Estimating Temperature and Emissivity from the DAIS Instrument

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Abstract. Land surface temperature (LST) and emissivity were recovered from thermal infrared data of the Digital Airborne Imaging Spectrometer (DAIS), which has 6 channels in the 8-13 µm waveband region. An Adjusted Normalized Emissivity Method (ANEM) was used, for which the initial emissivity assumption was selected for each surface type according to emissivity measurements available for the study area. DAIS data were corrected for atmospheric effects by means of a nearby radiosounding and a radiative transfer model. LSTs retrieved from original DAIS data were 4-12 ºC higher than “in situ” temperature measurements, what demonstrates the need for a local re-calibration of the DAIS thermal channels. In the present work, a linear re-calibration was performed using “in situ” measurements of temperature and emissivity for two reference fields. With the re-calibrated radiances, the ANEM algorithm was applied to other fields and results were compared with those from the original DAIS data and with ground measurements. In all cases, the re-calibrated data yielded more reasonable results than the original data in terms of both LST and emissivity. Results of this study illustrate the need for coincident ground measurements of temperature and emissivity in selected targets to calibrate DAIS thermal data.

1 Introduction

The recovery of land surface temperature (LST) and emissivity from thermal infrared remote sensing data is complicated since the problem is underdetermined. Thermal radiances vary with both temperature and emissivity, which are coupled in the measurements. If the thermal radiation is measured in N spectral channels, there will be N+1 unknowns: N emissivities (one per channel) and a single surface temperature. Separation of emissivity and temperature requires additional assumptions to break down the indeterminacy. Assumptions are often related to laboratory or field emissivity measurements. Additionally, at-sensor radiances must be corrected for atmospheric absorption and emission, which are mainly due to water vapour. In the present paper, we have addressed the temperature-emissivity separation problem using Digital Airborne Imaging Spectrometer (DAIS) data acquired during the intensive field campaign of ReSeDA on July 1997. DAIS is operated by the German Aerospace Research Establishment (DLR) and has 6 channels in the 8-13 µm waveband region (channels 74-79).

The present study starts with the processing of DAIS thermal infrared data. It includes the atmospheric correction using nearby radiosonde data and the MODTRAN radiative transfer code (Berk et al., 1989), and the local ground calibration of the DAIS data using two test fields as reference, hot and cold targets. The ground calibration was necessary as shown in a previous analysis of the DAIS data over ReSeDA (Coll et al., 2000a). In that study, a comparison with ground measurements taken in the area revealed discrepancies up to 12 ºC. Although the ground temperatures used by Coll et al. (2000a) had problems with the calibration, the large discrepancies were not entirely attributable to errors in the in the ground measurements or in the atmospheric correction. For the present paper, corrected ground temperatures were available and were used for a local re-calibration of DAIS.

Using the ground calibrated, atmospherically corrected DAIS data, a temperature-emissivity separation algorithm was applied. A variety of techniques for temperature and emissivity separation have been developed in the recent years, which differ basically in the assumption or emissivity model considered. The approach followed in this work is based on the Normalized Emissivity Method (NEM, Gillespie, 1986). This method assumes a maximum emissivity value that is used to solve for temperature in all channels. Then the maximum temperature is selected and taken as the actual LST, from which the emissivity can be calculated for the N channels of the sensor. In the NEM method the initial emissivity assumption is fixed for all
pixels, failing to account for differences in maximum emissivity between vegetation and geologic materials. In the present study, the maximum emissivity is varied for each surface type using the field emissivity measurements available for the main surfaces of the study area (Coll et al., 2000b). The Adjusted NEM (ANEM) approach used here combines the simplicity of the original NEM algorithm with the greater accuracy achieved by the use of field emissivity measurements.

