Experimental Evaluation of Thermal Camouflage Effectiveness

Pieter Jacobs

Physics and Electronics Laboratory TNO
PO BOX 96864
2509 JG The Hague
The Netherlands

ABSTRACT

The detectability of a target in the infrared spectral region is determined by differences between the radiative signatures of the target and the local background. This implies that both, the difference in surface temperature and emissivity ΔT resp. Δε and the distribution of these differences over the target area and the background, are of major importance. Therefore camouflage measures have to address both issues in order to achieve maximum signature adaptation to the background.

To determine the ability of a camouflage material to follow temperature changes in the background, temperatures measurements of camouflage systems and background elements have to be performed under a variety of meteorological conditions. Measurements of representative weather- and background conditions are needed to determine those situations, where the camouflage material effectively reduces the target signature. The degree of temperature reduction depends on the required level of protection, that is for detection, recognition and identification. Statistical analyses are given for various camouflage materials in relation to a number of background elements. Camouflage effectiveness is expressed in the percentage of time for which the apparent temperature contrast between the camouflage material and a background element is 1°C, 2°C or 5°C. Analyses are performed for five consecutive weeks of measurements in summer and winter, using data which were taken during a measurement campaign at Gilze-Rijen air force base in 1990.

Keywords: Infrared measurements, thermal contrast, camouflage, effectiveness.

1. INTRODUCTION

The success of the use of infrared (IR) equipment to locate an object in a background, is determined by system performance, atmospheric propagation and the intrinsic radiation contrast between the object and the background. To prevent targets from being detected or recognized at an early stage (at far range), the target signature can be manipulated by camouflage measures in such a way that it adapts better to the local background.

For camouflage measures to be effective in the thermal infrared, two conditions have to be fulfilled:

Temperature similarity

The camouflage measure must shift the range of apparent temperatures on the target within, or at least to be very close to, the temperature envelope of the background. Since in many occasions, targets are warmer than the background, this means that camouflage measures most of the time have to reduce target temperatures. However, recent studies in hot and arid regions demonstrated the opposite.

Spatial similarity

The shape of the camouflage measures has to be such, that the resulting temperature distribution over the target is similar to that of the local background (clutter). In practice this means that camouflage measures also have to create thermal patterns on the target.

Camouflage requirements are determined by the threat for a specific target. This threat generally can be differentiated into (aided) human perception and/or missile seeker algorithms. Furthermore, the

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level of camouflage depends on the desired degree of protection, that is for detection, recognition or identification. In the detection phase the target normally is not more than a (white) spot in the background, while in the recognition and identification phase, more target details are required. For detection, for instance, camouflage measures should emphasise the adjustment of the **average** target signature (temperature similarity), combined with shape distortion. For recognition, however, camouflage measures have to adjust the target signature in more detail to the background clutter (spatial similarity). Therefore camouflage effectiveness should also be expressed in terms of a reduction of the detection and/or recognition range. These ranges are determined by observer experiments (photo simulations) or by seeker calculations. Operational models are then used to convert these ranges to battle related parameters, like the survivability.

The first step, however, to determine the potential of a material to be an effective camouflage measure, is to determine the dynamics of the apparent surface temperature under the most prevailing weather conditions in relation to the dynamics of the most likely backgrounds under the same weather conditions. The temperature of the camouflage measures has to be studied in relation to the thermal behaviour of the various background elements, like grass, trees, soil, etc.. Backgrounds are difficult to model due to their very complex geometrical structure and by the fact that the mathematical description for some physical processes, which exist in a vegetation layer, are not yet accurate enough. This also is the problem when modelling light weight (small thermal mass) and textured camouflage materials, like nets and thermal screens, which are very sensitive to small variations in some input parameters. Models can be used to evaluate the general trend of the temperature behaviour of prototype camouflage measures. Especially, models are very helpful to determine the effect of material properties on the apparent temperature and to define optimum values.

The great advantage of measurements over calculations is the fact that the desired quantity, i.e. the apparent emittance or the apparent temperature of a background element is measured directly in relation to the prevailing weather conditions. Ideally, the signatures of targets, camouflage measures and backgrounds are measured simultaneously under various conditions and over long periods of time.

