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Modeling the thermal signature of natural backgrounds

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ABSTRACT

Two measuring stations have been established - the purpose being to collect comprehensive databases of thermal signatures of background elements in addition to the prevailing meteorological conditions. The databases have primarily been used as a foundation for the development and validation of models for the simulation of thermal signature.

The stations consist of a calibrated thermal camera for radiometric measurements, as well as a number of meteorological sensors - i.e. sensors for recording relevant parameters that influence thermal signature. Both stations are remotely controlled via telephone lines and it is possible to transfer the collected data from the stations.

At each measuring site 3-4 thermal images are automatically recorded every 15 minutes and every 5 minutes over 50 meteorological measurements are performed. The stations have been operating successfully over long periods of time and they have delivered reliable meteorological information and radiometric data.

Using this data models for simulation of thermal signatures for natural backgrounds have been developed. In addition the measurements have been used for the verification of a model for vehicles. The background signature model is based on plain one-dimensional heat-flow equations. Applied to three different types of background elements, the RMS-deviations from measured temperatures appear to be less than 1.7 K for periods of several days.

INTRODUCTION

Previous work done at FFI has revealed a need to be able to correctly assess the effectiveness of thermal signature reduction measures [1]. The effect of these measures will depend on the thermal signature of the background. In order to be able to make such assessments it is necessary to know how the thermal signature of the background varies with factors such as type of terrain, weather, time of the year etc.

FFI-project 775 had as its purpose to establish comprehensive databases of meteorological data and thermal imagery, through the establishment of autonomous measuring stations [2, 3]. The databases were to be used for calibration and verification of two thermal models: One model for natural backgrounds, developed at FFI, and one model for vehicles. This paper describes the measuring stations, and the model for predicting thermal background signature.

MEASURING STATIONS

Measuring Sites

In order that the databases be as comprehensive as possible it was necessary with diverse meteorological conditions. Therefore three different measuring sites were chosen: Bardufoss, Ørland and Rygge. These sites are located in the north,

west and south east of Norway respectively. The geographical location and height above sea level of the three sites as well as their expected weather type is summarized in table 1.

Table 1: Measuring sites with expected type of weather

Measuring site	Location and height	Weather type
Bardufoss	69° 3'N, 18° 34'E, 100 m	Cold winter, polar night and short warm summer with midnight sun
Ørland	63° 43'N, 9° 38'E, 20 m	Wet and very windy winter
Rygge	59° 24'N, 10° 43'E, 55 m	Warm, dry summer

All the measuring sites are located at military air bases. This provides the necessary security to avoid tampering with the stations. It also provides a certain infrastructure, with electricity and phone lines available, even though the stations are situated close to uninhabited natural terrain. The air stations are located close to public weather stations, giving the opportunity to verify our own meteorological data against that of the public stations.

It was also important that a wide variety of background types were available at the sites, to be able to model several types of terrain. The sites chosen fulfil this need, containing coniferous and deciduous trees, scrub, heather, rocks, gravel roads, grass etc.

Camera system for radiometric measurements

The measuring stations consist of two separate systems. One system is a housing containing two cameras: An infrared camera and an optical camera. The other system consists of a data logger connected to several meteorological sensors.

The cameras are mounted together in a metal housing, which again is mounted on top of a 5-meter tall mast. The housing and the cameras are controlled automatically by a PC workstation. This is done with software developed at FFI. The housing is enclosed, and opens a door in front of the cameras only when images are recorded. When the door opens a fan blows heated air out through the opening to prevent any precipitation or moisture from entering the housing. The housing is also heated to prevent freezing inside. A picture of the camera system can be seen in figure 1.

