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Accurate temperature measurement in thermography

by T. HAMRELIUS

AGEMA Infrared Systems AB, Development Department. Box 3, S-18211 Danderyd, Sweden

Abstract

In thermography there are many factors that affect and disturb the temperature measurement. For accurate temperature measurement it is crucial to know what those factors are and how they affect the measurement. This paper is an attempt to make an overview of these factors. It describes and exemplifies: how the atmosphere and emissivity affect the measurement; what algorithms the thermal imager uses to compensate for the radiation that does not originate from the object; how small object size affects the measurement; what features are needed to achieve instrument stability as a function of ambient temperature and time; and how all these factors differ between 3-5 and 8-12 μm waveband systems.

1. Introduction

To measure accurately with thermal imagers it is very important to be aware of the fact that the object temperature is not measured directly but indirectly through the IR-radiation incident onto the IR-detector. This radiation is a function of the object temperature but it is also influenced by other parameters. In fact, the detector receives radiation not only from the object but also from the surroundings, atmosphere and thermal imager *(figure 1)*. The measured signal is consequently a function of all these.

Before the measured radiation can be transformed into temperature it has to be corrected so that the measured temperature is a function only of the object temperature and not of the distance, emissivity or temperature of the thermal imager. An example of a measurement situation *(figure 2)* is meant to illustrate the relative amounts of radiation from the different sources .

This paper is about how all this unwanted radiation is dealt with in order to affect the measurements as little as possible and describes the influence from: the properties of the object, small object size *(§2):* and emissivity *(§3):* the reflected radiation from the surroundings *(§4):* the influence on the measurements from the atmosphere *(§5):* the software model for compensation for atmospheric attenuation and radiation not originating from the object *(§6):* a system which compensates for the radiation from the thermal imager and is needed to eliminate temperature drift (§7); and a short conclusion *(§8)*.

2. Temperature measurement on small objects

An ideal thermal imager would of course measure the same temperature for all object sizes. However, when looking at a small object whose image projected on the detector itself is smaller than the detector (i.e the object does not fill the whole detector area), the detector will measure an *average* of the object and background temperatures. Consequently, the measured temperature for very small objects will be affected by the size of the object.

You would think that the object would be large enough if its projection on the detector was as large as the detector. However, the image of the object is affected by optical diffraction and aberra-

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tions *blur* and by the bandwidth of the detector and electronics. Therefore, the image of the small object must be much larger than the detector, in order not to affect the measurement.

It is easy to measure this *averaging* effect, by placing a variable slit in front of a large black body radiator and measure the modulation of the output signal as a function of the slit width (the slit response function, SRF).

The usual way to specify the spatial resolution is to measure the slit width that gives 50% of full modulation and calculate how many slit widths there are along a line in the image (often referred to as number of resolving elements). When comparing with real objects, which are usually not shaped as a slit, it is probably better to use a circular target and measure the spot response function.

A practical way to use a spot response curve would be to decide upon the largest acceptable error from the *averaging effect.* The minimum object size for that accuracy level can then be calculated with the help of a spot response function curve and the object distance.

The 50% modulation values is suitable for specifying the smallest object size that can be *seen* or resolved in the image or how good the imager is for pure imaging purposes. However, when it comes to temperature measurement, 50% modulation could yield an extremely large measurement error and is by far not sufficient. More interesting from measuring point of view are object sizes that give 90-100% modulation.

One very efficient way to improve the performance, at high modulations is to build in a field stop in a detector image plane when designing the imager. This field-stop prevents stray radiation not derived from the *viewed* part of the object from reaching the detector. The spot response functions for an AGEMA system with a field-stop as well as a thermal imager without a field-stop are plotted *(figure 3).*

Although these two thermal imagers have almost the same resolution at 50% modulation the system with the field stop has got a resolution which is more than three times better at 98% modulation. This means that the object has to be more than three times larger for the system without the field-stop, if the same accuracy is needed.

