P6.3 CALCULATION OF DETAILED SURFACE TEMPERATURE MAPS USING THE HELIPOD AND THE TORNADO RECONNAISSANCE AIRCRAFT OF THE GERMAN AIRFORCE

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1. INTRODUCTION

The temperature T_0 of the earth surface is a important parameter for any processes that take place at the interface surface-atmosphere or surface-soil. The turbulent energy transfer between the surface and the atmosphere is triggered by T_0 and the (temperature) roughness length z_0. The convective structure of the atmospheric boundary layer (ABL) is probably connected to the horizontal variability of T_0. Meso-scaled circulations then superimpose the turbulent structure (Raasch and Harbusch 2001; Letzel and Raasch 2003). Numerical simulations of the ABL could be initialized by T_0 instead of the turbulent surface heat flux if z_0 is known. Actually this is the point why large-eddy simulations (LES) of a convective boundary layer (CBL) are still initialized by H_0 which is difficult to determine for a larger heterogeneous area without expensive and extensive field experiments. In such field experiments again, it can be expected that a non-homogeneous surface-temperature distribution has effect on ground-based measurements. Although it is not clear how high above the surface this effect is significant.

However, this investigation does not directly aim on surface-temperature conditioned foot-prints of ground-based measurements or on the improved initialization of a LES. Rather than this we examined how to do the first step: The area-covering measurement of T_0 of a strongly heterogeneous terrain during a field experiment. Of course the most elegant method to do this are satellite observations. Unfortunately T_0 cannot be observed remotely if the surface is covered by clouds regardless at which altitude. For short-time field campaigns like in the framework of LITFASS (Beyrich *et al.* 2002) it is important to obtain the surface temperature unattached to the sky cover while other experiments are running. This can only be achieved with area-covering measurements below the lowest cloud layer.

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Usual airborne research systems like the Do 128 (Corsmeier *et al.* 2001) or the Helipod (Bange *et al.* 2002) that provide high-resolution measurements of the turbulent processes in the ABL are equipped with surface-temperature sensors. But to achieve a high spatial resolution these systems travel at too low airspeed. It takes an hour or two to cover a heterogeneous surface of e.g. 20 km $\times$ 20 km. A much faster aircraft that was equipped with infra-red (IR) sensors was employed during the LITFASS-2003 experiment. The Tornado reconnaissance aircraft of the German Airforce was able to cover the regarded area within a few minutes. So effects of the instationarity of the ABL and the surface could be neglected during the flight. The IR cameras of the Tornado aircraft were optimized on contrast measurement and did not deliver a calibrated temperature. The following describes how the Tornado measurements were calibrated and which accuracy could be achieved.

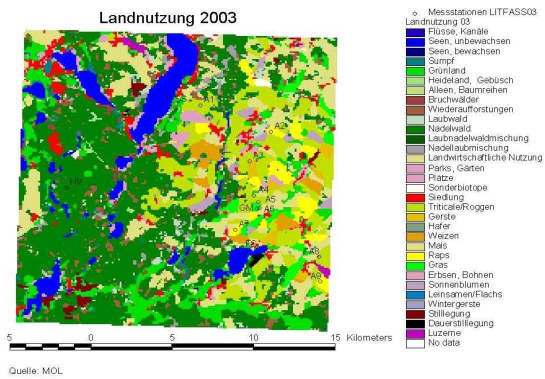

Fig. 1: *Map of the land use of the LITFASS site during the experiment in 2003 (Source: Claudia Heret, TU Dresden).*

2. EXPERIMENTAL SITE AND SETUP

The LITFASS-2003 experiment near Lindenberg (60 km south east of Berlin) was one of the largest campaigns carried out in Central Europe for years. It was part of the EVA-GRIPS (Regional Evaporation at Grid and Pixel Scale over Heterogeneous Land Surfaces) project in the framework of the German climate research program DEKLIM (Mengelkamp 2004). Research groups from all over Germany and the Netherlands observed mainly the water transport in the soil and in the atmosphere. The site with its heterogeneous distribution of grassland, forest, agriculture, and lakes was chosen as typical for Central Europe. Main topic of this joint field experiment was the energy exchange between the earth surface and the atmosphere. The data sampled using various methods and systems will be used for the initialization and validation of numerical models of the atmosphere.

Characteristic for the experimental site was its remarkable heterogeneity (Fig. 1). Within the main 15 km × 15 km site many kinds of agriculture use, forest, lakes, and small settlements were found. More than a dozen micro-meteorological ground stations were installed (Fig. 2) to measure soil and atmospheric parameters. During the main experimental phase in May and June, 2003, these ground-based measurements were supplemented by airborne systems.