2 Processing of thermal infrared DAIS data

The DAIS instrument is a 79-channel high resolution spectrometer covering the wavelength range between 0.5 and 13 µm. Details on the DAIS instrument can be found in Strobl et al. (1997) and Müller et al. (1998). DAIS scans perpendicularly to the flight line, each scan line containing 512 pixels (nominal swath angle ±32º). DAIS channels 74-79 cover the 8-13 µm waveband region. DAIS data are provided by DLR in digital counts calibrated to at-sensor radiances. In the thermal infrared channels one digital count equals 10⁻⁷ W/cm² sr µm. In-flight calibration is performed using two reference blackbodies with different temperatures. We used DAIS flight lines 5 and 7, which were recorded over the ReSeDa test site from an altitude of 2896 m on July 8, 1997. Ground spatial resolution was 6 m approximately. Figure 1 shows grey-tone images of 736 scan lines of 512 pixels from line 5 covering part of the ReSeDa experimental area. The image shows channel 76 (∼10.5 µm) thermal radiances at the aircraft level (no atmospheric correction), with values ranging approximately from 0.92 to 1.51 mW/cm² sr µm (blackbody equivalent temperatures from 23 to 58 ºC). Some fields are indicated in the image with reference numbers. Fields 121, 304 and 201 are sunflower crops with different vegetation cover; fields 126 and 500 are corn crops; field 203 is alfalfa and field 120 is a harvested wheat field containing a certain amount of stubble. Most of these fields can be observed in both flight lines with short time lag, so results for the two lines can be compared.

2.1 Atmospheric correction

At-sensor radiances, \( L_{\text{sens}}^j \), measured by DAIS in channel \( j (j=74-79) \), were corrected to at-surface radiances, \( L_{\text{surf}}^j \), as

\[
L_{\text{surf}}^j = \frac{L_{\text{sens}}^j - L_{\text{atm}}^j(\Theta)}{\tau_j(\Theta)}
\]

where \( \Theta \) is the scan angle, \( \tau_j \) is the atmospheric transmittance from the surface to the sensor altitude, and \( L_{\text{atm}}^j \) is the upwelling atmospheric radiation. The radiance at the surface, \( L_{\text{surf}}^j \), is related to the land surface temperature, \( T \), and emissivity, \( \varepsilon_j \), according to

\[
L_{\text{surf}}^j = \varepsilon_j B_j(T) + (1-\varepsilon_j) L_{\text{sky}}^j
\]

where \( L_{\text{sky}}^j \) is the radiance emitted downwards by the sky at a zenith angle of 53º. This implicitly assumes the so-called diffusive approximation (Kondratyev, 1969), which states that the flux density of the downwelling atmospheric radiances, \( F_{\text{sky}}^j \), is \( \pi \) times the atmospheric radiances at the above-mentioned angle. \( B_j \) is the Planck function weighted for the filter of channel \( j \). Look-up tables were calculated for \( B_j(T) \) for the six thermal channels of DAIS and the temperature range 200-350 K.

The atmospheric parameters \( \tau_j \), \( L_{\text{atm}}^j \) and \( L_{\text{sky}}^j \) were calculated from atmospheric profiles and the MODTRAN radiative transfer model (Berk et al., 1989). The atmospheric profiles were obtained from radiosonde data measured in Nimes by MétéoFrance at 12 UT, which were available through the ReSeDa database. The DAIS flight was about 2 hours earlier than the radiosonde launch time, and Nimes is 35 km west of the ReSeDa experimental area. Moreover Nimes is 60 m above sea level; thus the first levels of the radiosonde were extrapolated to the altitude of the test site (10 m). These differences may lead to inaccurate input profiles and thus to wrong at-surface radiances. However, no radiosondes were available at the test area for the DAIS flight. Using the Nimes radiosonde, the spectra of atmospheric transmittance and radiances were
calculated with MODTRAN and integrated to the DAIS channels. The angular dependency of $\tau$ and $L_{\text{atm}}$ was taken into account in the MODTRAN calculations since the scan angle of DAIS is $\pm 32^\circ$.