3. Emissivity

The largest uncertainty when measuring with thermal imagers is probably the emissivity of the object. The emissivity is unfortunately something the operator has to find out for himself and feed in to the computer. How to find the emissivity is beyond the scope of this paper. Still, what might be interesting to know is the resulting errors due to incorrectly assumed emissivity (the emissivity fed into the computer). The errors for some examples are plotted *(figures 4 and 5).*

A large temperature difference between 3-5 and 8-12 μm systems can be noted. In fact the 3-5 μm system is generally less sensitive to errors in the assumed emissivity, especially at high object temperatures.

This is due to the fact that Planck's law yields much steeper temperature to radiation functions for the 3-5 μm than for the 8-12 μm waveband. An increase in the temperature yields a relatively higher radiation increase for the 3-5 μm waveband. Consequently, a change in the radiation signal, caused by a different emissivity, will cause a much smaller temperature error for the 3-5 μm waveband.

In fact 3-5 μm waveband systems show a higher accuracy than 8-12 μm systems not only for temperature errors as a function of the wrong emissivity, but also in the following cases for the same reason:

- temperature errors for small objects, which are not large enough to give 100% modulation (SRF), are smaller for the 3-5 μm waveband;
- temperature errors as a function of a change in the atmospheric transmission are smaller for the 3-5 μm waveband;
- temperature errors as a function of emissivity variations over the object are smaller for the 3-5μm waveband;

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- temperature errors as a function of a wrongly assumed temperature of the surrounding are smaller for the 3-5 μm waveband.

4. Radiation from the surroundings

The radiation received by the detector from the surroundings reflected in the object will not cause any problems when measuring on high emissivity objects. The reflectivity of an opaque object is equal to one minus the emissivity and therefore the reflected radiation will be relatively small. However, when measuring on objects with low emissivity it is necessary to correct for the reflected radiation unless the object temperature is much higher than the temperature of the surroundings in which case the influence of the reflected radiation will be negligible. The smaller the emissivity gets and the lower the object temperature the larger influence the radiation from the surroundings will have. As an example the influence for some cases are plotted *(figures 6 and 7).*

When the temperature difference between object and surroundings is small both 3-5 and 8-12 μm systems are affected in approximately the same way. However when the object temperature is much higher than that of the surroundings the results from a 3-5 μm system are much less affected by the temperature of the surroundings than the results from a 8-12 μm system.

5. Atmosphere

Infrared radiation is absorbed and scattered in the atmosphere. Consequently, the radiation measured by the thermal imager is a function of the distance to the object. All thermal imagers operate in the 3-5 or 8-12 μm atmospheric window where the atmospheric transmission is relatively good. However, independent of which waveband that is used the atmospheric absorption is usually not negligible and must be considered in order to avoid loss of measurement accuracy.

The atmospheric absorption is mainly caused by carbon dioxide and water vapour. Hence, the absorption in the atmosphere also varies with the humidity.

As an example the measured atmospheric transmission for a 3-5 μm system and a 8-12μm system are plotted *(figure 8).* However, it is not the attenuation by the atmosphere that is interesting but the temperature errors induced by it, which for the same two systems are plotted *(figure 9).*
As can be seen from the diagrams the difference in temperature errors between the 3-5 and 8-12 μm systems is small even though the difference in transmission is much larger. This is because of the fact that a small signal change will result in a larger temperature error for the 8-12 than for the 3-5 μm waveband *(see §3).*

The small difference is quite the contrary to what many manufacturers of IR-systems state, "that if you use a 8-12 μm system the atmosphere will not affect your measurements and you do not need to compensate for the atmosphere". But the truth is that a thermal imager without compensation of the atmospheric attenuation will suffer from an unnecessary loss of accuracy when used at any other distance than at the calibration. One reason for the atmospheric attenuation for the 8-12 μm system is that the detector has some sensitivity also outside of the 8-12 μm range where the attenuation is relatively high.