2. DATA COLLECTION

To evaluate the thermal behaviour, camouflage measures of a number of prototype materials was installed in a measurement facility at Gilze-Rijen Air Force Base and were measured simultaneously with a large number of background elements. Figure 1 shows the experimental set-up. The CARABAS platform and cabin are located next to the concrete pad. The camouflage materials are due east of the platform and spread out over a grass area as big squares, leaving an airspace of 30-50cm.

Despite the fact that there were no targets behind the camouflage measures and the horizontal positioning of the materials, a direct comparison between camouflage- and background temperatures still is very useful.

The materials can be described as follows:
1 a green carpet type material (Danish texture mat)
2 a black version of the same texture mat
3 black-greyish tar paper
4 a conventional camouflage net*)
5 a camouflage net, sprayed with a Low Emissivity Paint (LEP) with an emissivity of $e = 0.75$**)
6 a grey coloured LEP ($\varepsilon = 0.60$) on concrete**)

*) the nets were applied horizontally 30-50 cm above a grass area
**) in both 3-5 and 8-12 μm

The CARABAS radiometer[1] autonomously and automatically measures the apparent irradiance of the selected elements in the 3-5 and 8-12μm spectral band every preset time interval. The radiometer is placed on an elevated platform (7m in height), next to a measurement cabin. Two external black body sources, positioned at 1m from the entrance pupil, are incorporated in the measurement cycle to check system performance continuously. A synoptic weather station (supplemented with a pygrgeometer) is placed South-East of the cabin at ±50m.

At regular intervals, the physical condition of most background elements, was recorded, like height, emission coefficient and possible mud/snow coverage. Figure 1 also gives an impression of the type and variety of background elements which are found at the Gilze-Rijen site (51°3'N, 5°5'E). The photograph of the measuring facility is taken in the summer of 1990. The grey area on the concrete, North of the cabin is the LEP. Table 1 gives an example of the format of the data as it is available on disk.

Fig.1. Measurement set-up at Gilze-Rijen AFB.

TARGET CODE	DATE	SHORT DESCRIPTION	ELEVATION	AZIMUTH
02818319158	13-08-1990	GRASS	HORIZONTAL	315°

TIME	T_3 °C	T_8 °C	T_a °C	RH %	Q_g W m^{-2}	Q_p W m^{-2}	v m s^{-1}	Φ_v (°)	PR mm	p hPa
00:30	18.7	19.5	20.6	83.3	0.0	392.9	2.2	27.7	0.0	1011.5
00:45	18.6	19.0	20.3	86.7	0.0	398.5	1.3	32.4	0.0	1011.3
01:00	18.0	18.7	19.9	89.2	0.0	391.3	1.5	28.6	0.0	1011.2

T_3, T_8: Apparent temperature in 3-5 resp. 8-12μm
T_a : Air temperature
RH : Relative humidity
Q_g : Global irradiance
Q_p : Longwave sky irradiance
v : Wind speed
F_v : Wind direction
PR : Precipitation
p : Atmospheric pressure

Table 1. Database example of collected data

The following background elements were measured in conjunction with the camouflage materials and the prevailing weather conditions:

1 different types of grass
2 deciduous trees at various orientations and at different ranges, varying 2 to 7m in height
3 coniferous trees, 4m height at 100m range
4 agricultural field (seasonal plant growing)
5 bare soil (ploughed rough surface)
6 concrete surface
7 water surface (small pond, 1m depth)
8 up- and down hill slopes (bare soil and grass covered). North and South facing.

3. DATA ANALYSES AND RESULTS

Since camouflage materials only can have a limited number of characteristics, designed, for instance, for winter/summer, desert/woodland, rural/urban conditions, its physical properties, like colour, temperature and texture, have to be based on statistics. The measurement campaign at Gilze-Rijen produced a database of more than a full year of data of 25 background elements and camouflage materials, taken at 15 min interval.

