility analyses designed to ensure that vulnerability of Army tactical materiel is known so that effective camouflage can be brought to bear. An equally important problem is the camouflage of key elements at fixed installations for which similar background information is needed.

Work on the AWGTSP has resulted in considerable progress in computer codes for prediction of the performance of surveillance, target acquisition, and terminal homing devices and prediction of target signatures. The target models have ranged from simple to complex, the more sophisticated approaches using combinatorial geometry. To date, targets have received considerably more attention than background; a compatible and equally capable background modeling capability is needed.

OBJECTIVES AND APPROACH

The study described herein was designed to generate a capability to realistically predict the temperature histories of natural and cultural features that commonly comprise the backgrounds to targets. With such a capability, it would be possible to examine the temperature contrasts that occur between targets and background features both with time and changing weather conditions. This in turn provides basic information needed to examine the performance of existing or proposed target acquisition devices and the effectiveness of alternative camouflage measures.

In the following paragraphs, two temperature prediction models are presented, one for terrain surface features and one for vegetation canopies. The terrain surface model was developed at the U. S. Army Engineer Waterways Experiment Station (WES), while the vegetation canopy model was developed at the Colorado State University under contract to WES. A brief description is given of each model followed by a discussion of model sensitivities and sample applications.

TERRAIN SURFACE TEMPERATURE MODEL

Philosophy

The Terrain Surface Temperature Model (TSTM) was developed to estimate the temperatures of actual or hypothetical material systems and for actual or hypothetical weather conditions. A premium was placed on simplicity and flexibility with respect to operational constraints. In short, a model was needed that considered the dominant physical phenomena that influence material temperatures and yet be reasonable to use. The model handles sensible heat transfer, latent heat transfer, the impact of cloud type and cover, and seasonal/geothermal heat fluxes. A brief description of the model framework is given in the next section; a complete description is available in Reference 1.

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Mathematical Framework

The model predicts surface temperatures for a multilayered (1-6 layers) system by determining energy transfer in, out, and through the system. The model assumes that the major energy fluxes are vertical (i.e., perpendicular to the layers) and that the layers are horizontally uniform. Temperature estimates result from solving the one-dimensional heat transfer equation:

$$\alpha^{2} \frac{T(z, t)}{\alpha z^{2}} = \alpha(z) \frac{\alpha T(z, t)}{\alpha t}$$

subject to the boundary conditions

$$\sum_{i=1}^{n} b_{it} = o \quad \text{at} \quad z = 0 \; ; \qquad \sum_{i=1}^{n} B_{it} = o \quad \text{at} \quad a\ z=B$$

where the observable surface is $z=0$; the lower surface is $z=B$; $\alpha(z)$ is the diffusivity; and both b_{it} and B_{it}, $i=1, 2, \ldots n$, denote heat fluxes at time t. An example geometry is shown in Figure 1. Within a layer, a simple explicit finite-difference technique is used, while at boundaries and interfaces a Newton-Raphson iteration scheme is applied.

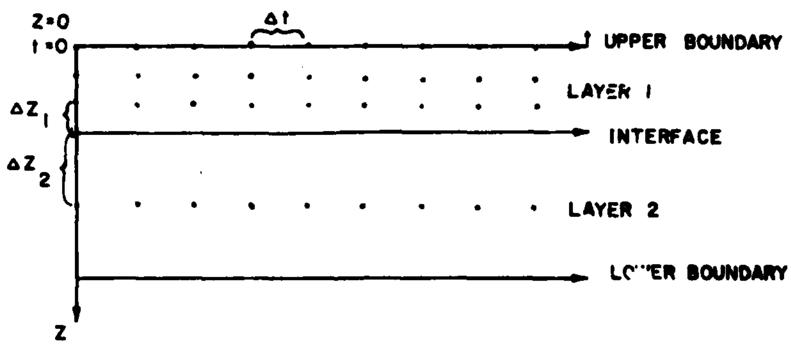

Figure 1. Sample layer geometry for TSTM

The surface boundary condition is estimated with the following heat balance equation:

$$S + I\downarrow - H - E - I\uparrow + G = 0$$

where

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S = solar insolation
I↓ = radiant energy from the atmosphere and clouds
H = sensible heat
E = latent heat
I↑ = radiant energy emitted by the top surface
G = heat conduction into the material

Solar insolation can be input as measured values or estimated using a procedure that was adapted by Balick (1) from the work of Small (2) and Sellers (3).

