Infrared thermography: principles and applications

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Summary

All objects with surface temperatures above absolute zero emit electromagnetic radiation. In this paper we describe the physical principles that allow calculation of the surface temperatures of objects from the wavelength and intensity of electromagnetic radiation emitted in the infrared region of the spectrum (infrared thermography). This technique can be applied to measure the surface temperature of animals without the need for physical contact with them. Infrared thermography allows a direct measure of radiative heat transfer from animals. Convective heat transfer can also be calculated from the detailed information on body surface temperature. We describe some recent applications of infrared thermography to remote measurement of surface temperature which allow identification of the main sites of heat loss from mammals and birds.

Introduction

All objects that have surface temperatures above absolute zero emit electromagnetic radiation. This radiation can be characterised by two features: its wavelength (λ) and intensity (Q). Both of these parameters are related by relatively simple physical laws to the surface temperature of the object (Holman 1986). It is therefore possible to use the intensity and wavelength of radiation emitted by an object to measure its surface temperature, without the need for physical contact. This allows the study of heat transfer from animals in situations where conventional measurements using thermistors could not be used (for example during flight: Lancaster et al. 1997, Speakman et al. 1997).

Both the intensity of emitted radiation, and the wavelength at which it is most intense, vary with the surface temperature of the emitting body. Objects at a particular temperature emit radiation over a range of wavelengths. The intensity of radiation emitted by an object, as a function of wavelength and surface temperature, can be described by:

\[ Q_\lambda = \frac{A}{\lambda^2 (e^{B/\lambda T} - 1)} \]  

(1)

where \( Q_\lambda \) is the intensity of emitted radiation (W) at any particular wavelength, \( \lambda \) is the wavelength (m), \( T \) is the surface temperature (K) and \( A \) and \( B \) are constants: \( 3.742 \times 10^{8} \text{ W} \cdot \text{m}^{-4} \cdot \text{m}^{-2} \) and \( 1.439 \times 10^{6} \text{ m} \cdot \text{K} \) respectively (Plank 1959). Equation (1) generates a series of curves which describe the amount of radiation emitted at each wavelength, for bodies of different surface temperatures (Figure 1). The total radiation emitted by a body (\( Q_{\text{tot}} \)) can be obtained by integrating equation 1 across the entire wavelength range. The value of this integral is:

\[ Q_{\text{tot}} = \sigma T^4 \]  

(2)

where \( \sigma \) is the Stefan-Boltzmann constant \((5.67 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4})\).

The wavelength at which the maximal intensity of radiation is emitted depends on the surface temperature: the higher the temperature, the shorter the wavelength at which most of the radiation is emitted. This relationship is described by Weins displacement law:

\[ \lambda_{\text{max}} = \frac{2.9}{T} \]  

(3)

where \( \lambda_{\text{max}} \) is the peak wavelength of emission (mm) and \( T \) is the surface temperature (K) (Figure 1). The sun, for example, has a surface temperature of around 5800 K (Holman 1986). The peak wavelength of radiation which it emits is therefore approx-
Fig. 1. The spectral emissive power of a black surface. The curves show emissive power as a function of wavelength for objects at several surface temperatures (calculated from equation 1). The area under each curve is described by equation 2. The peak of each curve is computed from equation 3.

Fig. 2. The electromagnetic spectrum. Wavelength is shown on a logarithmic scale.

The total intensity of radiation emitted by objects \( Q_{tot} \) is critically dependent on their surface temperature (equation 2) and the intensity of radiation which is emitted at any particular wavelength is strongly dependent on the surface temperature of the emitting body (equation 1, Figure 1). Measurements of the intensity of radiation emitted from the surfaces of bodies at any particular wavelength thus provide, in principle, a method for the measurement of surface temperature. Indeed the relative intensities of radiation at different wavelengths allow us to calculate the surface temperature of the sun and objects outside the solar system, despite the fact no human instrument has been within a million miles of the sun's surface or as yet very far outside the solar system. To measure the temperatures of objects on the surface of the earth in the range from \(-10 \) to \(50^\circ C \) (263–323 K) the most appropriate wavelengths are around 9–11 \(\mu m\), because (from equation 3) this is the region of peak spectral emission. These wavelengths are in the infrared range of the electromagnetic spectrum (Figure 2). Consequently measuring radiation emitted by such objects is generally called infrared thermography.