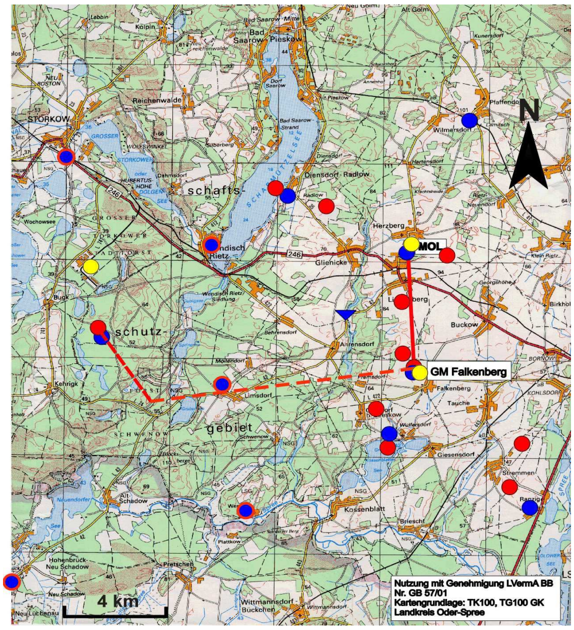

Fig. 2: *Location of the micro-meteorological ground stations during LITFASS-2003 (Source: Frank Beyrich, German Meteorological Service).*

3. AIRBORNE MEASUREMENT SYSTEMS

Beside ground-based stations, wind profilers, LIDAR, SODAR, scintillometers, and a 99 m tower, two airborne systems performed measurement flights. The helicopter-borne turbulence probe Helipod (Fig. 3; see also Bange and Roth 1999) measured the wind-vector, humidity, air and surface temperature mainly during low-level flights (80 to 100 m above the ground). The horizontal flight patterns covered more or less the entire area (Fig. 7). The surface temperature was measured using a IR radiometer (Heimann E 080). This instrument consisted of a KT 19 pyrometer that was periodically calibrated during the flight using a black-body radiator at a given temperature. It was assumed due to manufacturers' information that the absolute accuracy of this system was ± 0.1 K while fluctuations (relative accuracy) were resolved with ± 0.01 K. With this instrument no IR images but one-dimensional data series along the flight path of the Helipod were obtained (Fig. 7).

Fig. 3: *The helicopter-borne turbulence probe Helipod.*

Completely new to the German meteorological community was the use of military jets for research purpose. The Tornado aircraft of the 51th reconnaissance squadron 'Immelmann' (Fig. 4) were equipped with high-resolution IR cameras. The cameras were installed (together with other equipment) in a center-line pod under the aircraft (Fig. 5). Due to its high air speed the IR camera aboard the Tornado aircraft covered the experimental site of about 20 km times 20 km in less than 20 minutes. The surface temperature distribution changed slowly in time, so these photographs represented snapshots of the surface temperature of the entire area. The Tornado camera achieved a spatial resolution in the order of a meter or (depending on the altitude of the aircraft) even better. During LITFASS-2003 the Tornados flew varying missions at 500 and 5000 ft, respectively.

Fig. 4: *The Tornado aircraft of the 51th reconnaissance squadron 'Immelmann' in Jagel, Germany.*

Fig. 5: *The center-line pod under the aircraft contained the IR camera.*

The IR pictures sampled by the Tornado aircraft provided relative temperature distributions and were not calibrated. For the usual reconnaissance task the camera systems were optimized for a maximum contrast and not for absolute temperature measurements. But via the comparison with simultaneous measurements of other involved systems these gray-scale photographs could be calibrated by the surface temperature. Especially the horizontal flights at low altitude with the Helipod provided an excellent calibration tool. The measurements at several ground stations gave the opportunity for data quality control and cross-validation. On four days the Tornado and Helipod flights were combined in order to obtained calibrated surface temperature maps.

4. IMAGE CORRECTION AND GEO-REFERENCE

Before the calibration of the Tornado IR images could be done, some image corrections had to be applied to the raw data. Of course for a correct mapping and reproduction of the earth surface it was essential to know the aircraft position and attitude. Using the position and attitude angles of the Tornado for every individual image it was possible to correct the images in terms of horizontal shift and deformation (Fig. 6). To use a consistent coordinate system both Helipod and Tornado positions were referred to the GPS (Global Positioning System). Since a single GPS gives position accuracies in the range of a few ten to hundred meter, slight shifts between Tornado images and Helipod flight paths were expected and had to be accepted.

