



## Abstract

A fully automatic Horizontal Mobile Measuring System (HMMS) for atmospheric quantities has been developed. The HMMS is based on the drive mechanism of a garden railway system and can be installed at any location and with any measuring track.

In addition to meteorological quantities (temperature, humidity and short/long-wave down/upwelling radiation), HMMS also measures trace gas concentrations (carbon dioxide and ozone). While sufficient spatial resolution is a problem even for measurements on distributed towers, this could be easily achieved with the HMMS, which has been specifically developed to obtain higher information density about horizontal gradients in a heterogeneous forest ecosystem. There, horizontal gradients of meteorological quantities and trace gases could be immense, particularly at the transition from a dense forest to an open clearing, with large impact on meteorological parameters and exchange processes. Consequently, HMMS was firstly applied during EGER IOP3 project (ExchanGE processes in mountainous Regions – Intense Observation Period 3) in the *Fichtelgebirge Mountains* (SE Germany) during summer 2011. At a constant 1 m above ground, the measuring track of the HMMS consisted of a straight line perpendicular to the forest edge, starting in the dense spruce forest and leading 75 m into an open clearing. Tags with bar codes, mounted every meter on the wooden substructure, allowed (a) keeping the speed of the HMMS constant (approx.  $0.5 \text{ ms}^{-1}$ ) and (b) operation of the HMMS in a continuous back and forth running mode. During EGER IOP3, HMMS was operational for almost 250 h. Results show that – due to considerably long response times (between 4 s and 20 s) of commercial temperature, humidity and the radiation sensors – true spatial variations of the meteorological quantities could not be adequately captured (mainly at the forest edge). Corresponding dynamical (spatial) errors of the measurement values were corrected on the basis of well defined individual response times of the sensors and application of a linear correction algorithm. Due to the very short response times ( $\leq 1 \text{ s}$ ) of the applied commercial  $\text{CO}_2$  and  $\text{O}_3$  analysers, dynamical errors for the trace gas data were negligible and no corrections were done.

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# 1 Introduction

The heterogeneity of terrestrial surfaces requires high spatially resolved measurements of atmospheric quantities to quantify their heterogeneous structure close to the surface. Forest ecosystems, which cover a large portion of the earth's surface, are particularly affected by increasing heterogeneity due to wind throws, pests and human activities, such as deforestation. High spatial resolution can be achieved by sampling at various locations (Oncley et al., 2009). This can be realised either by a large number of locally fixed sensors or by (fast moving) mobile measuring systems.

Application of mobile measuring systems started in the middle of the last century. They are used when the spatial representation of the investigation site is required to be as exact as possible, and the number of available, locally fixed sensors is insufficient. In former studies, mobile measuring systems mostly carried radiometers above and under forest canopies to measure the areal distribution of upwelling and/or downwelling radiation (e.g. Leonard and Eschner, 1968; Mukammal, 1971; Brown, 1973; Baldocchi et al., 1984a, b; Péch, 1986; Lee and Black, 1993; Chen et al., 1997; Privette et al., 1997; Blanken et al., 2001). Comparable measurements above grasslands were done by Rodskjer and Kornher (1967, 1971). To study wind velocity and tower-induced errors of its measurements, Dabberdt (1968) built a mobile system which carried an anemometer. Örländer and Langvall (1993) and Langvall and Löfvenius (2002) describe their "Asa-Shuttle", a mobile system, which measures, in addition to radiation, the air temperature along a horizontal transect of decreasing shelterwood density of Norway spruce. The system of Singh et al. (2008) is able to move in two dimensions, the vertical and horizontal. They used their system for the study of river and lake aquatic systems. The mobile system of Gamon et al. (2006) carries a dual-detector spectrometer to measure ecosystem spectral reflectance. The TRAM (Transect Measurement) system of Oncley et al. (2009) runs in a loop, measuring wind velocity (ultrasonic anemometer), the CO<sub>2</sub> concentration, air temperature and humidity. They were able to create a measurement track through a forest ecosystem and over a creek (AmeriFlux