### 2.2 Local re-calibration of DAIS thermal data

In order to assess the quality of the DAIS data, a preliminary check was undertaken. We used (1) ground measurements of temperature in two reference fields, (2) emissivity data for the DAIS channels, $\epsilon$, (calculated from ground measurements as shown in Coll et al., 2000b), and (3) the atmospheric parameters of the preceding subsection. With these data, at-sensor DAIS radiances can be simulated and compared with the original DAIS data extracted for the reference targets. The ground temperatures were measured by INRA as part of the ReSeDA experimental set-up, and are shown in Table 1 for the time of the two DAIS flights. $T_{\text{rad}}$ represents brightness or radiometric temperatures in the 8-14 $\mu$m waveband, that is, as given by the radiometers and not corrected for emissivity. To correct for emissivity effects (including the reflection of the sky radiance) and thus calculate the ground LST, 8-14 $\mu$m effective emissivities are required. Emissivities were obtained from field measurements as described in Coll et al. (2000b). The emissivity-corrected temperatures (LST) are also given in Table 1.

The extraction of the original DAIS data was made for line 5, fields 121 (hot target) and 203 (cold target). The location of the measurement sites was known with precise UTM coordinates, so that they can be easily identified in the DAIS images with an accuracy of 1-2 pixels. The comparison of simulated and original radiances is shown in Fig. 2. The original DAIS data are the average values for the 5×5 pixels extracted from line 5 around the estimated site of measurement, with one standard deviation as error bar (in terms of temperature, it is about $\pm 1.5$ °C for field 121 and $\pm 0.5$ °C for field 203). For the simulated data, the error bars correspond to an assumed uncertainty of $\pm 1$ °C in LST, which is the typical absolute accuracy of infrared thermometers.

The comparison of original and simulated radiances is a check of the accuracy of (i) the in-flight calibration of the DAIS thermal data, (ii) the atmospheric correction, and (iii) the ground measurements. However, the large differences shown in Fig. 2 suggest clearly the need for a local re-calibration of most DAIS thermal channels. This is a problem that has been previously noticed in other DAIS flight campaigns (P. Strobl, personal communication). Part of the problem is related to the scan mechanism used by DAIS, which is of the Kennedy type. In this case, there is a considerable fraction of intrinsic background radiation in the signal measured by the detector, which must be compensated in order to obtain the scene radiance (Strobl and Zhukov, 1998). Taking the simulated data as the re-calibrated at-sensor radiances, $L_{\text{rad}}$, a linear equation can be derived for each channel relating the re-calibrated and original at-sensor radiances,

$$L_{\text{rad}}(rc) = G_j \times L_{\text{rad}}^\text{sim} + N_j \quad (3)$$

with $G_j$ and $N_j$ being respectively the gain and offset of the re-calibration equations, which depend on the channel. Table 2 shows the coefficients of Eq. (3) as calculated for line 5 data. It should be recognised that the re-calibration equations introduce uncertainties in $L_{\text{rad}}^\text{sim}(rc)$, since they are affected by both measurements errors and spatial variability of the extracted DAIS radiances. Therefore, a re-calibration uncertainty about $\pm 1-2$ °C in terms of channel brightness temperatures is not unlikely.

### Table 1. Radiometric temperatures ($T_{\text{rad}}$) and emissivity corrected temperatures (LST) measured at the indicated fields at the time of the DAIS flights.

<table>
<thead>
<tr>
<th>Field</th>
<th>$T_{\text{rad}}(\text{C})$</th>
<th>LST (ºC)</th>
<th>$T_{\text{rad}}(\text{C})$</th>
<th>LST(ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>203</td>
<td>24.1</td>
<td>24.7</td>
<td>25.2</td>
<td>25.8</td>
</tr>
<tr>
<td>121</td>
<td>34.0</td>
<td>35.3</td>
<td>36.4</td>
<td>37.7</td>
</tr>
<tr>
<td>102</td>
<td>29.2</td>
<td>30.1</td>
<td>30.7</td>
<td>31.6</td>
</tr>
</tbody>
</table>

### Table 2. Coefficients for the linear re-calibration of DAIS thermal channels, Eq. (3). $N_j$ in DAIS digital counts.

<table>
<thead>
<tr>
<th>channel</th>
<th>$G_j$</th>
<th>$N_j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>74</td>
<td>0.68181</td>
<td>2961</td>
</tr>
<tr>
<td>75</td>
<td>0.77273</td>
<td>1650</td>
</tr>
<tr>
<td>76</td>
<td>0.53743</td>
<td>3963</td>
</tr>
<tr>
<td>77</td>
<td>0.72938</td>
<td>2065</td>
</tr>
<tr>
<td>78</td>
<td>0.75423</td>
<td>1923</td>
</tr>
<tr>
<td>79</td>
<td>0.65872</td>
<td>2933</td>
</tr>
</tbody>
</table>

### Figure 2. Simulated (continuous line) and original (dashed line) at-sensor radiances in the DAIS thermal channels for the two indicated fields, line 5.