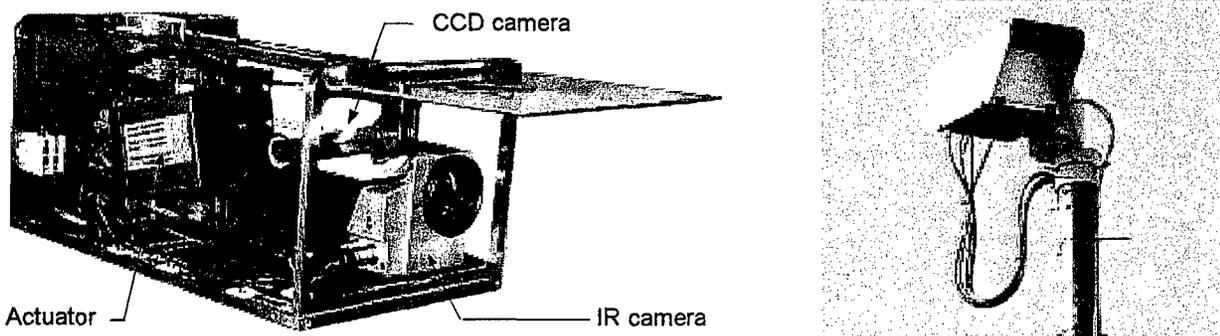


Figure 1: Camera housing without cover and with door open (left) and camera housing mounted on pan/tilt on top of the mast (right)

To be able to include as many different types of background elements as possible the field of view of the cameras is not fixed. The camera housing rests on a computer controlled Computar PT10 pan/tilt head. This pan/tilt can rotate and tilt the cameras, and thereby change their field of view. Operation of the pan/tilt is performed by the above-mentioned software.

Every 15 minutes this system records several visual and thermal images, and stores them on the hard drive of the controlling PC. The pan/tilt goes through a number of preset positions, and for each of them the cameras record images.

The distances from thermal camera to the scene is between 20 to 70 meters. At such short range the thermal transmission will not have a significant effect on the measurements except for during periods of dense precipitation.

Measuring Meteorological Parameters

The system for measuring meteorological parameters consists of several sensors connected to a Campbell Scientific CR10x data logger. Most of the sensors are placed among the background elements, and some have also been placed in a 5-meter tall mast. The mast is used for measuring wind direction and speed in addition to air temperature and humidity at two and five meter height. There are also four radiation sensors for measuring in- and out going radiation. A picture of the mast can be seen in Figure 2.

Sensors for measuring all parameters considered influential on thermal signature have been included: Air temperature and humidity, short wave (solar) irradiation, long wave (sky) irradiation, wind speed and direction, in addition to precipitation.

The logger takes measurements every 30 seconds. From calibration curves the data is then converted to normal units for temperature, wind speed etc. Every 5 minutes the logger stores an average of the last 10 measurements from each connected sensor in its internal memory.

Since the memory of the logger is restricted to data for only a few days it has been connected to the computer at the measuring site. It is possible to download the memory of the logger to the computer, thereby freeing logger memory.

Measuring Thermal Signatures

The measurement of thermal signature is based on the thermal images from the infrared camera. Two different types of cameras are used: FLIR Instruments ThermoCAM PM 595 and Agema Systems Thermovision 570. The two types have the exact same specifications: A spectral range from 7.5 to 13 μm , a field of view of 24° x 18°. Both cameras give images of 12-bit depth with a resolution of 320 x 240 pixels. The cameras are calibrated and have a thermal sensitivity of 0.1 K.

By averaging the pixels covering one background element the apparent temperature of that element can be found. Repeating this operation for several consecutive images gives the temperature variation over time. An illustration of this process is shown in figure 3.