The atmospheric attenuation can be compensated for by built-in atmospheric models that compute the atmospheric transmission as a function of the object distance, relative humidity and atmospheric temperature. However, most thermal imagers do not compensate for the atmospheric attenuation and will as a consequence lose accuracy when measuring at any other distance than at the calibration.

In thermal imagers with built-in software models that compensate for atmospheric attenuation the errors will be a lot smaller. How much smaller is difficult to tell as the errors depend on how good the particular atmospheric software model is for the atmosphere at the time of the measurement. The following test (plotted in *figure 9)* will at least exemplify the improvements as compared to non corrected systems, which can be expected.One conclusion that can be drawn is that measurements with

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compensated 3-5 μm thermal imagers will generally be less affected by the object distance than uncompensated 8-12 μm systems.

The atmosphere also emits radiation (since its emissivity is equal to its absorptivity) and if the atmospheric transmission is low this radiation is quite substantial and should be compensated for. This radiation affects the measurements in approximately the same way as the radiation from the surroundings *(see figures 6 and 7).*

6. The software model for the measurement situation

For the actual correction for the radiation contributions and the atmospheric attenuation *(see figure 1)* there is a software model implemented in the AGEMA thermal imagers. This software model needs the following input data from the operator: the object emissivity, distance to the object, temperature of the atmosphere, relative humidity and temperature of the surroundings (reflected ambient).

The measurement formula that is used in the software model takes into account all these parameters and can under some assumptions be written and derived as follows:

$$Imeas = I(Tobj)*\tau*\epsilon + I(Tsur)*(1-\epsilon)*\tau + I(Tatm)*(1-\tau) \qquad (1)$$

where *Tobj* is the surface temperature of the object, *I(T)* the radiation value (signal value proportional to the radiation from a perfect blackbody at the temperature T integrated over the spectral response of the thermal imager), τ the mean atmospheric transmission within the spectral response of the thermal imager, *Imeas* the radiation value for the total radiation measured by the thermal imager, ϵ the mean emissivity of the object within the spectral response of the thermal imager, *Tatm* the mean temperature of the atmosphere between the object and the thermal imager and *Tsur* means temperature of the surroundings that are reflected in the object,

7. Stability of the thermal imager

In order to get results that are independent of the temperature of the thermal imager, it is necessary to compensate for the radiation emitted by the thermal imager and the telescope lens *(see figure 1).* This radiation is a consequence of the fact that mirrors and lenses absorb radiation and therefore also emit radiation due to Kirchoff's Law (The emissivity of an object is equal to its absorptivity).

The compensation for this radiation is something that most users of thermal imagers have little knowledge of and should not need to bother about since a well designed thermal imager should compensate for this automatically. However, very few thermal imagers compensate for this properly and will consequently present an object temperature affected by the temperature of the thermal imager itself.

To emphasize the importance of an accurate compensation, the drift error as a function of the ambient temperature for two systems were measured *(figure 10).* The first is an AGEMA system, with a compensation system, described as below and the second is a thermal imager with a simpler type of compensation. A non-perfect temperature compensation will result in an error when the thermal imager is used at any other ambient temperature than at the calibration. It will also result in drift after power-on of the system because the thermal imager is being heated up by its own power dissipation.

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How the compensation works in AGEMA systems

The most common way to reduce drift is to use a clamping system with only one built-in temperature reference that the thermal imager *looks upon* to calibrate itself. AGEMA systems use two built-in blackbodies at different temperatures that make it possible to compensate for both offset and gain drift. These variations could be caused by a number of reasons like; radiation emitted by the optics; changing background radiation onto the detector; aging and temperature drift of the detector and electronics; varying transmission due to the lens temperature (applicable only to germanium optics) etc..

However, the described system can only compensate for the optics that are placed between the temperature references and the detector *(figure 11)*. Consequently, the temperature references should be placed outside the imager for the system to compensate for all of its optics. However, this is in practice not possible.