The Fig. 7 displays the measured surface temperature along the flight path of the Helipod around noon on 17 June, 2003. The entire area was covered by 2 km wide stripes of Tornado IR photographs. These image stripes were subdivided into smaller images that contained at least two passes of the Helipod (one in North-South and one in West-East direction) for later calibration. Each image was positioned into the map using GPS coordinates. Since the GPS accuracy was limited, most of the image positions had to be corrected by eye referring to the underlying map.

5. IMAGE CALIBRATION

The largest problem of the image post-processing was the internal algorithm that controlled the IR camera of the Tornado during the flights. This algorithm tracked automatically but delayed the camera's aperture when the brightness (the temperature of the earth surface) changed below the aircraft. The algorithm was not known and could not be provided by the manufacturer. So the images were non-uniformly exposed and therefore difficult to calibrate. The first step was therefore to develop an algorithm that identified the delayed tracking of the camera's

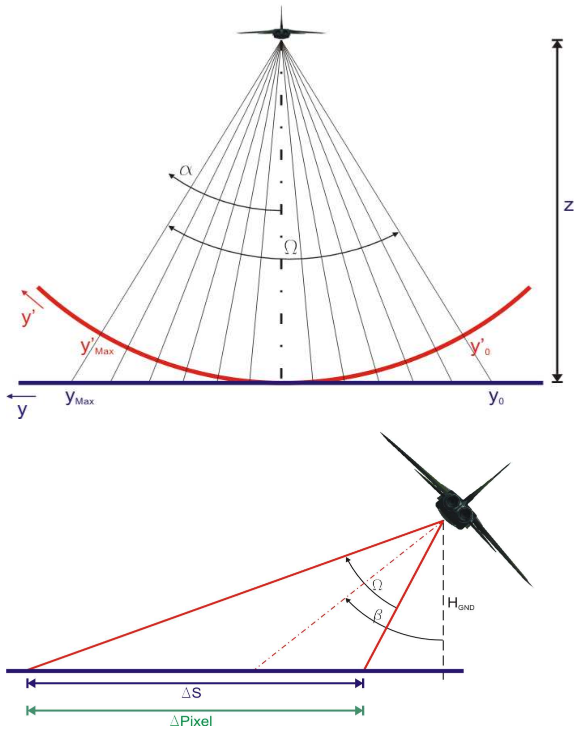

Fig. 6: *For the correct mapping of the IR images and the reproduction of the earth surface some considerations about flight mechanics and navigation had to be done.*

aperture. How this was done will be published elsewhere.

The actual calibration was performed using the Helipod measurements within the individual IR images. The example IR image in Fig. 7 is again displayed in Fig. 8 as a zoom-in to demonstrate the strategy. The position uncertainties of both systems were too large for a pixel-wise comparison of the Helipod-measured T_0 and the grayscale images of the Tornado camera. The positioning error can be identified in the lower part of the image, were the Helipod crossed the edge of the forest (in the IR image) while the Helipod-measured a surface temperature that still belonged to the cooler forest surface. A method was found to solve this problem which again will be published elsewhere. The result is displayed in Fig. 9 as a calibration curve between the gray tones of the IR images and T_0 as measured by the Helipod. The calibration rule turned out to be simple, the calibration curve could be approximated as a linear relation between T_0 and the gray scale.

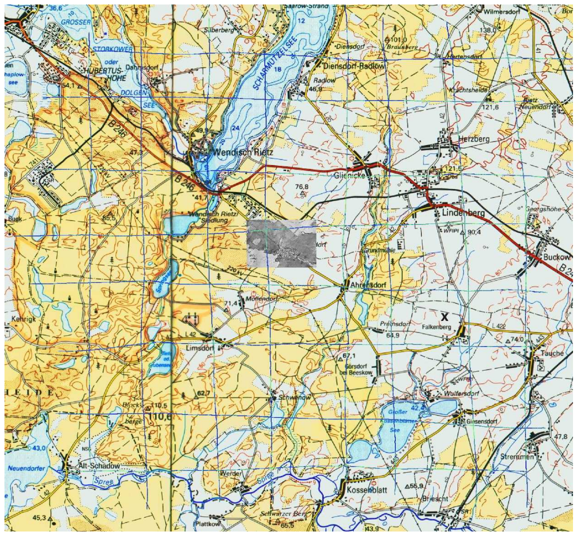

Fig. 7: *Surface temperature (thin green and blue line) as measured by the Helipod on a flight pattern named 'Big Grid'. In the center of the map an exemplary image photographed by the Tornado aircraft was positioned using GPS data.*