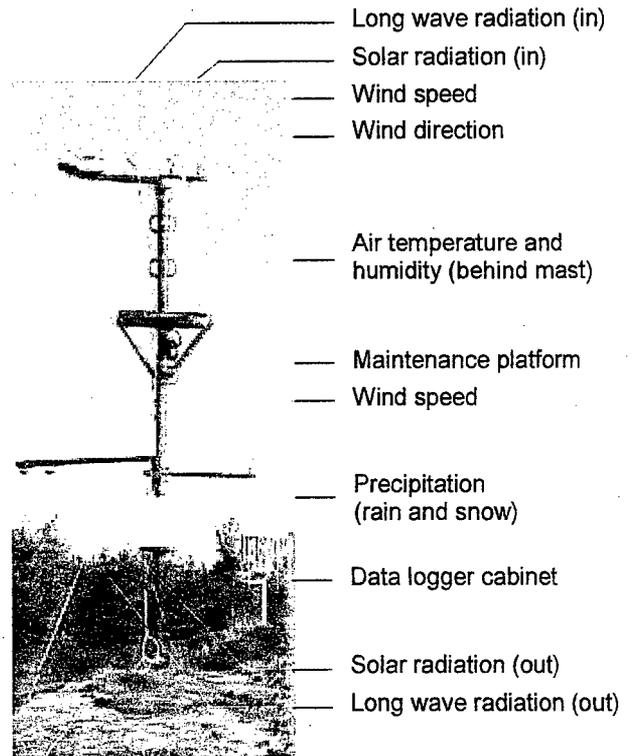


Figure 2: Mast with meteorological instruments. Precipitation sensor in background

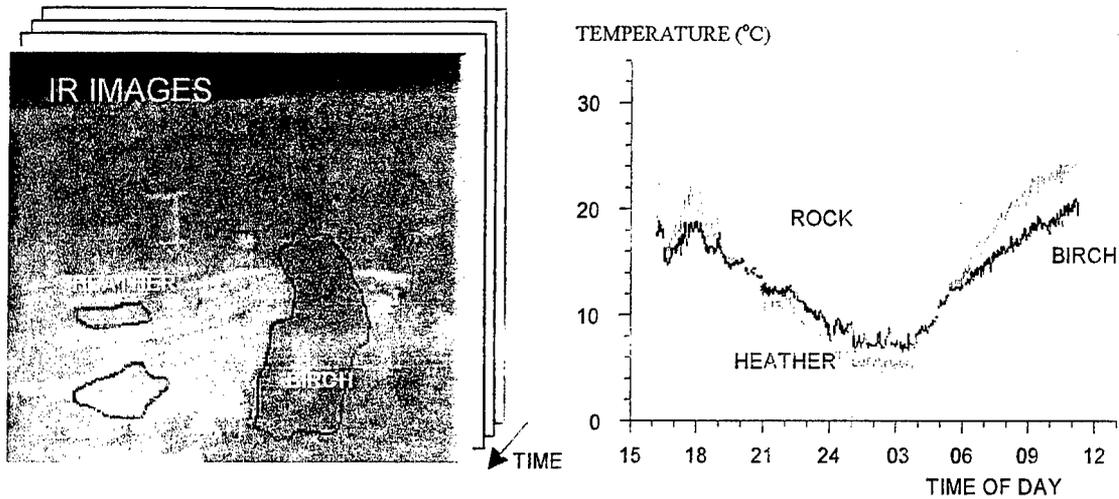


Figure 3: IR images used for studying temperature variation over time. The curves on the right are average temperatures from the background elements plotted versus time.

BACKGROUND MODELING

There have been developed several mathematical models to simulate thermal signature. Several of these models utilize very complex physical descriptions of the problem. Hence they require high computing power, advanced mathematical solutions and may require a long time to converge on a solution.

On FFI-project 775 it was decided to go with a simple solution due to the short time available. It was seen as desirable to limit the computing power needed for simulations to single workstations. A very promising model has been developed at FGAN-FOM, and the choice of model was based on the results from this model [4].

