Acquisition and processing of airborne thermal infrared data during the ReSeDA experiment

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Received ??? – Accepted ???

Abstract

During the ReSeDA experiment, airborne multi-directional and multi-temporal Thermal Infra-Red remote sensing data were acquired with a wide angle camera. The data acquisition was performed on 19 days from March to September 1997 over a 5 × 5 km² flat agricultural area located near Avignon, South-East of France. Flight altitudes were 3000 and 1500 m, corresponding respectively to 20 m and 10 m pixel sizes.

More than 15 thousands images were recorded on tapes, digitized and processed. This paper describes the experiment and the data acquisition, as well as the data processing methods including the absolute radiometric calibration of the sensor, the correction of instrumental angular effects, the removal of atmospheric effects, and the geometric matching. Errors analysis and potential applications of the data set are also presented.

1 Introduction

With the present on-orbit satellite earth observation systems and the near future satellite projects, more and more remote sensing data will be available over the whole spectral domain with good spectral, directional, spatial and temporal sampling. The main objective of the European ReSeDA program is to improve the use of such multi-sensor and multi-temporal observations for monitoring soil and vegetation processes at local and regional scales thanks to the assimilation of remote sensing data into canopy and soil functioning models (Baret et al. 1999). Seguin et al. (1999) showed that the suitable pixel size when considering the European agricultural field scale is 40 m. At the present time, the unique tool for having access to such a spatial resolution is airborne remote sensing. During the ReSeDA experiment that lasted from December 1996 to December 1997, a set of 19 flights has been performed over the 5km × 5km experimental site (E4°45’, N43°46’) with a thermal infrared camera for completing the ReSeDA database. This paper describes the data acquisition, the specific methods carried out for image processing, as well as the quality assessment of the generated TIR database.

2 Airborne images acquisition

The images were acquired from March to October 1997 with a thermal infrared camera INFRAMETRICS 760 flown on board a PIPER PA28 ARROW4 aircraft.

The INFRAMETRICS 760 is a classical video camera that delivers 25 images per second. Observed targets are scanned by a system of two oscillating mirrors, and the beam is focused toward an HgCdTe detector cooled at 77 K by a Stirling system. Radiometric resolution is about 0.2 and 0.4 °C for brightness temperature dynamics of respectively 20 and 50 °C. The standard image size is 250 lines × 256 columns. During the ReSeDA experiment, the camera was used with both a 80 ° aperture lens that allowed multi-directional observations, and a spectral filter ranging from 7.25 to 13.25 μm.

The 19 flights were performed around the solar noon at the following dates: 12/03, 26/03, 10/04, 16/04, 18/04, 24/04, 01/05, 02/05, 15/05, 22/05, 09/06, 12/06, 24/06, 08/07, 28/07, 29/07, 04/09, 09/09, 18/09/97. Twelve of them were carried out at a 3000 m altitude with both the INFRAMETRICS 760 and the airborne PolDER sensor flown on board (Leroy et al., 2000), while observations were performed at 1500 m altitude for scaling change research purpose. For the 7 other days, only 1500 m altitude was considered without PolDER on board.

The 3000 m altitude flight lines were set up in order both to cover the whole site and to perform multidirectional observations (Fig. 1). Four lines were parallel to the solar plan and one was perpendicular. Three 1500 m altitude flight lines were designed parallel to the solar plan. The spatial resolutions were 10 and 20 m for respectively 1500 m and 3000 m altitudes.

The 25 Hz thermal infrared video images were recorded using a professional magnetic recorder, and then digitized at a 1 Hz frequency.
Fig. 1: Aircraft schematic flight plan: four lines are oriented roughly parallel to the solar direction, and one line perpendicular to that direction. The square represents a 5 km x 5 km area around the Alpilles site (Original draw from Leroy et al., 2000).

3 Data Processing

Four kinds of processing have been performed:
(a) the absolute radiometric calibration of the sensor, in order to derive the target brightness temperature at sensor level from the image digital count;
(b) corrections of instrumental angular effects such as geometric distortions and radiometric response;
(c) atmospheric corrections, in order to estimate ground level surface brightness temperature;
(d) geometric matching of each image to a geographical map (Lambert II projection).