There are several factors which complicate the measurement of surface temperatures of objects from the intensity of their emitted infrared radiation. Most importantly the intensity of emitted radiation is dependent upon the nature of the surface of the emitting material. An object which is a perfect emitter at all wavelengths is known as a black body. Equations 1–3 were derived for such perfect emitters. Imperfect emitters by definition emit less radiation than a black body at the same temperature. To express the extent of imperfection of an emitter the material is given a value which expresses its ability to emit radiation as a proportion of that possible at the same wavelength by a black body. This value is known as the emissivity. By definition the emissivity of a black body is equal to 1.0, and constant at all wavelengths. A body for which emissivity is less than 1.0, but still constant at all wavelengths, is known as a grey body. In real life, however, most bodies are neither grey nor black and the emissivity is dependent on the wavelength of radiation being considered. The surface characteristics which govern emissivity also control the ability of a material to absorb radiation. A perfect emitter of radiation is also a perfect absorber of radiation at the same wavelength. In fact the absorptivity of radiation at any wavelength is equal to the emissivity of the material at the same wavelength. This phenomenon is known as Kirchhoff's law.

Measurements of biological materials in the 9–11 \(\mu m\) range have generally found that absorptivity (and thus emissivity) of infrared radiation is between 0.9 to 0.97 (Porter and Gates 1969) independent of
the surface colour in the visible spectrum range, as perceived by a human observer. The high emissivity is probably because biological materials have very high water contents (generally greater than 65%) and water has an absorptivity in the infrared range of about 0.96 (Hottel 1954). When measurements are made of biological material using infrared thermography it is generally assumed that the surface emissivity has a fixed value between 0.95 and 0.98. It should be borne in mind, however, that minor changes in the apparent surface temperature might instead represent alterations in surface emissivity of an object which actually has a uniform surface temperature.

The intensity of emitted radiation received from an object is affected by the angle at which the object is viewed because electromagnetic radiation travels in straight lines. If an object is viewed at a very shallow angle to the emitting surface then there is a reduction in the intensity of thermal radiation received and the object will appear cooler than it actually is. Temperature measurements may therefore be spurious for objects viewed at very shallow angles if the geometric view factor is not taken into account. In practice the effect of viewing angle is negligible for objects with rough surfaces, such as animals, until the angle is less than 10°. As the angle declines from 30° to 0° there is an exponential decline in the intensity of radiation received until none is received at a viewing angle of 0° (Sparrow and Cess 1966, Clark 1976).

The distance between an emitting object and the sensing device also affects the absolute amount of radiation detected. The intensity of radiation declines following the inverse square law. However transmission may also be affected by the material through which the radiation passes. Gasses may absorb certain wavelengths of radiation and may scatter it, reducing the amount which passes directly from the object to the sensor. Ozone for example absorbs radiation in the 170 to 210 nm range and water vapour absorbs in several regions of the spectrum above 1100 nm. Over long distances these effects can be substantial. Even in a cloudless sky the radiation from the sun at 500 nm wavelength is attenuated by approximately 25% by the time it reaches the earth’s surface, relative to the amount which impinges on the upper atmosphere (Holman 1986). In general, however, scattering and absorption by atmospheric gasses are relatively trivial effects over the distances (typically <10 m) that are involved in the remote sensing of the surfaces of animals by infrared thermography.