The Brunt equation (3) is used to estimate radiant energy from the atmosphere. Cloud contributions are treated with an empirical factor adapted from Geiger (4), and both cloud type and the amount of cloud cover are considered. Ground radiation energy loss is treated using conventional grey body emitter theory. Sensible heat loss is estimated by an equation following Lamb (5) that provides the operational advantage of not requiring roughness characteristics for the surfaces being modeled. Latent heat loss is modeled after Lamb (5) with the addition of a saturation factor which allows dry to saturated moisture conditions on the surface.

The bottom boundary can be described with three options: a constant temperature; a constant heat flux or a constant heat flux with an airspace below the bottom boundary; and an additional constant radiating surface below the airspace.

Model Inputs

Inputs to the model include atmospheric constants, atmospheric hourly data, surface-sun orientation, initial temperature profile, and material properties. Atmospheric constants required are atmospheric pressure (mb), dust content (particles cm^{-3}), precipitable water (mm), wind speed (m sec^{-1}), cloud type index and meteorological instrument shelter height above the surface (cm). The shelter height value represents the height above the ground that air temperature and wind speed are measured.

Atmospheric hourly data required for the 24-hour diurnal cycle forecast include air temperature (^{o}C), relative humidity (%), cloud cover (tenths, 0.0 - 1.0), wind speed (m sec^{-1}), and total insolation (cal cm^{-2} min^{-1}). Solar insolation can also be computed as previously mentioned.

Material properties are needed for the surface and each of the layers. Surface properties required are thermal emissivity, optical absorptivity, and percent saturation of the surface. Each layer is defined by its thickness (cm), thermal diffusivity (cm^2 min^{-1}), and thermal conductivity (cal min^{-1} cm^{-1} $^{o}K^{-1}$).

Model Output

The principal model output is the temperature of the surface with time. Any time step could conceivably be used; however, 15 to 60 minutes appears to be the most useable range. Input or computed values of solar insolation, energy absorbed, atmospheric IR emission, surface convection, and evaporative heat loss are printed out to assist in evaluating the predicted temperature data.

Parameter Sensitivity and Example Output

A sensitivity analysis was accomplished to examine model output behavior with systematic changes in model inputs. A study of the results showed that the model output was by far most sensitive to air temperature. Other parameters that when changed created significant changes in the output included the conductivity and emissivity of the surface layer, cloud cover, and surface absorptivity. Changes in conductivity and emissivity equally affected daily minimum and maximum temperatures as did changing cloud cover type, while changes in absorptivity affected the daily maximum temperatures much more severely than the daily minimums.

The TSTM has been validated using weather data from various locations in the United States and the Federal Republic of Germany (FRG). Figure 2 shows a comparison of predicted and measured temperatures for a 15-cm-thick concrete pad. The concrete pad was modeled as a two-layer system with the pad underlain by a 700-cm layer of soil. The measured data were obtained with a thermistor

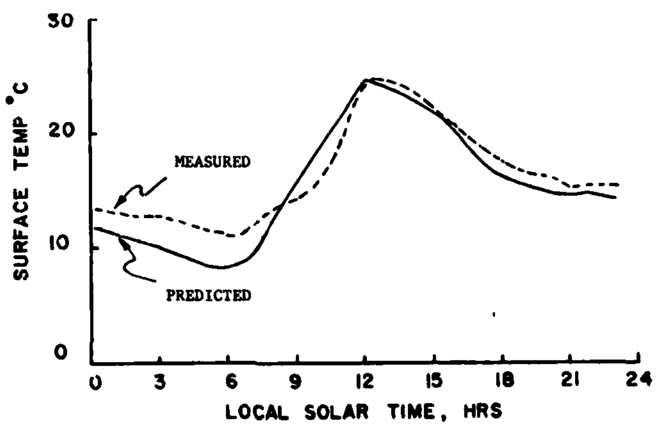

Figure 2. Predicted and measured surface temperatures for a 15-cm-thick concrete pad, 4 Oct 1979, in Federal Republic of Germany

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attached directly to the surface of the concrete pad. The agreement between the predicted and measured curves in the figure is quite good, especially between about 0800 and 2400 hours. The difference in the curves from approximately 0-time to 0800 hours could have resulted from an inaccurate estimate of the concrete conductivity (no measured values were available) or increased cloud cover at night (cloud cover data were not available for the nighttime).