3.1 Absolute Radiometric Calibration

Cameras such as the INFRAMETRICS 760 are generally calibrated with an absolute accuracy of 2 °K. Checks on this absolute accuracy with a constant-temperature blackbody showed two phenomena: (a) the camera estimate increased as a function of time with a maximum amplitude of 3 K, and (b) 120 minutes after instrument ignition, the measured temperature tended towards a stable value, which could be lower or greater than the black body temperature depending on the difference between ambient and target temperatures (Fig. 2).

In order to improve the calibration accuracy, measurements were performed with the camera aiming at a blackbody for different ambient (15, 25 and 35 °C) and target (15, 25, 35, 45, and 55 °C) temperatures. For one couple of ambient-target temperatures among the 11 situations, both the measured temperature and the sensor internal one were recorded during 3 hours. The analysis showed an overestimation when the internal temperature was higher than the target one, and an underestimation when it was lower. This could be explained by the difference between the thermal emission of lens towards the detector and the loss of target's incoming radiance due to the lens absorption. Moreover, it has been observed that the internal temperature of the sensor was well correlated to the "Scanner temperature" printed on the video images every 24 seconds. Consequently, a simple 2nd degree polynomial has been adjusted to estimate the actual target brightness temperature by taking into account the "Scanner temperature" and the measured one. Results presented a Gaussian calibration residue distribution (difference between sensor and reference temperatures) with a mean value of 0 °C and a standard deviation of 0.23 °C (Fig. 3).

3.2 Corrections of instrumental angular effects

Due to the optical properties of the wide angle lens used with the INFRAMETRICS 760, we had to remove instrumental angular effects. Three kinds of corrections were performed.

Firstly, geometrical distortions were modeled from the results of an experimentation consisting in imaging a regular mesh grid. A 3rd degree polynomial model was calculated to superimpose the reference and its image. Optical center has been accurately located, and did not correspond to the digitized image center.

Secondly, sensor radiometric directional sensitivity has been characterized. The experiment consisted in observing a homogeneous water surface while the sensor-target system was radiometrically isolated and in thermal equilibrium with its environment. The angular variation of the water emissivity was assumed to be negligible between 0 ° and 40 °. The resulting images were noisy on sides, and didn’t obey to any low degree polynomial fitting. Therefore, we decided to generate an image of temperature difference between each pixel and the optical center. This image presented an dynamic of 0.8 °C. It was next subtracted to each brightness temperature image at the sensor level during the processing.
Fig. 3: Results of the improved absolute calibration of the INFRAMETRIC 760 camera from 11 days measurements (3 ambient and 5 blackbody temperature)

Thirdly, the lens aperture has been determined thanks to an experiment that consisted in aiming at a rectangular frame. The size of this frame was variable and adjusted such as its image coincided with shot. This allowed to estimate the lens aperture thanks to a linear regression between the frame size and the target - sensor distance. Next, we computed each pixel zenith view angle by assuming that the image and the target were symmetrical with respect to the optical center. Finally, we took account for geometrical distortions since they involved that the symmetry was not valid anymore. This provided corrections about 6° for high zenith view angles.

3.3 Atmospheric corrections

Analysis of atmospheric effects on the airborne TIR images

Atmospheric perturbations are induced by both thermal emission and absorption of the radiance outgoing from land surfaces. As these effects are induced mainly by water vapor, they strongly depend on air temperature and humidity. It is well known that great differences between remotely sensed brightness temperature and ground level one can occur, up to 10K (Becker and Li, 1990). The most famous correction method is the Split-Window applied to multi-spectral sensors like NOAA-AVHRR (Becker and Li, 1990). However, this method requires at least two spectral measurements and therefore can not be used with single channel sensor. In this context, atmospheric corrections of the INFRAMETRICS 760 data were performed using the atmospheric radiative transfer code MODTRAN 3.5 along with radiosoundings launched at the solar noon from the Nîmes meteorological station 30 km away.

In order to define a correction strategy, atmospheric effects on the airborne multi-directional and multi-temporal thermal infrared data were deeply analyzed by taking into account the experimental context. It has been shown that for two typical atmospheric situations, airborne sensed brightness temperatures were smaller than ground level ones, while the difference could reach 5 or 10 °K respectively for a dry and wet atmosphere and a surface brightness temperature of 40 °K (Fig. 4). Besides, important angular effects were underlined: for a 40 °C target, the 45 ° off-nadir sensed brightness temperature could be 2 °C lower than the nadir one (Fig. 5). This difference is comparable to the angular variation of ground level temperature due to surface structure and water state of vegetation cover (Prévot et al., 1995). Therefore, such angular effects have to be removed for studies focused on thermal emission by vegetation canopies.