### 3 Temperature and emissivity inversion

Equation (2) shows the coupling of LST and emissivity in $L_{\text{atm}}^\text{sim}$ and also that of emissivity and sky radiance in the reflection term. In order to break down the coupling of emissivity and LST, multispectral temperature-emissivity separation methods make an assumption in terms of
emissivity or emissivity variation with wavelength, which is typically based on laboratory and field measurements. One of the simplest algorithms is the Normalized Emissivity Method (NEM; Gillespie, 1986). It assumes a unique emissivity value, $e_{NEM}$, for all channels and all pixels. Then Eq. (2) can be solved for temperature for the N channels of the instrument as

$$B_j(T_{NEM}) = \frac{L_j^{surf} - (1 - e_{NEM})L_j^{sky}}{e_{NEM}}$$

(4)

and $T_{NEM,j}$ is calculated through inversion of the averaged Planck function. Equation (4) provides a set of N values of temperature (one per channel) from which the maximum value is selected, $T_{max} = \max(T_{NEM,j})$. The maximum temperature is now used in Eq. (2) to solve for the N channel emissivities, that is,

$$e_j = \frac{L_j^{surf} - L_j^{sky}}{B_j(T_{max}) - L_j^{sky}}$$

(5)

$T_{max}$ and Eq. (5) provide a first estimate of LST and emissivity, respectively. The accuracy of these estimates depends on the initial assumption of $e_{NEM}$. It can be easily seen that, for a given emissivity spectra, the assumed $e_{NEM}$ should be close to the maximum emissivity in the N channels of the sensor. Then, $T_{max}$ will occur at the channel with maximum emissivity and it will be close to the actual surface temperature. Thus, we have applied the NEM algorithm with variable $e_{NEM}$ values, selected according to the nature of each surface. This Adjusted NEM algorithm (ANEM) was adopted in the present work, as actual values of maximum emissivities were available for different fields of the experimental area. Inspection of databases of spectral emissivity measurements (e.g., Salisbury and D’Aria, 1992) indicates that maximum emissivities occur in the 10.5-12.5 $\mu$m window region for most natural surfaces. In addition, the variability of emissivity is smaller at these wavelengths, with most surface types having emissivities within the range 0.95-0.99. This fact makes easier to choose an adequate value for the maximum emissivity. Models like that of Valor and Caselles (1996) provide a simple means for determining and mapping maximum emissivities with sufficient accuracy using visible/near infrared information. Our calculations show that for temperatures around 300 K, an error of $+0.01 (-0.01)$ in $e_{NEM}$ yields an error of only -0.5 °C (+0.5 °C) in LST.

4 Results and discussion

The ANEM algorithm was applied to the two DAIS flight lines. Recovered LSTs and channel emissivities are presented in this section for several selected fields. The processing of the DAIS data involved three steps. (i) Local re-calibration of DAIS at-sensor radiances: $L_{\text{em}j}(rc)$ is obtained from $L_{\text{em}j}^{\text{sens}}$ (DAIS original at-sensor radiances) using Eq. (3). (ii) Atmospheric correction: $L_{\text{surf}j}$ is calculated from $L_{\text{em}j}^{\text{sens}}(rc)$ using Eq. (1) and the atmospheric parameters $\tau_j$ and $T_j^{\text{atm}}$. (iii) Application of the ANEM method to the at-surface radiances, $L_{\text{surf}j}$. The input maximum emissivities, $e_{NEM}$, were chosen for each field according to measurements shown in Coll et al. (2000b). It can be set to 0.99 for fields with green vegetation, even for covers as low as 20%. This was the case for most of the alfalfa, corn and sunflower crops. For the wheat stubble field (120), $e_{NEM}=0.96$ was selected. These maximum emissivity values usually occur for channel 79.