VEGETATION CANOPY THERMAL MODEL

Philosophy

The Vegetation Canopy Thermal Model (VCTM) was developed to approximate the thermal behavior of a layered vegetation canopy by a mathematical abstraction of the material and geometry characteristics of the canopy and the energy transfer mechanisms that occur there. The model is physically based and considers geometric arrangement of canopy elements, scattering of direct and emitted energy within the canopy, increased absorption of elements due to the thermal emissions of neighboring elements, and the directional variation of energy radiated from the canopy.

The vegetation canopy is abstracted as three statistically independent infinite horizontal layers as illustrated in Figure 3. Within each layer, the leaves, branches, and other canopy elements are described as a statistical ensemble giving their orientations and number densities. An energy budget equation is formulated for each layer that accounts for inflow and outflow of energy. The roots of the resulting system of equations are the average surface temperatures in the layers.

The VCTM assumes steady-state conditions. Time-dependent events are modeled by incremental changes in steady-state energy flow. Spectral structure in the thermal wavelengths is not considered and scattering of thermal energy within the canopy is neglected. In addition, individual canopy elements are considered to radiate thermal energy in an isotropic manner. A detailed discussion of the VCTM is given in Reference 6.

Mathematical Framework

The mathematical framework for the VCTM is designed to handle individually the effects of canopy geometry, thermal radiation transfers, solar radiation absorption, thermal existance, transpiration, and convection. The values computed from these operations allow calculation of the total energy budget for each canopy layer and the thermal existance from the canopy.

The most important aspect of canopy geometry for describing radiation transfer is the frequency of gaps in the canopy and the extinction of radiation within the canopy. To compute gap frequency

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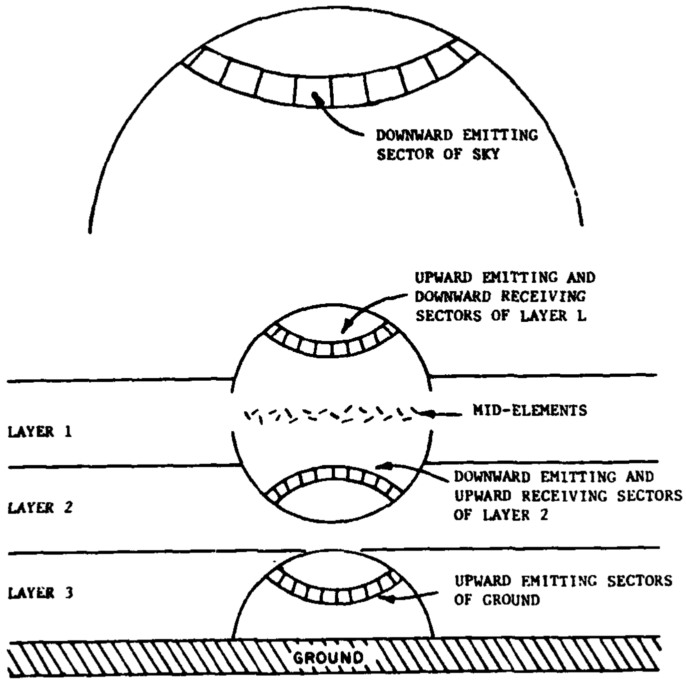

Figure 3. Abstraction of VCTM showing canopy layers, sky, ground, and hemispherical sector concept for computing energy transfer

and extinction, the hemispheres above and below a canopy layer are discretized into 9 hemispherical inclination bands. Each of these bands are further discretized into 18 azimuthal sections (see Figure 3). The radiation transfers between the three canopy layers, the ground, and the sky are calculated within each sector. An in-depth discussion of the theory involved is given in Reference 7.