Description of the General Background Signature Model

The signature model presented in this paper is based on heat transfer from objects with only one surface exposed to the surroundings. To further simplify, it is modeled as a one-dimensional heat transfer. The background elements are divided into uniform layers, with only the top layer being exposed to the environment. All the other layers simply transfer heat through one-dimensional conduction. The mathematical equations that describe this process are presented in equation 1.

$$\begin{aligned}
 \frac{dT_s}{dt} &= \alpha \cdot W_{sun} + \varepsilon \cdot W_{sky} - \varepsilon \cdot \sigma \cdot T_s^4 && \text{Radiation} \\
 &- (\delta_1 + \delta_2 \cdot v_a) \cdot (T_s - T_a) && \text{Convection} \\
 &+ \rho \cdot (\delta_1 + \delta_2 \cdot v_a) \cdot (e(T_a, Rh) - e(T_s, 100\%)) && \text{Evaporation} \\
 &+ \kappa \cdot (T_1 - T_s) && \text{Conduction} \\
 \dots &&& \\
 \frac{dT_i}{dt} &= \kappa \cdot (T_{i+1} - 2 \cdot T_i + T_{i-1}) && \text{Conduction in} \\
 &&& \text{layer no. } i \\
 \dots &&& \\
 \frac{dT_n}{dt} &= \kappa \cdot (T_c - 2 \cdot T_n + T_{n-1}) && \text{Conduction in} \\
 &&& \text{layer no. } n
 \end{aligned}
 \tag{1}$$

In equation 1 α , ϵ , σ , ρ , κ , δ_1 and δ_2 are the parameters of the model, T_s is the surface temperature of the background element, T_a is the air temperature and T_i is the temperature of layer number i . T_c is the temperature of the lowest layer, and does not vary with time. The meteorological data required is W_{sun} , W_{sky} , v_a , T_a and Rh , which are the short and long wave irradiation, wind speed, air temperature and humidity respectively. $e(T_a, Rh)$ is the water vapour pressure given by the air temperature and humidity.

When the values for the parameters are known, the surface temperatures are calculated by converting the differential equations in equation 1 into difference equation of a certain time step. For each time step the temperature change is calculated and added to the temperature of the previous time step. The input required for this operation is a starting temperature profile, i.e. one temperature for each layer, as well as meteorological data for each time step. Thus a curve of surface temperature versus time is generated, based on certain values of the model parameters.

The fit of the model is calculated as the root mean square error, or the RMS error, between the model curve and the temperature for the relevant background element as extracted from the thermal images. Varying the parameter values until the RMS error is minimized results in the final estimation of the parameters.

Minimizing the RMS error is a trivial problem for linear functions. However this is not generally the case for differential equations. We have therefore used a combination of the simplex "downhill method", and the Levenberg-Marquardt method [5, 6].

General Edge-of-Forest model

This model is a general edge-of-forest model. It has been developed on the basis of both coniferous and deciduous trees and is therefore valid for most types of trees. However the model is less complex than the general model presented above.

In this model there is no conduction, as this factor will have a negligible effect on trees. In addition to this, the humidity measurements did not seem to have significant impact on the results, and therefore the humidity term was dropped to simplify further.

A plot of the edge-of-forest model together with actual measured temperatures as well as a best-fit curve appears in figure 4. The best-fit curve is a plot of the parameter values that gave the smallest RMS error for the days plotted. It gives very good results for the period shown, but does not perform as well as the general edge-of-forest model for other periods.

The general edge-of-forest model was developed on the basis of several 5-day sequences from a 9-month period. It has been plotted for the entire period of nine months. For this period it gave an RMS error of about 1.9 K. It is however not that difficult to get these results for the edge-of-forest, since foliage temperature has a tendency to follow that of the air quite closely.

The average difference between the edge-of-forest model and the measured temperatures has been plotted in figure 5. As can be seen from the plot the model accuracy degenerates rapidly below about 260 K. This can be explained by several factors. As the temperature drops below freezing, icing may affect the reflective properties of the trees. Also the phase changes back and forth between ice and water will absorb and liberate energy. In addition the fact that low temperatures will occur mostly during periods when there are no leaves on the deciduous trees will change their thermal properties. Finally there are fewer data containing low temperatures, meaning that the parameter estimation will weigh the lower temperatures less.