If all optics in the thermal imager have the same temperature this would not be a problem. However, this is only true if the ambient temperature does not vary or there are no temperature gradients in the thermal imager due to internal heating. A solution that works also under varying conditions is a system where the temperatures of the optics placed before the temperature references, are measured with built-in temperature sensors. The contribution to the incident radiation onto the detector can then be automatically computed and deducted.

If the thermal imager is an 8-12 µm imager, which usually means it has germanium optics, the transmission of the lenses is a function of the lens temperature which also has to be compensated for. This is also done by the mentioned microprocessor system that measures the temperatures of the lenses and adjusts the gain to compensate for the varying transmission.

8. Conclusion

To measure accurately with thermal imagers it is very important to correctly compensate for all radiation that does not originate from the object. The following summary includes the most important features needed to achieve this.

1. A *software implemented model of the measurement situation* for *compensation* of the effects on the measurements from the *emissivity, atmosphere* and *radiation* from the surroundings *reflected in the object.*

2. An *atmospheric transmission model* to reduce the influence from the object distance. This atmospheric model should preferably compute the transmission as a function of the *distance, atmospheric temperature* and *relative humidity.*

3. A *good temperature drift compensation* is needed to reduce the influence from the temperature of the thermal imager. This system should have *two temperature references* for *eliminating both gain and offset drift.*

4. In order to measure accurately even when the objects are small the thermal imager needs to have *high slit response function* values not only for 50 % modulation but *for modulations up to 100%.* This ability is greatly improved if the thermal imager has a *built-in field stop* in an *detector image plane* to avoid stray radiation onto the detector.

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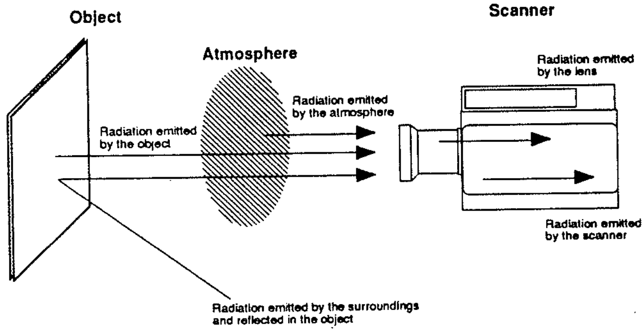

Figure 1. *The radiation contributions in the general measurement situation.*

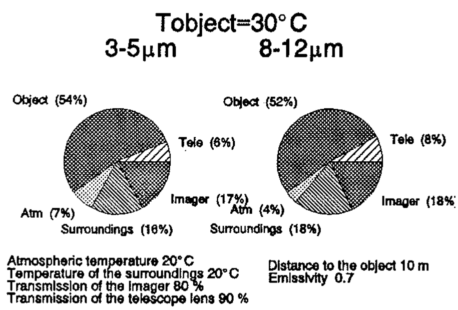

Figure 2. *The relative amounts of the radiation contributions.*

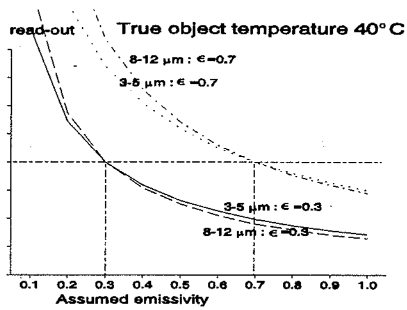

Figure 4. *Temperature read-out as function of the assumed emissivity factor.*

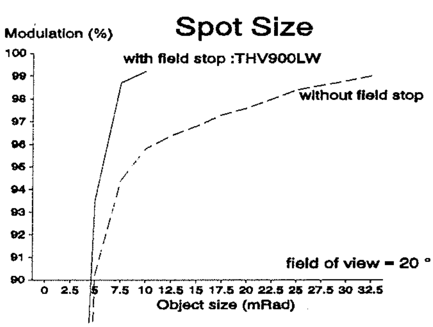

Figure 3. *Spot response functions for thermal imagers with and without a field stop.*