Thermal radiation transfer is handled by allowing each layer to emit and receive thermal radiation in the hemisphere occurring above and below it. The computations are first made for a component in the middle of a layer, termed the mid-element. The equation that calculates for a particular sector, the flux density absorbed by a mid-element at a particular inclination angle from any given source layer $\frac{\Phi_{ijklm}}{m^2}$ is

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$$\frac{\phi_{ijk\iota m}}{m^2} = \sigma \cdot \varepsilon_\iota \cdot T_\iota^{\,4} \cdot CONT_{j\iota m} \cdot SECTOR_j \cdot ABSORB_m \cdot COS_{ijk}$$

where:

σ = Stefan-Boltzmann constant

ε_ι = average emissivity of elements in layer ι

T_ι = true average surface temperature (^{o}K) of the mid-elements in layer ι (unknown)

$CONT_{j\iota m}$ = contributing coefficient for mid-elements in layer m absorbing flux from elements in layer ι for all sectors within hemispherical band j

$ABSORB_m$ = average thermal absorption coefficient for elements in layer m

$SECTOR_j$ = quantity $(\sin \Theta_2 - \sin \Theta_1)/9$ defining the inclination limits of sector i in hemispherical band j

Within source sector i in hemispherical band j, $\frac{\phi_{ijk\iota m}}{m^2}$ is the thermal flux density absorbed by a mid-element in layer m inclined at inclination angle k from source elements in layer ι represents the sky and ground in addition to the three canopy layers.

The total flux density emitted by elements in layer ι and absorbed by a particular mid-element in layer m at an inclination k is computed by summing the product $CONT_{j\iota m} \cdot SECTOR_j$ over j (from 1 to 9) and COS_{ijk} over i (from 1 to 18). The total flux density absorbed by a mid-element in layer m at inclination k is computed by summing all sources

$$\frac{\phi_{km}}{m^2} = \sum_{\iota=1}^{5} \frac{\phi_{k\iota m}}{m^2}$$

where ι = 1, 2, 3, 4, 5 represents the sky, layer 1, layer 2, layer 3, and the ground, respectively. Nine equations for each layer are constructed. For each layer the appropriate equation is weighted by the frequency of occurrence of elements within the corresponding inclination class. The nine equations are summed to compute the average absorbed thermal flux density within the three canopy layers.

Solar radiation absorption is handled using a stochastic model, Solar Radiation Vegetation Canopy Model (SRVC), developed at the

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Colorado State University (7). The SRVC predicts the diurnal apparent directional reflectance of a vegetation canopy and allows realistic consideration of the complex scattering and absorption of light as a function of canopy geometry. The thermal exitance of all canopy mid-elements and the ground is calculated by the Stefan-Boltzmann Law.

Transpiration is handled using a relation developed by Gates (8). The driving force is the difference between water vapor density within the leaf and in the free atmosphere beyond the boundary layer. Physically based formulas are available to compute the necessary parameters with the exception of leaf resistance to water vapor diffusion.

The convection equation developed by Tibbals et al. (9) is used to describe forced convection. Sky thermal exitance is calculated using an empirical equation dependent only on air temperature near the ground surface.

The pieces for computing the total energy budget for each canopy layer have not been described. These relations result in a system of three nonlinear equations and three unknowns. A least quadratic convergent numerical routine (10) is used to solve for the roots of the equations, the average temperature of the canopy layers. The model also predicts the effective radiant temperature (ERT) and equivalent thermal exitance in the nine viewing inclination bands at ten-degree intervals above the canopy. The contributions of each canopy layer and the ground are considered in the calculation. The ERT for a sensor looking horizontally into the canopy is also predicted using the Stefan-Boltzmann Law with appropriate emissivity and average layer temperature values.

Model Inputs

Inputs to the model include environmental factors, canopy geometry descriptors, and thermal and optical properties of canopy components. The environmental factors are entered on an hourly basis; all other parameters are considered static.

Environmental factors required are air temperature (within the canopy), ground temperature, relative humidity (within the canopy), wind velocity (within the canopy), and total incoming solar irradiance above the canopy.

Canopy geometry parameters include Leaf Area Index (LAI), Leaf Angle Distribution (LAD), Branch Area Index (BAI), and Branch Angle Distribution (BAD). The LAI is the total one-sided leaf area that occurs over a unit of ground area. Values can be measured or derived from the literature. The BAI is derived by measuring the length and width of tree limbs at various points in the canopy and using conical and cylindrical approximations. The values for LAD and BAD are obtained from photography using optical Fourier transform techniques. In practice, values for LAI, BAI, LAD, and BAD can be estimated from

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the literature although values for noncrop vegetation types are limited.