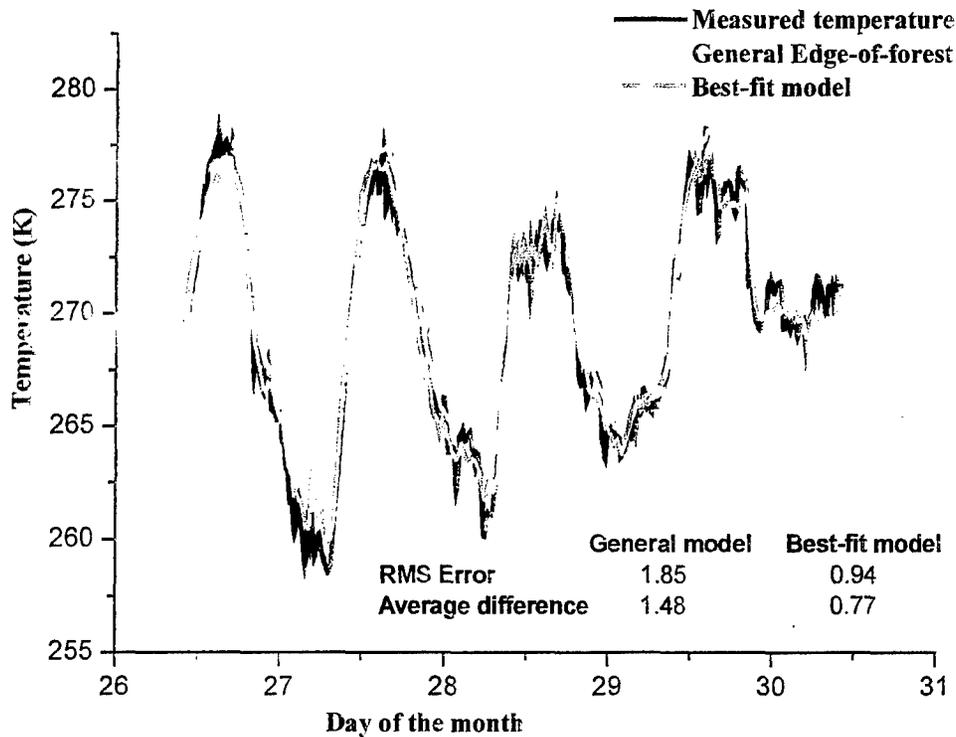


Figure 4: Plot of Edge-of-forest models for late March 2001, with values for average difference and RMS error inserted.

Rock model

Like the edge-of-forest model this model is a simplification of equation 1, since also here the air humidity has been excluded. Modeling of the rock has been tried both with and without the conduction terms. Without the conduction terms the model performs quite well for short periods of time. However, it does not perform as well when extended beyond a few days.

The conduction is modeled by dividing the rock into 20 layers vertically. The conduction coefficient is assumed to be equal between each layer. No assumptions are made about the thickness of the layers, other than that the lowest layer will be sufficiently deep to be at a constant temperature. This constant temperature was set to 277 K. The initial temperature of the 20 layers is simply a linear interpolation between the measured surface temperature and the constant temperature of the lowest layer. This means that the model will need some time to adjust, since the initial ground profile does not contain any temperature history. The conduction is assumed to be constant with depth, and independent of the time of year, wetness etc.

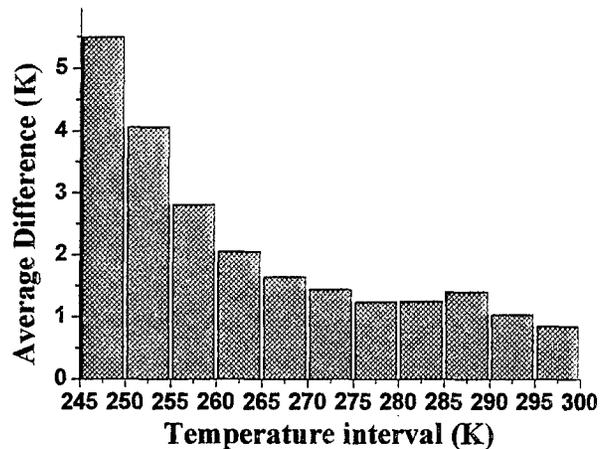


Figure 5: Average difference between general edge-of-forest model temperature and actual measurements