Before starting a search through the database, the desired situation is defined, by selecting, the time period (season), the desired weather conditions, wind- and/or sunlit, dry conditions. Also limits can be given to weather parameters, for instance, only those time points are selected for which the global irradiance is $100 < Q_{sun} < 200$ (W m^{-2}). Subsequently, the database is searched and at every event where the selected and actual weather conditions do match, the apparent temperatures of all selected elements are stored. This way, the thermal behaviour during specific weather conditions as well as statistical analyses over longer periods of time can be studied.

4.1. Temporal Behaviour

The temporal behaviour of background and camouflage temperatures is needed to study camouflage performance under specific weather conditions. As an illustrative example, figure 2 shows the measured apparent temperatures (in 8-12μm) of various background elements in relation to some camouflage materials on two cold days (16 and 17 December 1990). Figure 3 shows the temperature variation of similar background elements in relation to the same camouflage materials on two hot days (13 and 14 August 1990).

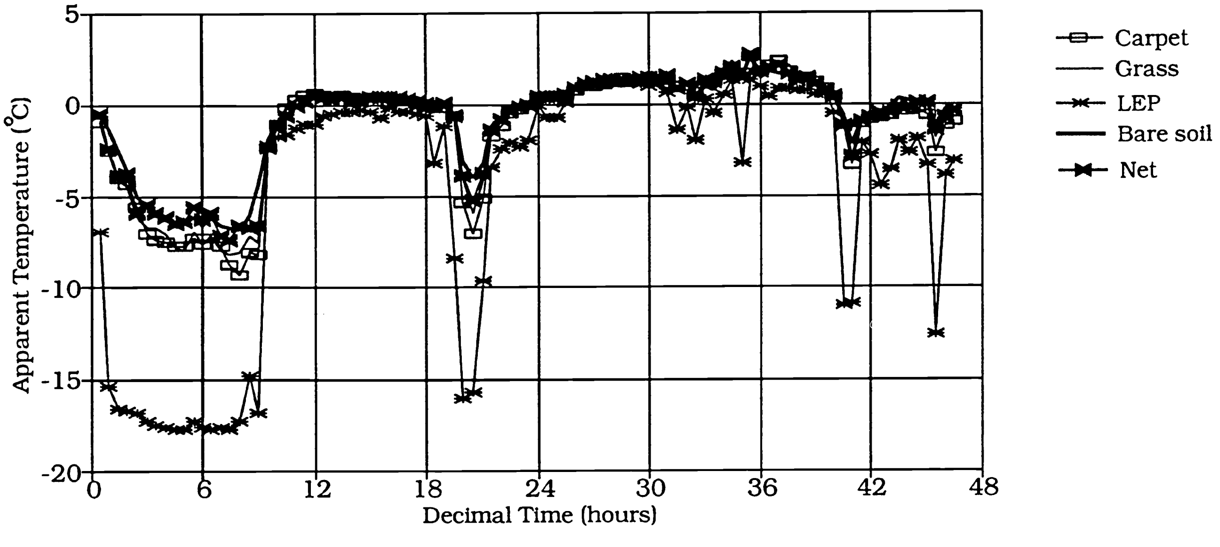

Fig.2. Apparent temperature of camouflage materials and background elements in December 1990.

The effect of the low emission coefficient of the camouflage net is spectacular (negative apparent temperature) during the very clear night of 13 December. Generally, it can be concluded that the temperature differences during wintery conditions are quite small. This is due to the fact that vegetation behaves like 'dead' material in winter time and therefore is not different than other materials with constant physical properties, like camouflage materials. During sunny conditions, the temperature differences may become very large, for instance, the difference between the net and the carpet exceeds 25°C!, at 15:00 hours on August 13.