## AMTD

7, 4551–4588, 2014

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from a replica Diesel hydraulic locomotive and mounted under an aluminium plate (300 mm × 1000 mm) incorporating a downward-facing U-profile to increase mechanical stability. This plate serves as the carrier platform of the (a) sensors, (b) data acquisition, and (c) control system for speed and position. The HMMS moves on original LGB rails with a track gauge of 45 mm. The rails are made of brass: due to its high electrical conductivity, electrical power for the entire HMMS system was supplied through the rails (infeed: 24 VDC, 5 A). This infeed covers the total use of the HMMS, which is approx. 3 A for all devices and the rest is used for the drive mechanism, which differs depending on the speed and/or the inclination. The power was fed in continuously every 25 m starting in the middle of the HMMS track (forest edge) and going into both directions (feed points were at positions: 25 m, 50 m, 75 m, 100 m, 125 m) to avoid power loss over long distances. Spring-mounted pick-up shoes (sliding contacts) on both sides of the engines tapped the power from the rails.

Speed and the driving direction of the HMMS are controlled by an analogue throttle (provided by LGB). It's potentiometer is controlled via the HMMS software and a data acquisition (DAQ) device with an analogue output (for a more detailed description of the DAQ device see Sect. 2.1.2). The output of the analogue throttle can be set ranging from 0 VDC (motor standstill) to 24 VDC (full throttle), with the polarity determining direction (+: forwards, -: backwards).

The Sensors and Micro PC of the HMMS need a 12 VDC supply with constant polarity. This is provided by a DC/DC-converter in the second electrical circuit of the HMMS, which has a programmable and stabilised output. Occasional breakdowns of electrical power are buffered by an on board storage battery (12 VDC, 0.8 Ah).

For determination of position and speed, as well as for changing the driving direction, the HMMS was equipped with a commercial raster bar code scanner (CLV412-1010, SICK Vertriebs GmbH, Düsseldorf, Germany). The applied "Code 39" bar code contains information of the distance from the starting point. Besides determination of the position and speed, it is possible to programme distinct speed profiles along the

measuring track. The position of each bar code can be used as a turning point for reversing the driving direction of the HMMS.

A transparent cover, made of Makrolon<sup>®</sup>, was attached to the carrier-platform to protect HMMS electronics and sensors against dirt and moisture (i.e. drizzle and short showers, but not prolonged wet conditions). Four lateral holders at each corner of the carrier-platform (No. 19 in Fig. 1) prevent the HMMS from falling (measuring height during EGER IOP3: 1 m).

### 2.1.2 Software and data acquisition system

The HMMS software (Gesellschaft für Akustik und Fahrzeugmesswesen mbH (GAF), Zwickau, Germany) was installed on a Micro PC (Quanmax QBOX-1010). This is a very small, light-weight, and low power BOX PC with a sufficient number of ports to connect all parts of the HMMS. All measured data were stored on the internal hard disc drive (HDD) of the QBOX-1010.

Through a 16-bit data acquisition (DAQ) device (USB-6211, National Instruments, Austin, USA) the HMMS software manages the control of speed, the determination of position, the driving direction, and the data acquisition of the HMMS. The DAQ device, a very compact box with 16 analogue input and two analogue output channels (additional 4 digital inputs/outputs), handles the two pyranometers, the two pyrgeometers, two extra PT-100 temperature sensors for the pyrgeometers, and the air temperature and humidity sensor. The CO<sub>2</sub> and O<sub>3</sub> analysers and the bar code scanner are connected via serial ports directly to the QBOX-1010. For a detailed overview of all applied sensors see Sect. 2.1.3.

The sensors' sampling rate can be set in the range from 1 to 5 Hz, with a 200 times higher internal oversampling rate to improve resolution and reduce potential (although highly unlikely) aliasing effects, caused e.g. by noises of the power frequency (Bentley, 2005). Oversample Mode is a common practice also used in data loggers. Because of the movement of the HMMS, we used only the first 10% of the internal sampling rate for linear averaging, in order to allocate the measured values to an exact position,

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without having blurring effects. Depending on the chosen sampling rate, data files are updated on the HDD of the QBOX-1010.

### 2.1.3 Sensor system

Due to the demands placed on the sensor system, which are mentioned in the introduction, the final selection of sensors and analysers resulted in a compromise between their weight/size and acceptable response times. The latter may be described by the time constant, which is a sensor/analyser specific quantity. Generally, the smaller the time constant, the smaller are the dynamical errors and consequently spatially smoothing effects of the measurements. An overview of the HMMS sensors and analysers is shown in Table 2, and more detailed information, particularly of their individual time constants  $\tau_{63}$  – which have been determined in our own laboratory tests (see Sect. 3.1) – are given in Table 3.