A plot of the rock model for 5 days in May 2001 is plotted in figure 6. The plot contains a best-fit curve and a curve for a long-term model. The best-fit curve has been fitted specifically for the last part of May, while the long-term model has been verified for the period of early March to late June. As can be seen from the plot the long-term model has problems with the highest temperatures. This is probably due to the fact that these are extreme temperatures for the period upon which the model is based. The RMS error of the long-term model is 2.3 K for the entire three-month period. The segment of the long-term model presented in figure 6 represents the period with highest RMS error.

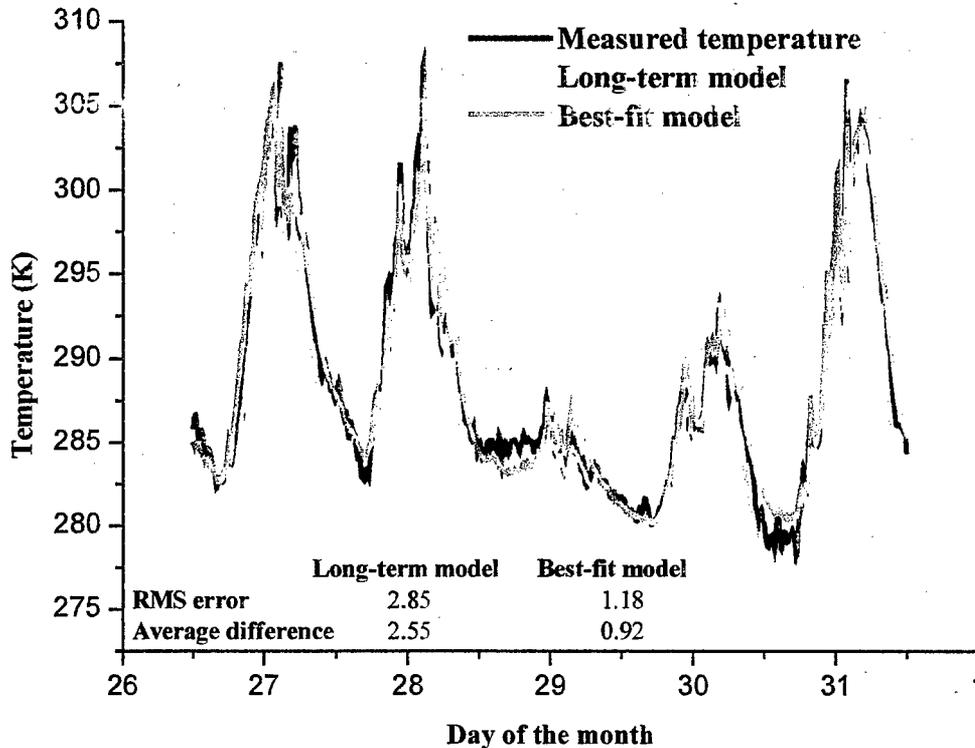


Figure 6: Plot of rock models for late May 2001, with values for average difference and RMS inserted.

Model parameters

Model parameters for the general edge-of-forest model and for the long-term rock model are presented in table 2. The model values are the parameter values that are input into the model. The modified values are the model values multiplied by a factor so that the long wave emissivity coefficient ϵ becomes 0.95. The value 0.95 was chosen as a fairly common value for the long wave emissivity coefficient for natural materials. The multiplication factor represents the heat capacity of the elements modeled. The only parameter that has not been modified by the heat capacity is σ , as this term only appears in the model in conjunction with ϵ .

As can be seen from table 2 the parameters take values that do not seem "unphysical" in nature. There are no negative parameters, which would imply cooling of the background element when energy is added to it. The short wave absorptivity coefficient α is between 0 and 1, but deviates slightly from tabulated values [7]. In addition Stephan-Boltzmanns constant σ is close to its actual value of $5.67e-08 \text{ Wm}^{-2}\text{K}^{-4}$. The reason for the deviations is probably that the model to a certain extent accounts for effects not incorporated in it.