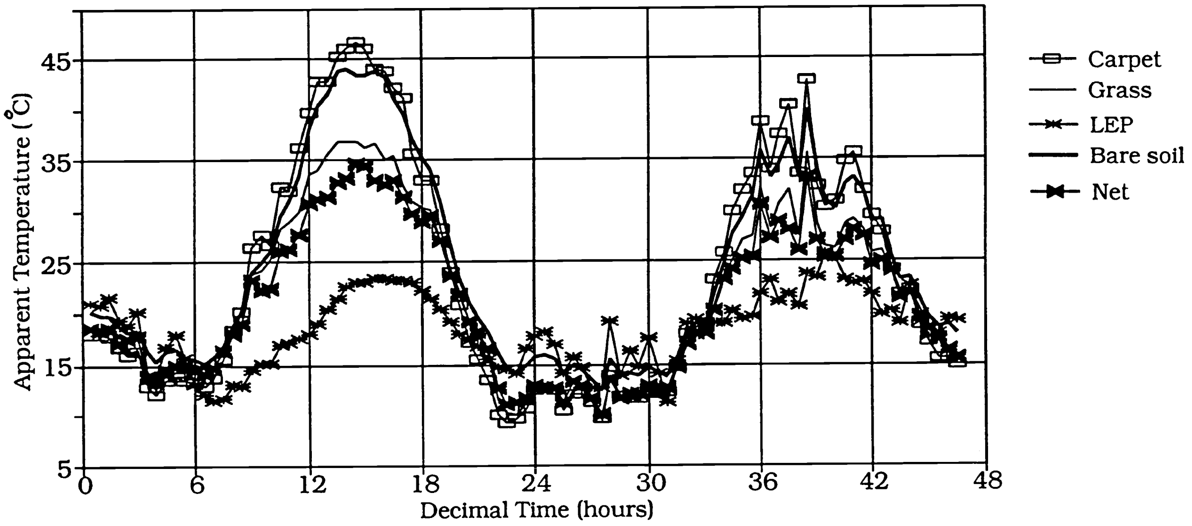

Fig.3. Temperature of camouflage materials and background elements in August 1990.

4.2. Temperature Statistics

For statistical analyses, two time periods are used, being 19 July - 28 August 1990 and 10 November - 19 December 1990. These periods should be representative for a summer season and a fall/winter season in NW Europe. Table 2 and 3 show the average apparent temperature and RMS variance of some background elements[2] for the summer and winter period. The RMS variance σ is calculated as:

$$\sigma = \left[\frac{1}{N} \sum_{i=1}^{N} (T_i - T_m)^2 \right]^{0.5}$$

T_i : Momentary temperature (°C)
T_m : Average temperature (°C)
N : Total number of measurements

The tables show that in winter time the temperatures of the background elements are quite close. The trees are colder than the air temperature because, since leaves are missing, part of the measurement area on the trees is filled with sky background. During day time in summer the temperature spreading is more pronounced and materials with a large thermal mass, like concrete, remain much warmer during night time.

Statistical analyses of the temperature differences between background elements them selfs and between camouflage materials and background elements, are carried out for each period. As was to be expected, the temperature differences in the background and between the camouflage materials are very moderate in winter time. The situation during the summer period is quite different from that in winter time: due to the temperature controlling mechanism of the vegetation (by evaporation and condensation), the contrast with non-vegetated surfaces can become quite big. Figure 4 and figure 5 show a comparison of the temperature difference distributions for the summer and winter period during day and night time. The distributions are very wide (20-30°C), showing a variance up to 9°C. The figures show the long 'warm tail' in the distributions for the texture mat during day time in summer, indicating that it gets too hot. The LEP net, which is placed horizontally, is much cooler than the tree line during night time. Whether a given temperature contrast can be detected, depends on the performance of the IR sensor and on the atmospheric propagation. The final impact on the detection or recognition process therefore, depends on the momentary situation, i.e the local contrast.

In terms of a **temperature contrast** ΔT, camouflage effectiveness γ can be defined as the percentage of time in which the contrast between the camouflage and a background element is smaller than a required (desired) temperature X:

$$\gamma = \frac{\{ \Delta T \mid |\Delta T| \leq X\,(^\circ\mathrm{C}) \}}{N} \times 100\%$$

N is the total number of contributing sample points

For a target at close range, already a small value of X will lead to detection, while for greater ranges the temperature contrast needs to be larger, because of the atmospheric attenuation. Calculations for γ have been performed for values for X of 1°C, 2°C and 5°C, during day (sunrise-sunset) and night time (sunset-sunrise) for the summer and winter period. To get an impression of the contrast values which exist in a natural background scene, temperature contrast values between a few background elements have been included in the calculations.