**Practicalities**

Small hand held devices which measure surface temperatures of objects using the principles outlined above are available for approximately 500 US$. The devices have a measuring cell which detects radiation in the range 900–1000 nm. A lens focuses radiation from a definable field onto the measuring cell and the intensity of radiation is used to assess the temperatures of objects in the field. The emissivity of the object is assumed to be 0.95 and it is generally not possible to adjust the estimated temperature for inaccuracies in this estimate. The accuracy of these devices is generally quoted to be in the range of 1–3 °C if the emissivity is correct.

More sophisticated devices do not involve point measurements of temperature but generate a complete false colour image in the infrared range using a thermographic camera. One such system, used in our laboratory, is the Agaema Infrared Systems Thermovision 880 system linked to a dedicated thermal imaging computer (TIC-8000) running CATS E 1.00 software. A 20° lens with a broadband coating provides sensitivity to radiation in the 600–1200 nm waveband. Infrared radiation from objects in the field of view of the thermal camera is focused onto a semiconducting mercury cadmium telluride detector which is cooled to −196 °C with liquid nitrogen. The intensity of incident infrared radiation is determined from the increase in temperature and hence change in resistance of the detector caused by the incident infrared radiation. Field width varies from 0.12 m at 0.5 m (focal depth −0.02 to +0.03 m) to 3.2 m at 10 m (focal depth 4.4 m to ∞). Images can be stored digitally either singly or in sequences and manipulated using the CATS E 1.00 software to provide sophisticated summaries of the surface temperatures of objects and estimates of the temperature at any particular point. No prior assumption is made of surface emissivity which can be varied by the user in the range 0 to 1.0. The software can take into account the effects of attenuation of infrared radiation by the atmosphere and atmospheric self emission if air temperature, pressure, and humidity are known. The number of pixels occupied by the image of an animal varies, based on the distance between the animal and the camera. If images taken at different distances are to be compared they must be scaled using, for example, the length of the animal as a reference (Lancaster et al 1997). Complete systems like this cost from 50k to 130k US$ and provide estimates of surface temperatures of objects of known emissivity to the nearest 0.1 °C, for objects with surfaces between 10 and 50 °C.

**Applications**

In this section we shall review several previous applications of infrared thermography to explore the thermoregulatory behaviour of animals.
Mammals

Bats

Webb et al. (1992) used infrared thermography in conjunction with measurements of body core temperature and metabolic heat production to quantify heat exchange between roosting long-eared bats (Plecotus auritus) and their surroundings. Body surface temperature measured by infrared thermography allowed quantification of the relative importance of heat loss by radiation and convection. Gross radiative heat loss was 0.41–0.47 W or 46–70% of total heat flux from a roosting bat although this was almost completely balanced by radiative heat gain. Net heat transfer by radiation represented less than 10% of metabolic heat production measured by oxygen consumption. Convection and evaporation accounted for 41–44 and 37–38% of metabolic heat production respectively.

Bats have expansive areas of naked skin on their wings but their bodies are covered in insulating fur. It has been generally presumed that the wing membranes provide a convenient route by which bats can dissipate the heat that is generated when flying. This suggestion has received considerable support from studies where stationary bats have been subjected to heat stress, by placing heat pads on their bodies, and measuring wing temperatures by placing thermocouples on the wings (Cowles 1947, Reeder and Cowles 1951, Kluger and Heath 1970). These studies show that when stationary bats are experimentally heat stressed they flood the wings with blood in an attempt to dissipate the heat load. Lancaster et al. (1997) used infrared thermography to show that the wings of Egyptian fruit bats (Rousettus aegyptiacus) remain at temperatures less than 1°C above ambient during flight (Figure 3) and that wing temperature did not vary with elapsed time during flights of up to 30 minutes duration. Heat generated as a by-product of mechanical power production during flight did not therefore lead to the raised wing temperatures in the same way as that reported in stationary bats subjected to heat stress (Kluger and Heath 1970). Despite the small thermal gradient between the wings and ambient air, twice as much heat was dissipated from the wings than from the body of a flying bat due to the large wing surface area (Lancaster et al. 1997). Bat wings are thus important for heat dissipation during flight, but infrared thermography and heat transfer analysis demonstrate that this is due to their large surface area and rapid movement of air over the wing surface rather than because the wings are raised to temperatures significantly above ambient.