For air temperature and relative humidity measurements, the HMMS was equipped with a HMP155 temperature and humidity (HUMICAP<sup>®</sup> 180R) probe (Vaisala Oyj, Vantaa, Finland). Both sensors of the HMP155 probe had the highest time constants of all HMMS sensors. A common practice to reduce these time constants is to place the sensors in an aspirated radiation shield tube. To achieve that, the two sensors were detached from the original sensor housing and the sintered PTFE filter, and were then mounted in a double thermal radiation shield tube after Assmann (Assmann, 1887, 1888) and Frankenberger (Frankenberger, 1951). Aspiration has been facilitated by a small PC fan maintaining a linear speed of approx.  $4 \text{ ms}^{-1}$  within the tube. According to the manufacturer's information, the time constant of both sensors of the original HMP155 probe is  $< 20 \text{ s}$ . While our modifications reduced the time constant of the temperature sensor to approx.  $12 \text{ s}$ , there was no change of the relative humidity sensor's time constant. Since the sintered PTFE filter was removed from the HMP155 probe, we changed the relative humidity sensor approx. every 70 operating hours during EGER IOP3 to minimise potential problems of humidity measurements due to the accumulation of dust on the sensor. In comparison with measurements by locally fixed (aspirated)

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(Zahn et al., 2012). Therefore, the signal of the HMMS O<sub>3</sub> analyser was adjusted in-situ by simultaneous O<sub>3</sub> concentration measurements performed at a fixed location 0.5 m lateral to the HMMS track at the turning point of the HMMS in the forest (see Fig. 2, label “49i”). Every time the HMMS passed this point, the fast response O<sub>3</sub> analyser at the HMMS was adjusted to the O<sub>3</sub> monitor (approx. every 10 min). These measurements were performed by a commercial state-of-the art UV-absorption O<sub>3</sub> analyser (Thermo Instruments, model 49i; MLU GmbH, Mödling, Austria).

### 2.2 Correction of sensor response time induced spatial errors

The input signal of most sensors will follow a very sudden change in the measured quantity with certain delay and damping effects. This effects are commonly characterised by an individual sensor response time, or time constant. The bias is usually due to (a) the sensor itself, (b) the sensor’s housing, and/or (c) the sensor’s inlet system, particularly for gas analysers (cf. Mayer et al., 2009). The signal’s temporal adaptation of so-called first-order measuring systems to a sudden temporal change of the quantity to be measured can be described in the following form (e.g. Brock and Richardson, 2001; Foken, 2008)

$$X_o(t) = X_i(t) + \tau \frac{dX_i}{dt} \quad (1)$$

where  $\tau$  is the time constant and  $t$  stands for the time. The time constant  $\tau$  characterises the dependency between the input signal  $X_i$  and the output signal  $X_o$ , in other words the inertia of the sensor and/or the measuring system, respectively. Equation (1) has the following exponential solution

$$X(t) = X_\infty \left( 1 - e^{-\frac{t}{\tau}} \right) \quad (2)$$

where  $X_\infty$  is the final value of  $X(t)$  after final adaptation to new conditions.

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The time constant of a sensor is of much greater importance for mobile measuring systems than it is for standard tower and other stationary measuring systems. The movement of the measuring system means that the time constant can result in an error in time and also in space. The total error of a measuring system is referred to as the dynamical error. A linear change in a measured quantity is achieved when

$$X_i(t) = 0 \quad \text{for } t \leq 0 \quad (3)$$

and

$$X_i(t) = a \cdot t \quad \text{for } t > 0 \quad (4)$$

with  $a$  as a constant and  $X(0) = 0$  as the initial conditions. This leads to a change of Eq. (1):

$$a \cdot t = X_i(t) + \tau \frac{dX_i}{dt} \quad (5)$$

The exponential solution is:

$$X(t) = a \cdot t - a \cdot \tau \left(1 - e^{-\frac{t}{\tau}}\right) \quad (6)$$