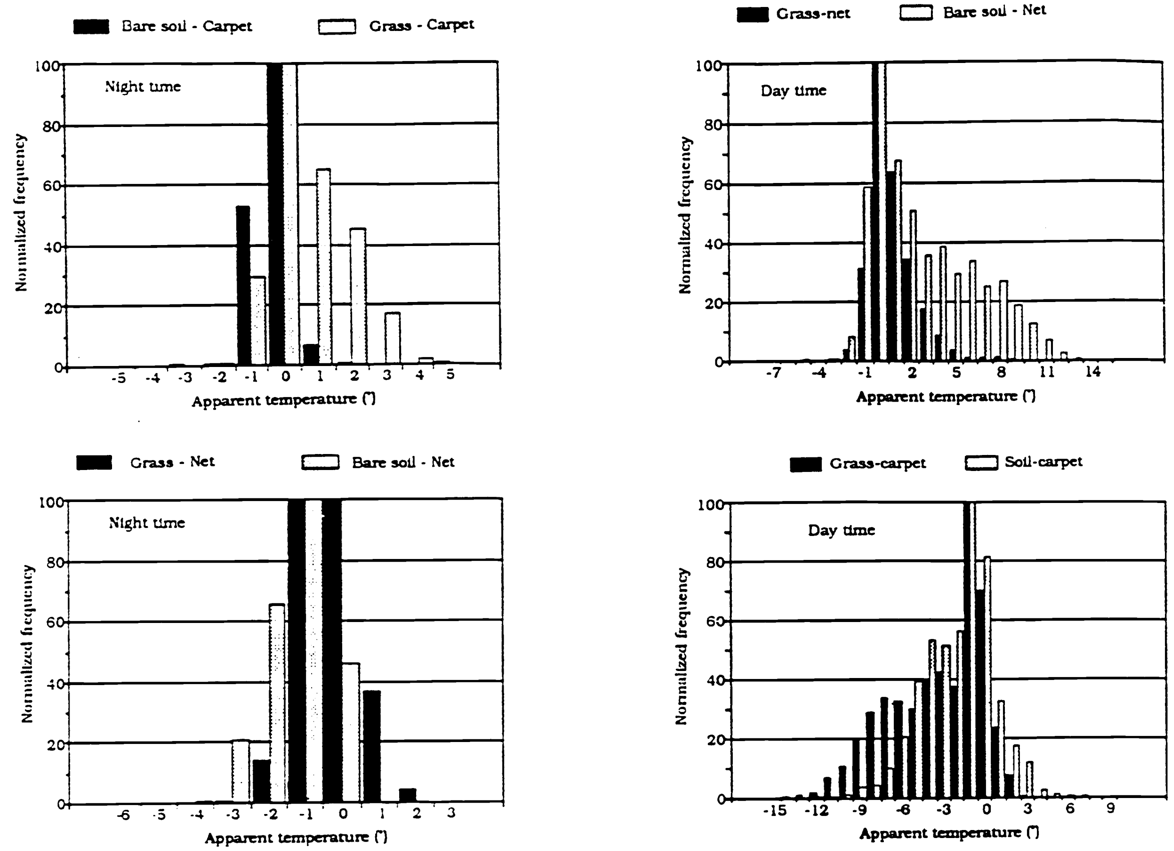

Fig.4. Temperature difference distributions during day and night time in the summer.