Foxes

The function of some of the anatomical differences between fox species which live in different climates can be explained from analysis of heat transfer revealed by thermography (Klir and Heath 1992). Thermal images of foxes at ambient temperatures between −25 and 33 °C showed that the nose, lower legs, paws and front of the ears were important thermoregulatory surfaces in red foxes (Vulpes vulpes), Arctic foxes (Alopex lagopus) and kit foxes (Vulpes macrotis). The back of the ears and face were important for heat transfer only in red and kit foxes. Arctic foxes are adapted to live in a colder climate than the other two species by reduction in the proportion of the body surface used to regulate heat loss to the environment: only 21% of the surface of arctic foxes was important for heat exchange, rather than 33–38% in the red and kit foxes. Infrared thermography also revealed an adaptation of kit foxes to a hot environment. The noses of kit foxes were the only parts of the bodies of any of the three species that were cooler than ambient temperature. At ambient temperatures greater than 22 °C, kit fox noses were adapted to allow heat loss by evaporative cooling. Infrared thermography thus demonstrated mechanisms for heat conservation or dissipation which adapted these superficially similar animals to life in different climates.

Birds

Starlings

Unlike bats, the wings and bodies of birds are both highly insulated. Previous studies of birds in simulated heat stress have suggested that the feet may be a significant route for heat dissipation (Steen and Steen 1965, Martineau and Larochelle 1988). Field observations support this suggestion. Flying aerial insectivores extend their feet in the middle of the day when they are under maximal thermal stress from solar radiation – presumably to dissipate the excess heat uptake (Bryant 1983). Thermal images of starlings (Sturnus vulgaris), flown in a wind tunnel, demonstrate the relative importance of different parts of the body for heat dissipation (Figure 4, Table 1). The head, feet and inner part of the lower surface of the wing were the hottest parts of the bird whilst the unvascularised feathers in the wings and tail were less than 1 °C warmer than ambient air temperature. Net heat transfer by radiation (q_rad) from twelve sections of the body was calculated directly by digital thermography assuming an emissivity (ε_bird) of 0.95 for the bird (Coussins and Bowler 1987) from:

\[ q_{\text{rad}} = A \cdot v_{\text{bird}} \cdot \sigma \left( T_{\text{bird}}^4 - T_{\text{wall}}^4 \right) \]

where \( A \) is the area of each section of the bird (m²), \( T_{\text{wall}} \) was measured by thermography assuming an emissivity of 0.95 (Holman 1986). \( T_{\text{bird}} \) was the
Table 1. Mean (sd) surface temperature, surface area, rate of convective and radiative heat transfer and percentage of total heat loss from twelve sections of the surface of 4 starlings during wind tunnel flight at 12.45 (sd 0.1) m/s. Data shown are from one section of the body per bird. Two images were analysed per bird because the back and upper surface of the wing were visible only during the down stroke, and the remaining sections of the body were seen in images taken when the wing was raised. Chamber wall temperature, used to calculate net radiative heat transfer, was 2.6 °C (sd 1.3) above air temperature.