Inputs describing thermal properties of canopy and ground components are thermal absorption and emissivity and leaf resistance to water vapor diffusion. Optical properties needed are spectral absorption and transmission of leaves (or needles) and the spectral reflectance of the ground surface.

Model Outputs

The principal output of the model is the average temperature for each canopy layer and the ERT of the canopy as a function of view angle above the canopy for each time increment. In addition, values of ground thermal exitance, sky thermal exitance, absorbed solar flux density of each layer, thermal exitance of each layer, absorbed thermal flux of each layer, convectional exchange, and transpirational exchange are displayed in the output.

Parameter Sensitivity and Example Output

Sensitivity analysis were run to examine the impact of systematic changes in parameter values for both daytime and nighttime conditions. The data used were obtained at Leadville, Colorado, on 15 and 16 July 1977.

Results of the sensitivity analysis showed the following:

a. Within a reasonable range (0.96 - 1.00), changes in emissivity did not significantly change the average layer temperature (less than 1-deg change).

b. Within a range of 0.3 - 1.2 min cm^{-1}, a change in leaf resistance to water vapor diffusion had only a small impact on average layer temperature. At lower values, such as 0.15 min cm^{-1}, which may be appropriate for a full sun condition on a summer day for conifers, the model output becomes much more sensitive to this parameter.

c. A significant change in canopy geometry for lodgepole pine did not significantly impact the thermal radiation transfer within the canopy. However, canopy geometry did clearly affect the contribution of thermal radiation from each layer to the ERT above the canopy as a function of view angle.

d. Air temperature is the single most important parameter for predicting the average temperature of components in each layer.

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An example of the model output is shown in Figure 4. The example shows simulated average layer temperatures for a lodgepole pine using environmental data obtained in Leadville, Colorado, on 15 and 16 July 1977. The simulated values are compared to radiometric temperature measurements obtained with a hand-held radiometer. Additional outputs are available for Douglas fir and oak-hickory canopies.

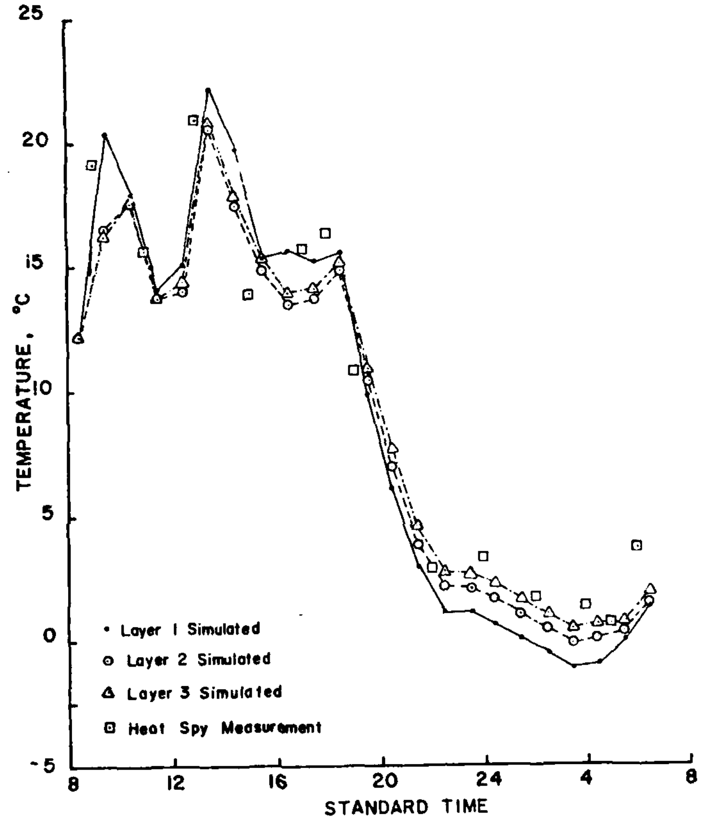

Figure 4. Simulated and measured (radiometric) temperatures for lodgepole pine for 15-16 Jul 1977 in Leadville, Colorado (horizontal perspective of canopy)

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MODEL APPLICATIONS

Models such as the TSTM and VCTM open new avenues to study target acquisition and camouflage problems. An initial concept and prototype products for a comprehensive data base-modeling capability for target acquisition sensor development and evaluation is presented by the author in reference 11. The concept includes a terrain and weather data base from which the basic inputs to the TSTM and VCTM can be formulated. The weather data and associated terrain input are used to compute the range of temperature expected for specific terrain features in a given season. Figure 5 shows an example generated for a grassy area in Fulda, FRG, for the summer season. Curves, such as those shown in Figure 5, can be compared with similar forecasts or measured data on targets to determine under what conditions and time-of-day the target will contrast most with the background.