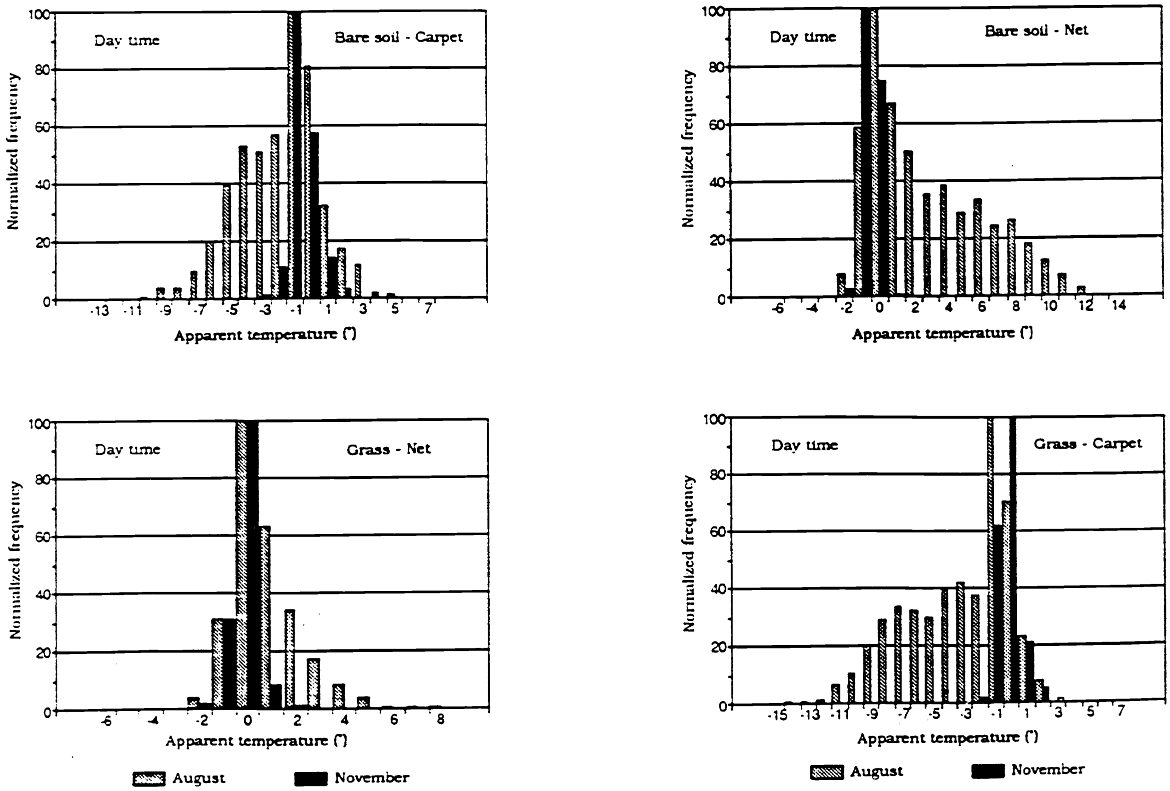

Fig.5. Comparison of temperature difference distributions in summer and winter time.

Table 4 and table 5 show the results of these calculations. Also the mean temperature contrast ΔT_m and the variance σ have been incorporated. The tables again show that during winter time the temperature contrasts are very moderate.

	DAY TIME				NIGHT TIME			
	3 - 5μm		8 - 12μm		3 - 5μm		8 - 12μm	
Element	T_m	σ	T_m	σ	T_m	σ	T_m	σ
Grass	25.1	9.0	25.8	9.1	12.3	4.1	13.2	4.4
Concrete	28.5	7.4	27.5	7.1	19.9	3.7	19.2	3.9
Soil	26.7	9.7	26.8	9.7	12.0	4.4	13.0	5.2
Trees (S)	24.0	5.1	24.2	5.1	14.1	3.8	14.9	4.2
Trees (NE)	20.1	5.5	20.2	5.5	14.1	3.9	14.8	4.2
		T_m	σ			T_m	σ	
air temperature		20.9	5.5			14.0	3.7	

Table 2. Average background temperatures during the summer period (T_m and σ in °C).