The procedure was applied on a pixel by pixel basis for both flight lines 5 and 7. Results are presented here in Figs. 3 and 4 for two selected fields as average channel emissivities and temperatures for arrays of 5×5 pixels. For a given field, the data extraction was done for the same spot in the two lines so that it was expected that the retrieved emissivity remained unchanged, whereas line 7 should yield an increase in surface temperature of 1-2 °C according to the measurements of Table 2. In Figs. 3 and 4, the retrieved emissivity spectra are plotted for the centre wavelength of the DAIS channels, the error bars representing one standard deviation over the 5×5 pixels. The derived LST is shown in the legend. For purposes of comparison the results obtained with the original DAIS data (without local re-calibration) are also shown. For each field, the corresponding emissivity spectrum obtained from Coll et al. (2000b) is plotted as a reference.

![Figure 3. NEM emissivities obtained from re-calibrated DAIS data (bold line) and original DAIS data (continuous line) in field 126, lines 5 and 7. The derived LSTs are shown in the legend. Reference spectra are plotted for comparison (dashed line).](image-url)

In all cases, the results obtained with the re-calibrated data were more reliable than those obtained with the original DAIS radiances. With the original data $T_{\text{max}}$ usually occurred for channel 76, which was several degrees warmer than the expected surface temperatures. Consequently, the retrieved emissivities in the other channels were largely underestimated. For line 5 re-calibrated data, Fig. 3 (field 126-corn, full cover) shows an emissivity spectrum more in accordance with the reference emissivity. However, certain spectral variation is observed which does not agree with the reference spectrum. Emissivities retrieved with NEM are quite sensitive to the channel temperatures, $T_{\text{NEM}}$, from which the maximum temperature, $T_{\text{max}}$, is selected. As estimated by our calculations, a difference $T_{\text{max}}-T_{\text{NEM}}$ of 1 $^\circ$C results in an emissivity difference of 0.02. For field 126, line 5, the 6 channel temperatures were within 0.9 $^\circ$C. Notice that the re-calibration process itself could introduce such temperature variations. However it is apparent that the results for the re-calibrated data were better than for the original DAIS data, including the retrieved LSTs. Although no temperature measurements were available for field 126, the derived LST was close to the temperature measured for the full cover alfalfa field 203 (24.7 $^\circ$C, Table 1). Results for other fully vegetated crops (e.g., sunflower fields 201 and 304, and corn field 500, not shown) were mostly similar to those of field 126.

In the case of field 120, line 5 (Fig. 4), the retrieved emissivity shows larger discrepancies compared to the expected values especially for the longer wavelength channels. The retrieved LST is more reliable as it is comparable to the measurements for the “hot” field 121. Problems with the emissivity for the long wavelength channels could be due to uncertainties in the re-calibration, which were particularly larger for the hot target used in this work. Our hot spot (field 121) had a certain amount of vegetation so its LST was not the maximum of the temperature range. For the same reason it was not as uniform as the cold target (field 203, full cover), as revealed by the higher variability observed in the DAIS data extracted for the re-calibration. Additionally it is more difficult in this case to make ground LST measurements comparable to the airborne measurements.

On the other hand, the emissivities obtained for line 7, Figs. 3 and 4, are not consistent with the results for the same spots in line 5. These discrepancies were also observed in the original DAIS data. In this case the derived emissivities in channels 78 and 79 were much higher for line 7 than for line 5. It indicates that the differences in radiance between these and the central channels were smaller for line 7. When the re-calibration equations derived from line 5 data were applied to line 7, the maximum temperatures were consequently obtained for channel 79. Thus the assumed $T_{\text{NEM}}$ was recovered in this channel, the other channel yielding lower emissivities. Although some improvement was obtained compared to results for the original DAIS data, it seems that line 7 should require an independent calibration. However, results are more reliable in terms of temperature since the derived LSTs are a few degrees higher for line 7 than for line 5 in concordance with the measured data.