FURTHER WORK

The models need to incorporate effects that have not been considered in the first version. This includes solar angle of incidence for elements that are not horizontal, precipitation and possibly thermal irradiation from surrounding terrain.

There are also plans to model snow. In this case it will also be necessary to record the condition of the snow in some way. There are no plans to incorporate the physical three-dimensional structure of the background elements, as this will make the model unnecessarily complex.

Table 2: Parameter values for the general edge-of-forest model and for the long-term rock model

Parameter	Edge-of-forest model		Rock model	
	Model Value	Modified value	Model Value	Modified value
α	2.66e-06	0.25	5.92e-06	0.63
ε	1.00e-05	0.95	8.89e-06	0.95
δ	1.40e-04	13.30	9.06e-06	8.25
δ_2	7.00e-05	6.65	7.72e-05	0.97
σ	5.84e-08	5.84e-08	6.40e-08	6.40e-08
κ	N/A	N/A	1.22e-05	12.99

If time allows it there are plans to make one of the measuring stations mobile. This will allow for measurements in other types of climates than only in the three fixed measuring sites chosen so far. However, this operation will be very time consuming.

Currently the measuring stations are only used for purposes of delivering data for the model calibration and evaluation. However they are ideal for evaluating vehicle and personnel thermal camouflage. The stations will to a certain extent be made available for the Norwegian military to use for this purpose.

Finally, the models and the collected data will be used as an aid in assessing the effectiveness of thermal sensors. When parameters have been estimated for all kinds of backgrounds it will be possible to estimate the temperature variation in given backgrounds for given meteorological conditions. If this is used in conjunction with calculations of atmospheric propagation the performance of thermal sensors can be evaluated.

CONCLUSION

The measuring stations can deliver data that is sufficiently accurate to be used for modeling of thermal signature. The use of a camera instead of a radiometer has allowed a more precise pinpointing of the location of relevant background elements, thereby increasing the accuracy of the measurements. It also gives the possibility of studying the temperature variations over the background element.

So far two general sets of model parameters have been estimated: One model for a general edge-of-forest, and one for bare rock. The edge-of-forest model has been plotted for a period of nine months, giving an RMS error of 1.9 K. The rock model has been plotted over a period of 3 months, resulting in an RMS of 2.3 K.

The models have resulted in parameters that seem reasonable from a physical perspective. Some of the parameters deviate slightly from tabulated values, but this is not unexpected as the model is much less complex than the thermal systems it simulates.

Modeling has shown that even with very few parameters it is possible to obtain model parameters that result in a very good model for periods of at least two months. Such results can be obtained even for parameters that obviously represent

“unphysical” values, due to the existence of local minima in the fit-function. Therefore it is important when modeling to try different starting values for the parameters, as the mathematical methods used for estimating the parameters may not always converge on the global minimum.

The models developed are simple and quick. They can be used to estimate thermal signatures in short time on a single workstation. The accuracy of the models is sufficient to apply to the evaluation and assessment of thermal camouflage, and will therefore be a valuable tool in further work at FFI.

AKNOWLEDGEMENTS

This paper presents work done at FFI-project 775. I would like to extend my gratitude to my co-workers on the project: F B Olsen, E Strømman, T Høimyr and M Søderblom.

The success of this project has depended on the continuous operations of the measuring stations. Even though they are autonomous there have been several problems along the way. To keep the stations in operation despite these problems it was necessary to have someone to look after them. Therefore one person at each of the air stations was appointed as contact person. The cooperation of the contact persons J E Sjøgren, Major S A Karlson and Major P K Wikestad at Rygge, Ørland and Bardufoss respectively, is very much appreciated.

Thanks also to FGAN-FOM, for providing all the equipment for the measuring station at Bardufoss, and for giving us valuable information on the development of their own thermal signature model.

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