	DAY TIME				NIGHT TIME			
	3 - 5µm		8 - 12µm		3 - 5µm		8 - 12µm	
Element	T_m	σ	T_m	σ	T_m	σ	T_m	σ
Grass	5.3	4.1	5.7	4.1	2.3	4.8	2.9	4.8
Concrete	5.0	3.9	4.8	3.9	2.8	4.1	2.9	4.1
Soil	5.1	4.1	5.4	4.0	2.4	4.7	2.9	4.8
Trees (S)	2.3	2.4	2.5	2.2	0.7	2.9	1.0	2.7
Trees (NE)	2.0	2.4	2.4	2.2	0.3	3.1	0.9	2.9
		T_m	σ			T_m	σ	
air temperature		4.8	4.0			3.0	4.4	

Table 3. Average background temperatures during the winter period (T_m and σ in °C).

The contrast between the LEP and the background elements shows that the LEP has a modest negative effect (i.e. too cold) on the apparent temperature, in both spectral regions. During day time in summer, there are some remarkable differences in temperature behaviour in the two spectral bands. In the 8-12µm region the LEP gives a much lower temperature contrast with the background elements than in the 3-5µm band. This is explained by the fact that the solar reflectance in the 3-5µm region is increased by the enhanced reflectivity due to the LEP ($\rho = 1 - \varepsilon$). Furthermore, the reflectance of 'cold' sky radiation is enhanced, because the atmospheric transmission coefficient in the 8-12µm is greater than in the 3-5µm region. At night time, the contrast between the concrete and the LEP seems too small (i.e. the LEP temperature is too high), but this is caused by the high surface temperature (big thermal mass) of the concrete, which largely compensates the effect of the LEP.

Expressed in a percentage of time, the contrasts in winter time are within 2°C for almost 90% of time, that is, 31 days out of 35! (except for the LEP). In summer time the camouflage effectiveness, for both day and night, very much depends on the type of camouflage and the type of background element to which it is compared to. For instance, if concrete has to look like (simulate) grass, the main camouflage effort will be to match the time response of the concrete with that of the grass.

5. CONCLUSIONS

The experimental quantification of the behaviour of the apparent temperature of background elements and of potential camouflage measures looks promising. Although the efforts to acquire the necessary data are quite substantial, the output of the analyses directly show the potential of a camouflage measure to adapt to the background conditions. The camouflage effectiveness percentages for the different contrast values can directly be used to analyse sensor system performance against camouflaged targets.

Comparison with indoor measurements in climate chambers is desirable in order to establish a relation between results of the two measurement procedures. This possibly could lead to the avoidance of the demanding effort of long term outdoor measurements.

To include the thermal interaction between the target and the camouflage measure, targets should be part of a follow up exercise. If this is not feasible, controllable black bodies should be used to simulate the target. Also the camouflage materials should be placed in a more realistic way.

Preferably, a total camouflage concept is applied in order to determine over all camouflage efficiency, for instance, by photo simulation techniques or by seeker algorithms. This implies that high quality imagery (thermal and geometrical resolution) is required over statistically significant periods of time.

3 - 5μm	DAY TIME					NIGHT TIME				
	Statistics		γ (%)			Statistics		γ (%)		
	ΔT_m	σ	1°C	2°C	5°C	ΔT_m	σ	1°C	2°C	5°C
Grass-Soil	-1.0	1.8	44	69	98	-0.1	1.9	61	88	96
Grass-Concrete	-2.7	3.1	17	33	77	-7.5	3.0	2	5	23
Trees-Grass*	-4.4	3.9	14	26	57	-2.2	2.1	14	35	94
Grass-Carpet	-1.6	2.4	34	56	89	+1.1	2.2	56	81	94
Grass-LEP	+1.0	3.0	24	45	89	-3.1	2.5	15	28	78
Grass-Net	+1.7	2.5	35	58	89	+0.0	1.9	69	92	96
Soil-Carpet	-0.7	2.4	36	59	96	+1.3	1.5	35	69	99
Soil-Net	+3.1	2.8	27	47	75	+0.3	1.3	66	93	99
Concrete-LEP	+3.8	2.2	10	24	69	+4.6	1.4	4	7	56
Trees-Net	-1.7	2.3	28	51	92	+2.4	1.6	17	41	96
8 - 12μm	ΔT_m	σ	1°C	2°C	5°C	ΔT_m	σ	1°C	2°C	5°C
Grass-Soil	-0.3	1.7	54	78	99	-0.0	1.7	79	94	96
Grass-Concrete	-1.0	3.6	21	39	82	-5.9	3.3	12	16	37
Trees-Grass*	-5.0	4.1	14	26	53	-2.0	1.9	28	45	97
Grass-Carpet	-1.6	2.6	36	57	88	+1.1	2.0	47	83	96
Grass-LEP	+7.9	6.2	12	18	34	+0.6	3.1	34	57	88
Grass-Net	+2.8	3.0	36	51	77	+0.1	1.5	90	95	97
Soil-Carpet	-1.3	2.6	37	56	92	+1.3	2.2	47	69	97
Soil-Net	+3.6	3.5	29	43	67	+0.3	1.2	76	96	99
Concrete-LEP	+9.2	4.1	5	7	17	+6.7	4.0	15	20	32
Trees-Net	-1.0	1.9	42	65	98	+2.1	1.9	30	44	96