Finally, results for line 7 re-calibrated data can be validated using the “in situ” measurement of LST available for field 121. This measurement was not used for obtaining the re-calibration equations, although the measurement site was covered by line 7. Results for this field are shown in Fig. 5, where the available LST measurement of Table 1 is shown in the legend. As in Figs. 3 and 4, line 7, the resulting emissivity is only good for channel 79 (where $T_{\text{max}}$ is obtained), with the other channels yielding underestimated values. However, the recovered LST is only 0.4 $^\circ$C higher than the measured value. This gives some confidence to the LSTs derived with line 7 data.

In the case of field 120, line 5 (Fig. 4), the retrieved emissivity shows larger discrepancies compared to the expected values especially for the longer wavelength

![Figure 4](image)

Figure 4. Same as Fig. 3 except for field 120, lines 5 and 7.

Finally, results for line 7 re-calibrated data can be validated using the “in situ” measurement of LST available for field 121. This measurement was not used for obtaining the re-calibration equations, although the measurement site was covered by line 7. Results for this field are shown in Fig. 5, where the available LST measurement of Table 1 is shown in the legend. As in Figs. 3 and 4, line 7, the resulting emissivity is only good for channel 79 (where $T_{\text{max}}$ is obtained), with the other channels yielding underestimated values. However, the recovered LST is only 0.4 $^\circ$C higher than the measured value. This gives some confidence to the LSTs derived with line 7 data.

![Figure 5](image)

Figure 5. Same as Fig. 3 except for field 121, line 7. The “in situ” measured LST is given in the legend.
5 Conclusion

LST and emissivity were recovered from DAIS thermal data using an adjusted NEM algorithm in which the initial emissivity, $\varepsilon_{\text{NEM}}$, was selected for each surface type from available emissivity measurements. This strategy requires the maximum emissivity for each surface type. However the variability of maximum emissivity is small, with most surface types being in the range 0.95-0.99. Maximum emissivity depends strongly on the presence of vegetation. The Vegetation Cover Method (VCM) proposed by Valor and Caselles (1996) provide a means for determining and mapping maximum emissivities that can be used with DAIS visible/near infrared images. The comparison of LST and emissivities retrieved from thermal infrared DAIS data with ground measurements demonstrated the necessity of a local re-calibration of the DAIS thermal channels. As an example, recovered temperatures were 4-12 °C higher than the values measured in fields 203 and 121. For a given field, variations in channel temperatures (after atmospheric correction) were very high, with the extreme channels 74 and 79 yielding much lower temperatures than the central ones. This leads to recovered emissivities with unlikely spectral shape and very low values at the extreme wavelengths. Differences were also found when comparing results for two consecutive flight lines. For spots covered by the two lines, the spectral contrast observed in the channel temperatures was smaller in the case of line 7. The observed discrepancies can not be entirely attributed to possible errors involved in the data processing (atmospheric correction, ground measurements of emissivity and LST). Rather they suggest a miscalibration of the DAIS thermal channels; a problem that has been already noticed by DLR in other DAIS data takes. In a recent DAIS campaign held in Spain, 1998, a best in-flight calibration was achieved, but ground calibration was still necessary. In this case, we used three targets for a linear calibration with a set of calibration coefficients for each flight line. The results obtained for this data set were much encouraging and demonstrated the utility of calibrated DAIS images for temperature-emissivity separation (Coll et al., 2000c).

In the present work, a local re-calibration was performed using “in situ” measurements of temperature and emissivity. LST data were limited to the two fields mentioned above so that only a linear re-calibration was possible. With the re-calibrated radiances, the NEM method was applied to other fields and the results were compared to those from the original DAIS data. In all cases, the re-calibrated data yielded more reasonable results than the original data, considering both the LST and the emissivity spectra. Derived temperatures were in the range of the “in situ” measured LSTs, and emissivities were closer to the reference spectra. As expected, results were worse for line 7, suggesting that a particular set of re-calibration equations is needed for each line. The re-calibration equations used here were derived from line 5 data since the cold target was not included in the image of line 7.

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