6. RESULTS AND DISCUSSION

The calibration rule was then applied to the IR images to turn the gray tones into false colors. The result of the calibration is displayed in Fig. 10 in detail, and for the entire experimental site in Fig. 11. All positioning and calibration errors were now visible as traces left from the Helipod flight path. In general this error seemed to be acceptable. In some images the T_0 data provided by the Helipod flight sections within the image were not sufficient to achieve a proper calibration (these images were flagged). This could happen in cases when the temperature variance due to different surface types along the Helipod flight was to small. The share of biased false-color images on all (about 100) calibrated images was about 5 %. For two images within the experimental site a calibration was not at all possible.

The comparison of the calibrated images (with exception of the biased images as mentioned) with the actually measured temperature (Helipod) led to a calibration error of less than ± 2 K. Compared to the temperature range of 40 K observed by the flights this corresponds to a relative calibration error of less than 5 %. Only three micro-meteorological ground stations offered real surface temperature radiation measurements.

Fig. 8: *Zoomed-in magnification of the IR image in Fig. 7.*

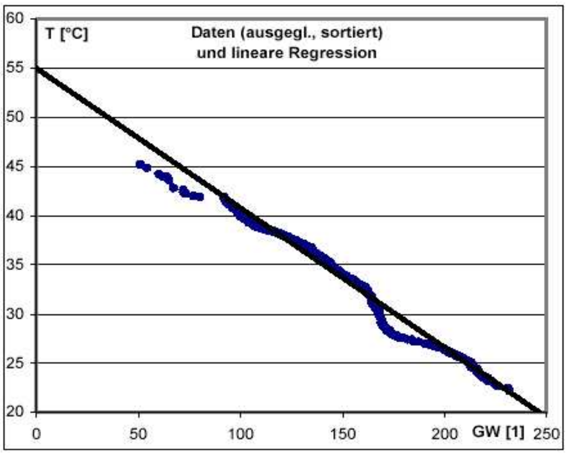

Fig. 9: *Calibration curve as extracted from Fig. 8.*

The comparison of the calibrated images with the T_0 observations at theses stations led also to a deviation of ± 2 K or 5 %, respectively.

7. CONCLUSIONS AND OUTLOOK

The investigated area - the experimental site of the LITFASS-2003 campaign - was much more heterogeneous than expected by the colleagues that worked for weeks and months in this area with their ground stations and other equipment. This was the first impressive result of the analysis of the calibrated surface temperature maps. Especially the influence of the water content of the soil is clearly visible. The maps show im-

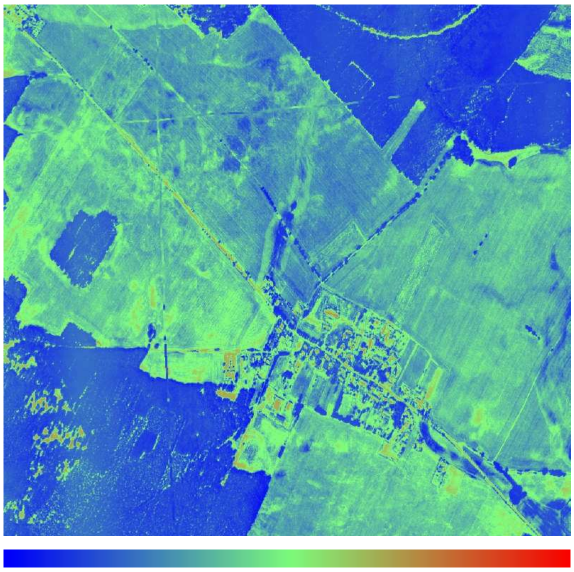

Fig. 10: *The same image as in Fig. 8 after the calibration. The temperature scale starts at 19^o C (blue) and ends at 63^{o}C (red).*

pressively that even on uniformly used agriculture fields there were large horizontal variations in the surface temperature. Crop fields that looked like homogeneous sub-areas within the heterogeneous site even from aboard the helicopter exhibited a complex heterogeneous structure in IR. The temperature variation within such a homogeneous looking field exceed easily 10 K within a few ten or hundred meters distance (see Fig. 10). This could become important for the installation of ground-based stations that were intended to measure area-representative characteristics of the vicinity. It is not clear which effect a strong surface-temperature heterogeneity had on the measurements at the ground stations at e.g. 2 m height. Those researchers running a numerical model that simulated the atmospheric flow in the area wonder if the models account for such a high degree of heterogeneity.