Figure 4: variation of the difference ΔT between brightness temperatures at sensor and surface levels against surface brightness temperature. Atmosphere of 27/02/97 (very dry) and 04/09/97 (very wet). Altitude = 3000 meters, zenith view angle = 0 °.

Fig. 5: variation of the difference ΔT between off-nadir sensed temperature and nadir one as a function of zenith view angle for a wet atmosphere (04/09/97) and a 3000 m altitude.

Since the radiosoundings were not launched from the experimental site, their representativity was assessed by comparing MODTRAN 3.5 simulations along with these
Practical corrections of atmospheric effects on the airborne TIR images

MODTRAN 3.5 program has been used along with Nimes radiosoundings to derive the surface brightness temperature from the remotely sensed one. However, MODTRAN 3.5 simulations were too demanding in computer resources when processing multi-directional and multi-temporal data. Therefore, we developed two methods to limit computation time (Jacob et al., 1999).

The first method required MODTRAN 3.5 simulations for every flight. It could be divided into 3 steps. Firstly, the simulations were performed by considering surface brightness temperature and zenith view angles ranging respectively from −10 to 60 °C (10 °C step) and from 0 to 50 ° (5 ° step). Secondly, a analytical simplified formulation has been calibrated over these simulations to establish the relation between the sensor level radiance \( R_{T(sensor),b} \), the ground level radiance \( R_{T(ground),b} \), and the zenith view angle \( \theta \):

\[
R_{T(sensor),b} = a \cdot R_{T(ground),b}^3 \cdot \left[ b + \frac{c}{\cos(\theta)} \right] \cdot \left[ d + \frac{e}{\cos(\theta)} \right]
\]

where \( T(sensor) \) and \( T(ground) \) represent respectively temperatures at sensor and ground levels. These temperatures were linked to the corresponding radiance by the Planck’s law. Finally, this calibrated formulation has been used to compute a look up table with a resolution of 0.1 °C in remotely sensed brightness temperature and of 0.1 ° in zenith view angle. The comparison between the simplified formulation and the MODTRAN 3.5 simulations showed that the residual errors was very close to 0 °C, with a standard deviation of 0.025 °C.

The second method did not require MODTRAN 3.5 simulations for every flight, but only daily measurements of the air temperature and the integrated water vapor content. Indeed, the coefficients of the simple formulation were related to these variables by considering different atmospheric profiles of the experimental region. The advantage of this method is that it requires only few MODTRAN 3.5 simulations along with representative radiosoundings. However, the comparison with MODTRAN 3.5 simulations showed more important errors (about 0.5 °C), and could be only used for low accuracy applications. Consequently, the first method was applied to whole thermal camera database.

3.4 Field Validation of Radiometric and Atmospheric Corrections

In order to validate the atmospheric corrected ground level brightness temperature, simultaneous field measurements were performed for 5 days between the 07 July and the 18 September using an infrared thermometer EVEREST AGRI THERM 112ALCS. The thermometer was regularly calibrated \( in-situ \) during the data acquisition using two water bodies (one at the ambient temperature -20°C - and the other at a 45 °C temperature). The data were acquired over alfalfa, grassland and sunflower crops, as well as bare soil fields. This provided surface brightness temperature data ranging from 25 °C to 45°C, with an accuracy about 0.6°C. Each field was spatially sampled using a 20m grid pattern. Figure 7 displays an example of validation over bare soil. We observed that atmospheric correction amplitude reached 10°C, involving a difference between airborne and field estimates about 1.4 °C. This difference could be explained by both possible atmospheric correction errors and field measurements inaccuracy due to the absolute calibration. We should also notice that the spatial representativity was different from one data set to the other. This example of validation corresponded to a hot target that has nearly maximum atmospheric effects. When considering the other surfaces such as alfalfa and grassland, the correction amplitudes were smaller and the differences between airborne and in-situ estimates were less than 1 °C. In the Fig. 7, one should note that after atmospheric corrections, the standard deviation of the airborne data set has increased from 0.6 °C to 1.2 °C, and was then comparable to the one of the field data set.