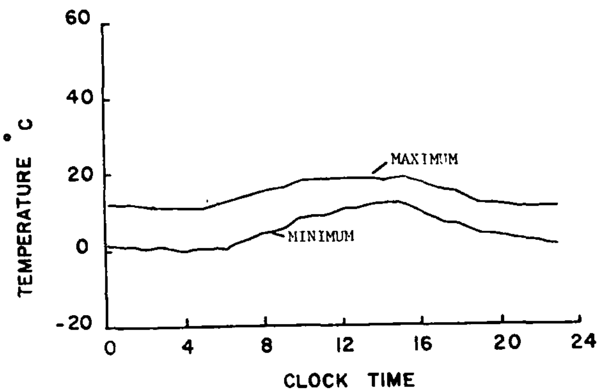

Figure 5. Example of output of VCTM for grass in the Fulda, FRG, area. The curves define the range of temperatures that the grass is likely to experience during summer conditions

Thermal models have a valuable place in developing fixed-installation camouflage design criteria. Figure 6 illustrates how the TSTM has been used to study the effectiveness of alternative camouflage measures in reducing temperature of key targets on fixed facilities. In the example, the impact of painting a roof surface with solar-reflecting paint is demonstrated.

More complex applications of the TSTM and VCTM are also ongoing. The WES is directing a NATO thermal camouflage field trial in the FRG.

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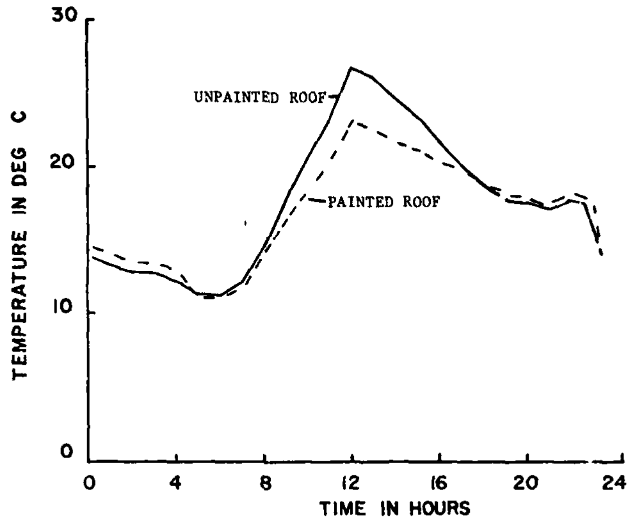

Figure 6. Use of TSTM to examine effectiveness of solar-reflecting paint for camouflage of fixed installations

In this experiment, the above models are being used in conjunction with image transformation techniques to study the effectiveness of alternative camouflage measures. Thermal images, obtained by ground-based and airborne sensors and showing key facilities at a military base as they appear uncamouflaged, are transformed to illustrate how they would appear with alternative camouflage measures and under different time and weather conditions.

CONCLUSIONS

The models presented herein represent a new dimension in the quantitative consideration of background features for target acquisition and camouflage applications. The model inputs include environmental factors that are for the most part available at recording meteorological stations and geometry and material properties that can be measured or derived from the literature. A gap exists in specific geometric descriptors for vegetation canopies; however, emphasis is being placed on generating the needed data.

Although the TSTM and VCTM are one-dimensional models, they can be used to realistically examine background features in a variety of situations. Finite-element methods are being examined to handle vertical walls, and a three-dimensional vegetation model has been

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initiated under a U. S. Army Research Office grant to handle sophisticated open canopy vegetation conditions.

Current applications of the models emphasize development of criteria for thermal camouflage of fixed installations. The thermal models provide a major advantage in this effort because the potential effectiveness of alternative camouflage measures can be judged before expensive field applications.

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