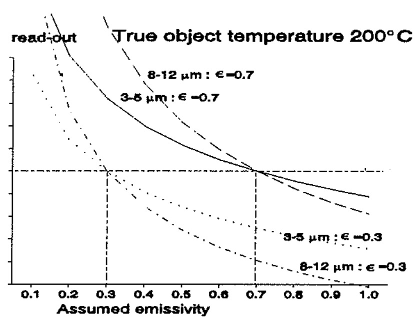

Figure 5. *Temperature read-out as function of the assumed emissivity factor.*

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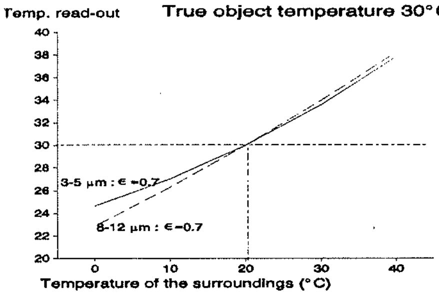

Figure 6. *Influence on read-outs from the reflected radiation from the surroundings (system compensated for a temperature of the surroundings of 20°C)*

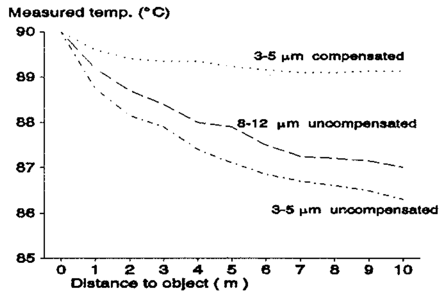

Figure 9. *How the atmosphere affects the temperature measurements of a 90°C blackbody*

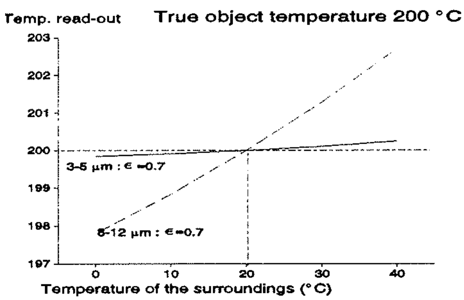

Figure 7. *Influence on read-outs from the reflected radiation from the surroundings (system compensated for a temperature of the surroundings of 20°C)*

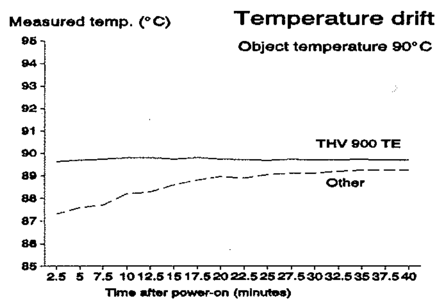

Figure 10. *Temperature drift when measuring on a 90 °C black body as a function of ambient temperature.*

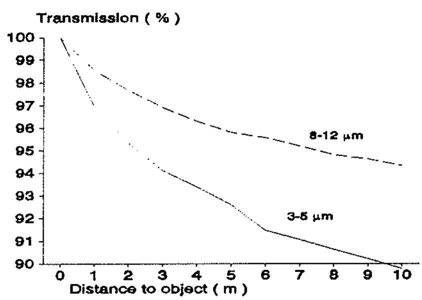

Figure 8. *Atmospheric transmission measured at a 90°C blackbody.(Atmospheric temperature 25°C. Relative humidity 33%)*

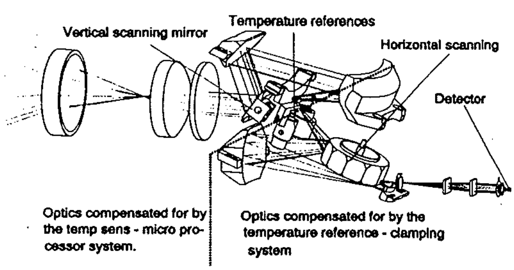

Figure 11. *Optical path of the THV 900*