<table>
<thead>
<tr>
<th>Section of body</th>
<th>Surface temperature (°C) (above air)</th>
<th>Surface area m² (×10⁻³)</th>
<th>Heat transfer by radiation (W)</th>
<th>Heat transfer by convection (W)</th>
<th>% total heat transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>3.3 (0.3)</td>
<td>16</td>
<td>0.030 (0.002)</td>
<td>0.34 (0.04)</td>
<td>6</td>
</tr>
<tr>
<td>Neck</td>
<td>1.1 (0.4)</td>
<td>6</td>
<td>0.004 (0.001)</td>
<td>0.10 (0.02)</td>
<td>2</td>
</tr>
<tr>
<td>Legs</td>
<td>5.2 (0.8)</td>
<td>2</td>
<td>0.006 (0.001)</td>
<td>0.09 (0.01)</td>
<td>2</td>
</tr>
<tr>
<td>Tail</td>
<td>0.8 (0.5)</td>
<td>10</td>
<td>0.005 (0.002)</td>
<td>0.14 (0.02)</td>
<td>2</td>
</tr>
<tr>
<td>Lower primaries and secondaries</td>
<td>0.4 (0.2)</td>
<td>180</td>
<td>0.043 (0.020)</td>
<td>1.47 (0.24)</td>
<td>24</td>
</tr>
<tr>
<td>inner lower wing</td>
<td>4.4 (0.5)</td>
<td>20</td>
<td>0.050 (0.006)</td>
<td>0.74 (0.09)</td>
<td>13</td>
</tr>
<tr>
<td>Pectoral</td>
<td>3.0 (0.8)</td>
<td>25</td>
<td>0.043 (0.011)</td>
<td>0.37 (0.02)</td>
<td>7</td>
</tr>
<tr>
<td>Flank</td>
<td>2.2 (0.6)</td>
<td>28</td>
<td>0.034 (0.009)</td>
<td>0.36 (0.06)</td>
<td>6</td>
</tr>
<tr>
<td>Peritoneal</td>
<td>1.9 (0.3)</td>
<td>14</td>
<td>0.015 (0.002)</td>
<td>0.23 (0.04)</td>
<td>4</td>
</tr>
<tr>
<td>Back</td>
<td>1.5 (0.3)</td>
<td>12</td>
<td>0.010 (0.002)</td>
<td>0.16 (0.04)</td>
<td>3</td>
</tr>
<tr>
<td>inner upper wing</td>
<td>3.1 (0.3)</td>
<td>20</td>
<td>0.035 (0.003)</td>
<td>0.57 (0.07)</td>
<td>10</td>
</tr>
<tr>
<td>Upper primaries and secondaries</td>
<td>0.3 (0.1)</td>
<td>180</td>
<td>0.028 (0.009)</td>
<td>1.33 (0.41)</td>
<td>22</td>
</tr>
</tbody>
</table>

mean surface temperature measured by thermography of that section of the bird's surface. The surface area of each section of the bird was the mean of that measured from four dead starlings which were wrapped in millimetre squared graph paper. The twelve sections of the body surface that were used in analysis of the thermal images were marked onto the graph paper and the number of squares counted.

The rate of heat transfer by forced convection from each part of the body was calculated from Newton's Law of Cooling:

\[ q_{\text{con}} = h \cdot A \cdot (T_{\text{bird}} - T_{\text{air}}) \]  

(5)

where \( q_{\text{con}} \) is the rate of heat transfer (W), \( h \) is the heat transfer co-efficient (W/m². °C), \( A \) is the area of each section of the bird (m²), \( T_{\text{bird}} \) the mean surface temperature of each section of the bird measured by thermography (°C) and \( T_{\text{air}} \) the air temperature (°C) (Holman 1986). Air temperature was measured using a shielded mercury thermometer. The heat transfer co-efficient was calculated for each section of the bird, assuming that this was the same as for laminar air flow over a flat plate of the same dimensions:

\[ h = \frac{\text{Nu} \cdot k}{x} \]  

(6)

where \( k \) is the thermal conductivity of air (0.02624 W/m. °C), \( x \) is the length of the section of the bird in the direction of air flow (m) and \( \text{Nu} \) is the Nusselt number. The Nusselt number was determined from:

\[ \text{Nu} = 0.332 \cdot \text{Re}_{0.5} \cdot \text{Pr}^{0.333} \]  

(7)

where \( \text{Pr} \), the Prandlt number (0.7) for air at ambient temperature was taken from Holman (1986). The Reynolds number, \( \text{Re} \), was calculated from:

\[ \text{Re} = u_{\text{air}} \cdot x / \nu \]  

(8)

where the rate of air flow past the bird (\( u_{\text{air}} \), m/s) was the forward flight speed for all sections of the body and forward flight speed plus 1.6 or 3.2 m/s for the inner and outer parts of the wings respectively. The additional air speed past the wings due to flapping was calculated from wing beat frequency and amplitude measured by 3-dimensional stereo cinematography (U. Möller, unpublished data). The
length of the section of the bird in the direction of air flow (x, m) was measured from the graph paper wrapped round the starling carcasses. The dynamic viscosity of air (v) was assumed to be $15.69 \times 10^{-6}$ m²/s (Holman 1986).