We should notice that this validation were performed over airborne data acquired after the 08 July. Before this date, we observed some abnormal working phenomenon of the camera like image brightness changes during the acquisition. These images were generally removed for the database construction.

![Fig. 6] Variation against surface brightness temperature of \( \Delta T = T_b \) sensor (from Nimes radiosounding) - T_b sensor (from in situ radiosounding). Atmosphere of 12/06/97. 1500 m altitude.
3.5 Geometric matching

The INFRAMETRICS 760 image registration was performed thanks to a geographic map corresponding to a Lambert II projection. Since the data set size was very large (more than 15 thousand images), we developed a geometric matching method focused on both the computation time and the ground control point identification. Since the coverage ratio between two successive images was about 90%, the method was based on correlation techniques by considering every image flight line by flight line. Firstly, a set of ground control points was determined over the image centered on the experimental site. Secondly, considering two successive images, more than 50 points constituting a regular mesh grid was located on the first and detected on the second by auto correlation technique. These automatically determined points were then checked and validated by visual analysis. Finally, a polynomial geometric transformation was adjusted between the two successive images, and each of them was re-sampled to the Lambert II projection with the nearest neighborhood method.

The visual control and the examination of residual errors showed that when considering the central area of each image (pixels corresponding to zenith view angle lower than 10°), images were well superimposed to the reference map (the typical standard deviation was less than 1 pixel). However, large errors up to 4 pixels occurred for off-nadir pixels. This could be mainly explained by both the large aperture optical system that induced irregular geometric deformations and the errors of the control point determination on the off-nadir image pixels. Since the coverage ratio between two successive images of a flight line was very important (about 90%), these off-nadir registration errors will have less influence for spatial analysis applications by selecting just central parts of images. But for directional analysis, which requires all off-nadir observations, it is recommended to work with at least 10x10 pixels windows in order to minimize these registration errors. For pixel level studies, forthcoming geometric refinement is necessary.

4 Conclusion

During the Alpilles/ReSeDA experiment, airborne TIR data acquisitions were performed on 19 days from March to September over the 5 x 5km experimental site. Acquired data have been processed radiometrically (absolute calibration, instrumental angular effects, atmospheric corrections) and geometrically (image registration to a Lambert II projection). The validation of radiometric processing was satisfying. However, the camera presented radiometric troubles before 8/07/97. Although erroneous data have been removed, the interpretation of the retrieved surface brightness temperature has to be considered with care.

This high spatial resolution data set can be used for multi-temporal and multi-angular analysis at the field scale for nearly complete vegetation growing cycles of winter and summer crops.

At the present time, these data were jointly used with the airborne PolDER ones in order supply the SEBAL model and to provide maps of surface energy fluxes over the ReSeDA experimental site (Fig. 8). The results were encouraging (Jacob et al., 2000). With the same data set, Gu et al. (2000), have successfully underlined the directional variation of the surface brightness temperature (Fig. 9). Besides, these high spatial resolution data could be used to extract information located on field measurements, where vegetation canopy structure parameter, micro-meteorological variables and surface fluxes were measured. This should allow the assimilation of thermal infrared data into canopy and soil functioning models.

We have generated an great set of airborne thermal infrared remote sensing data. Important efforts were devoted to the development of accurate and fast radiometric correction and image registration. These pre-processing have given satisfying results. Further works are necessary for the accuracy improvement of the off-nadir pixel registration, as well as for the operational implementation. At the present time, this airborne data acquisition system is completed by a 6 spectral channel XYBION video camera. All the data are now digitized on board to avoid radiometric perturbations induced by magnetic recording system. In
addition, GPS and inclinometer parameters are integrated to the acquisition system for facilitating image registration.

Acknowledgement:

This work was supported by European ReSeDA project and French PNTS. Authors would like to thank Dr. J.-P. Lagouarde for his kind collaboration to sensor characterization.

Reference

Baret F. et al., 1999; ReSeDA: Assimilation of Multisensor & Multitemporal remote sensing data to monitor vegetation and soil functioning, Second Report.


Fig. 8: Map of the sensible heat flux derived from the SEBAL algorithm using POLDER and INFRAMETRICS data over the ReSeDA site, July the 29th.

Fig. 9: Directional variation of the brightness temperature as observed by the INFRAMETRICS camera over a wheat field. The white star indicates the average sun position.