* South facing tree line, sunlit condition

Table 4. Camouflage effectiveness in summer time, expressed as a percentage of time γ

3 - 5μm	**DAY TIME**					**NIGHT TIME**				
	Statistics		γ **(%)**			**Statistics**		γ **(%)**		
Contrast	ΔT_m	σ	**1°C**	**2°C**	**5°C**	ΔT_m	σ	**1°C**	**2°C**	**5°C**
Grass-Soil	+0.1	1.1	63	92	100	-0.1	1.3	57	88	100
Grass-Concrete	+0.3	1.3	59	88	100	-0.5	1.7	48	78	99
Trees-Grass*	+0.4	1.2	59	91	100	+1.0	1.6	43	64	100
Grass-Carpet	+0.3	1.1	64	91	100	+0.7	1.4	51	82	99
Grass-LEP	+1.4	1.8	39	70	95	+0.5	2.0	43	72	97
Grass-Net	+0.1	1.1	66	92	100	-0.1	0.4	58	87	100
Soil-Carpet	+0.2	1.2	61	91	100	+0.8	1.4	52	81	99
Soil-Net	-0.1	1.1	65	93	100	-0.0	1.3	60	89	100
Concrete-LEP	+1.1	1.8	46	75	96	+1.0	1.8	46	73	96
Trees-Net	+0.2	1.3	58	88	100	+1.0	1.5	46	79	100
8 - 12μm	ΔT_m	σ	**1°C**	**2°C**	**5°C**	ΔT_m	σ	**1°C**	**2°C**	**5°C**
Grass-Soil	+0.3	0.6	92	99	100	-0.0	0.6	96	99	100
Grass-Concrete	+0.9	1.1	62	86	100	-0.0	1.1	68	94	100
Trees-Grass*	+0.2	0.4	97	99	100	+0.6	0.7	82	89	100
Grass-Carpet	+0.3	0.8	88	98	100	+0.5	0.7	87	98	100
Grass-LEP	+2.9	4.4	39	65	85	+2.1	4.0	48	74	85
Grass-Net	+0.2	0.6	94	99	100	-0.1	0.6	95	99	100
Soil-Carpet	-0.0	0.8	90	99	100	+0.4	1.4	85	98	100
Soil-Net	-0.1	0.3	99	100	100	+0.1	0.3	100	100	100
Concrete-LEP	+2.1	3.8	65	79	87	+2.1	3.9	67	79	85
Trees-Net	+0.3	0.4	91	100	100	+0.7	0.7	82	93	100

* South facing tree line, sunlit condition

Table 5. Camouflage effectiveness in winter time, expressed in a percentage of time γ.

Conclusions (continue)

The study provides a strong argument to investigate the development of 'adaptive' camouflage materials or systems, that is, to control a physical property of a material in relation to the variation of the environmental (meteorological) conditions. For instance, coatings which change colour as a function of temperature (thermo-chromes) or electrical current (electro-chromes). Emissivity can be controlled by using semi-conductor materials (Tungsten Oxide), or temperature control by piezo-electric layers. Such a new study would largely have to deal with material research.

6. REFERENCES

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