Heat transfer from starlings during flight by radiation represented only 2-11% of that by forced convection (Table 1). The hottest parts of a flying starling were the head, legs and inner sections of the upper and lower surfaces of the wing (Figure 4, Table 1). Most of the heat generated by a flying bird originates in the flight muscles as a by-product of the low conversion efficiency between metabolic and mechanical power (Ward et al 1997). Only 7% of the heat dissipated by a flying starling left the bird through the body surface directly external to the pectoral muscles since this part of the body of starling is well insulated by feathers. Heat generated in the flight muscles was instead transported by the blood to thermal windows such as the poorly insulated head, legs and inner part of the area under the wing. These three sections of the surface of a starling together dissipated 21% of heat lost by convection and radiation although they represented only 7% of the surface area of a flying bird. The primary and secondary feathers accounted for almost half of the heat loss, although they were raised an average of only 0.3–0.4 °C above ambient air temperature and the tips of the primary feathers were not visible in most images (Figure 4). This was surprising since flight feathers are not vascularised over most of their length. Heat was presumably transferred to the base of each feather from the blood and then passed by conduction along the length of the feather. The large surface area of the primary and secondary feathers (70% of the surface of a flying starling) and increased rate of convective heat transfer for a given temperature gradient (due to the extra air speed past the wings caused by flapping) allow the wings to become a major route of heat transfer despite their lack of vascularisation.

Heat loss from the legs represented only 2% of total radiative and convective heat transfer when the legs are raised and held in a streamlined position within the feathers. Heat loss from the legs could be increased sevenfold, to 14% of total heat transfer if they were trailed in the air stream. The increased heat transfer predicted from the extended legs was partly due to a fivefold increase in surface area, and partly from the higher heat transfer coefficient computed for extended legs which were treated as cylinders rather than a flat plate (Holman 1986). The legs may therefore play an important part in regulating heat loss from a flying bird. Birds flying under heat stress could significantly increase their heat loss by trailing their legs in the air stream.

Barn Owls

Thermography has recently been used to measure heat loss from barn owls (Tyto alba) during cold weather (McCafferty et al, in press). Barn owl distribution is thought to be limited by the ability to survive cold weather (Taylor 1994) due to poor insulation relative to that of other owls (Kelso and Kelso 1936). The eyes (over 33 °C) and lower abdomen (27–31 °C) were the hottest parts of a barn owl perched at an ambient temperature of 17.6 °C. Heat transfer from the head was almost double that from the rest of the body although it represented only 30% of the total surface area of the bird. Barn owls should therefore conserve heat whilst roosting at low ambient temperatures by closing up the facial disk since owls cannot tuck their heads under their wings in the way that many birds do under cold stress. McCafferty et al predicted that flying barn owls should not suffer cold stress during flight even on cold nights. So much heat is produced during conversion of chemical to mechanical power for flight that barn owls would overheat during prolonged flights if the surface area for heat dissipation did not increase substantially when the wings were opened. Thermal images of a flying barn owl were similar to those of flying starlings (Figure 4), showing that the areas under the wings and the legs were the hottest parts of the bird.