Hiring a military aircraft for meteorological purpose like a field experiment will surely not become a common routine. But the examination of this unique (at least in Germany) experiment with the Tornado aircraft gave many thought-provoking impulses to all researchers that participated in LITFASS-2003. Further analysis will follow.

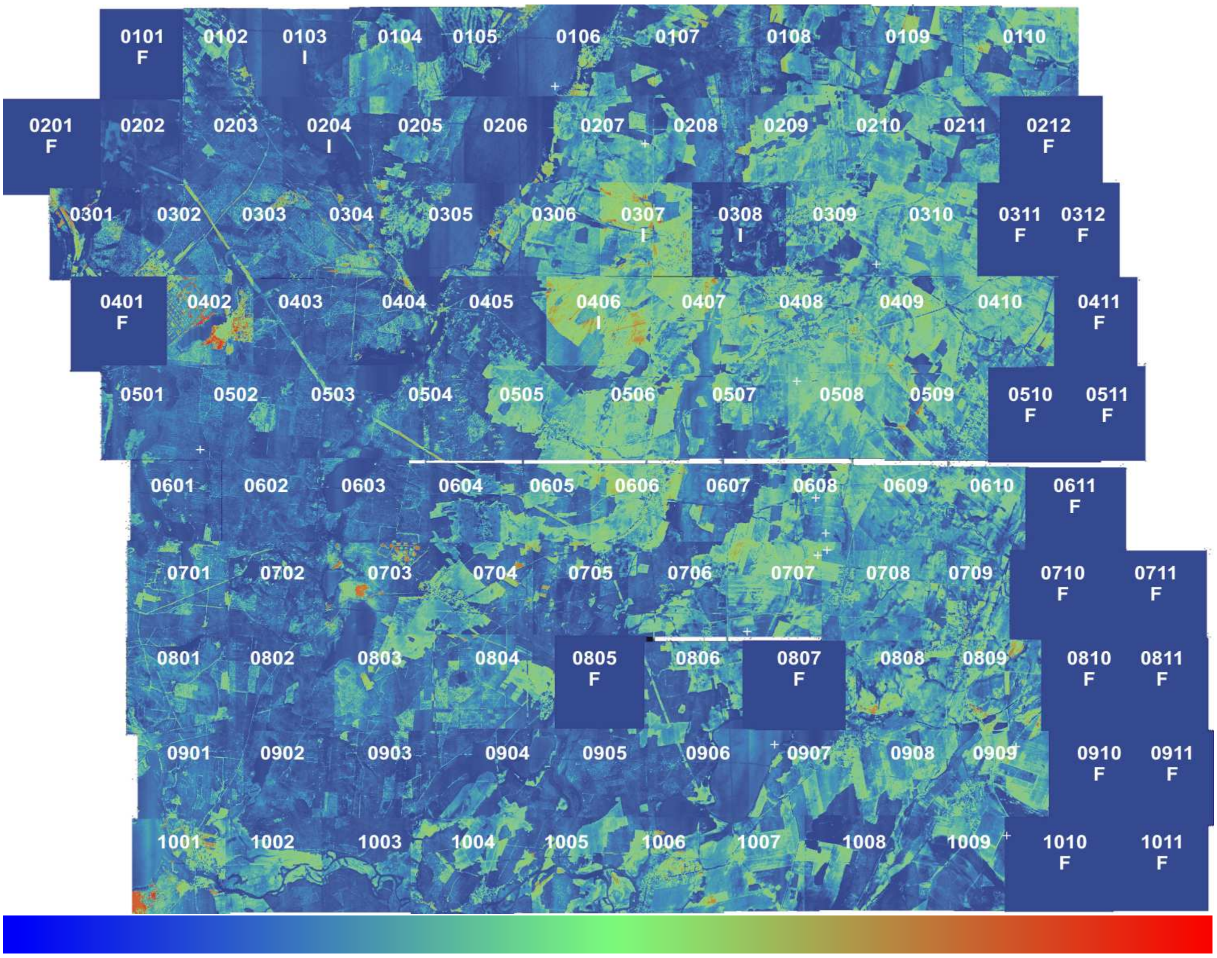

Fig. 11: *The calibrated surface-temperature map for the entire experimental site. The temperature scale starts at 19° C (blue) and ends at 63°C (red). Images with biased temperatures (systematic calibration error) were marked with an 'I'. Those images showing only a 'F' could not be calibrated.*

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