Discussion

Advantages

Infrared thermography provides a method for measuring the surface temperatures of animals without the need to physically contact them. Detailed surface temperature measurements are possible without the technical difficulty required to collect similar information using arrays of thermocouples or thermistors: a study of heat loss from the tail of captive coypu, for example involved a series of 600 thermocouples (Krattenmacher and Rübsamen 1987). Animal coats, which have low heat capacities, can give false surface temperatures readings if these are measured using conventional probes that are attached to the animal (Cena 1974). Since body surface temperature is influenced by both body and ambient temperatures (Bartholomew et al 1964; Webb et al 1992) it would generally be possible to infer deep body temperature of an animal using this methodology. Given the temperature of the surface, heat transfer by radiation and convection can also be quantified. This can be used to evaluate the relative contributions of various heat loss mechanisms to total heat loss (e.g Webb et al 1992) or the major anatomical routes by which animals are dissipating heat (Lancaster et al 1997; Speakman et al
The method is particularly useful for animals performing behaviours such as flight where surface temperature measurements by attaching instruments is difficult or impossible.

The technique is easy to apply requiring only minimal training in use of the equipment (several hours) and the thermal camera can be linked to a standard VHS recorder to take continuous images of objects. Some devices are portable allowing the possibility of remotely measuring the surface (and body) temperatures of animals in the field without the need to capture them.

**Disadvantages**

The principles of the method (see above) require one to know the emissivity of the surface to get an accurate reading of the surface temperature. Minor variations in surface temperature could therefore be confounded by minor variations in surface emissivity. This may limit the accuracy of the measurements. Accurate calculation of convective heat transfer from animals based on thermal images and derived body surface temperatures is also limited by the unknown characteristics of air flow over complex surfaces such as animals. Heat transfer by radiation, the route of heat loss measured directly by thermal imaging, typically represents about 10% of convective heat transfer (Table 1). Rates of convective heat transfer depend upon the heat transfer coefficient, which in turn depends upon whether convection is free or forced, whether air flow past the body surface is laminar or turbulent and upon local variation in air speed past each part of the body. These air flow characteristics are not known for complex and moving shapes like animals. Assumed air flow characteristics, such as those used in the analysis of heat transfer from starlings (above), may differ from those which actually apply.

Each image recorded by the thermal camera is made up of four interlaced scans of the field of view. Since the scanning rate per field is 1/25 seconds, every frame (i.e., every whole image) takes 4/25 seconds to scan. The thermal imaging camera can be linked to a VHS recorder but each frame also needs to be digitised before recording and thus the framing rate of VHS recorded thermal images is slower than for a standard VHS camera. This imposes a limit on the temporal resolution that is possible with the methodology. At present this is about 5–10 frames per second, although as the speeds of microprocessors increase the framing rate will also probably improve. Processing the images to obtain information on surface temperatures is extremely time consuming. Generally once a situation has been set up where the animal is reliably in the viewing field one could capture enough images in an hour to occupy a person processing the images for a month.

Although the machines are portable, the need for liquid nitrogen to cool the semi-conducting radiation detector may limit field applications. Moreover the cameras require topping up with liquid N₂ at regular intervals which restricts the length of time that the camera can be left in unattended operation. In our experience with the AGAEMA 880 system, this period is about 45 to 60 minutes, which severely restricts the ability to remotely view many wild animals which will not return to the viewing field within an hour of topping up the coolant in the camera. The liquid N₂ tips out of the reservoir if the camera is inclined to angles greater than 70° from the horizontal, preventing thermal imaging with the camera pointing vertically up or down.

The magnification of the lenses of the devices we have used require the animal to be within 1–3 m of the thermal camera. Although the focal range of the lens includes infinity, the level of detail in a thermal image declines when an animal is further from the camera because each pixel on the recorded image represents a progressively larger part of the body of the animal. During operation the camera is noisy and therefore a prolonged period of acclimation may be necessary before animals will approach the machine close enough to make detailed measurements of body surface temperature. Finally, the high resolution machines with temperature precision of c 0.1 K are expensive (c 65,000 US$ in 1998). The cheap (500 US$) devices are inaccurate (1-3 °C) and do not allow image capture and detailed analysis of surface variations in temperature.

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