The dynamical error can be defined as the second term on the right-hand side of Eq. (6). There are possibilities to correct the dynamical error mathematically and these corrections were done mainly for temperature sensors in aircrafts (e.g. Rodi and Spyers-Duran, 1972; McCarthy, 1973; Friehe and Khelif, 1992; Inverarity, 2000; Saggin et al., 2001). Correction algorithms also exist for the temperature and humidity measurements with radiosondes (e.g. Miloshevich et al., 2004), while another linear correction algorithm for temperature sensors in a vertical moving platform was developed by Mayer et al. (2009). Comparable corrections for measurements with horizontal measuring systems (named in Sect. 1) have not yet been made, because of (a) an

averaging along the measuring track (especially for radiation measurements in more homogeneous measuring sites), (b) a non-moving system while measurements are conducted, to guarantee a full adaptation of the sensor input signal to the prevailing environmental conditions and (c) the application of high-frequency sensors for which the dynamical errors are negligible. The measured values of the HMMS had to be corrected, because we (a) had a heterogeneous measuring site, with the focus on a forest edge (not suitable for averaging), (b) would have lost too many details with non-moving measurements and (c) had weight and money restrictions, so we had to abandon the application of high-frequency sensors (apart from the O<sub>3</sub> analyser).

### 2.3 Site description and application of HMMS

The first field application of the HMMS was during the EGER IOP3 project in June and July 2011 at the *Waldstein-Weidenbrunnen* site (50°08'31" N, 11°52'01" E, 775 m a.s.l.). It is a research site of the Bayreuth Center of Ecology and Environmental Research (BayCEER), and is located in the *Lehstenbach* catchment, part of the *Fichtelgebirge Mountains* (North-Eastern Bavaria, Germany). The site is also a FLUXNET site (DE-Bay, Baldocchi et al., 2001), where CO<sub>2</sub> flux measurements above a dense spruce forest have been conducted since 1996. Detailed information about the site can be found in Gerstberger et al. (2004), as well as in Staudt and Foken (2007). The research site is dominated by Norway Spruce trees of 27 m canopy height (as of 2011). On 18 January 2007, the "hurricane like" low pressure system "Kyrill" destroyed large areas of the dense spruce forest, including areas close to the research site (in a southerly direction). Meanwhile, the clearing's vegetation is similar to the understorey of the forest: grass, fern, bushes (mainly blueberries), young spruces (1–2 m), and deadwood. The scientific focus of EGER IOP3 were diel cycles of energy, water, and trace gases of the soil-vegetation-atmosphere-boundary-layer system of this disturbed forest ecosystem. To investigate the forest edge's impact on the exchange processes, turbulence flux tower measurements were performed at the clearing, at the forest edge, and within and above the forest (see Fig. 2; more details in Serafimovich et al., 2011).

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In addition to these locally fixed towers, the 150 m long measuring track of the HMMS was built in a NNE to SSW direction, perpendicular to the forest edge (75 m in the forest and the clearing, respectively). The track is marked by the dotted line (labelled “HMMS”) in Fig. 2. The elevation difference between start (forest) and end (clearing) point of the HMMS track was approx.  $-8$  m ( $-5\%$ , or  $-3^\circ$ ). Applying a sampling frequency of 1 Hz, the HMMS ran with a quasi-constant speed of  $0.5\text{ ms}^{-1}$  approx. one meter above ground. The HMMS was usually started in the forest, where the  $\text{O}_3$  concentration was continuously monitored by the  $\text{O}_3$  monitor Thermo Instruments, model 49i (see Fig. 2, label “49i”). For a complete reverse run (300 m; forest-clearing-forest) the HMMS needed approx. 10 min.

Taking into account appropriate weather conditions and the main project issues, almost 250 h of data were collected during various day- and night time periods within the 6 weeks of EGER IOP3.

### 3 Results and discussion

By means of laboratory tests we determined the individual time constant  $\tau_{63}$  for most sensors used on the HMMS. The results of the laboratory tests are presented in Sect. 3.1.

Following this, we want to present results from 28 June 2011. There was an almost cloudless sky and, due to preceding dry weather conditions high air temperatures and low humidities also prevailed. Low humidities during nighttime ( $< 90\%$ ) led to the absence of early morning fog and dew. The time series of HMMS were nearly complete during 28 June. Unfortunately, the time series of the ozone concentration reveals larger gaps due to connection problems of the  $\text{O}_3$  analyser. We present the application of the correction algorithm (Sect. 3.2), radiation induced errors in  $\text{CO}_2$  concentration measurements (Sect. 3.3) and diurnal variations in all measured quantities (Sect. 3.4).

### 3.1 Sensor response time determination

A detailed knowledge about the individual sensor response time is unavoidable if the response time induced dynamical errors are to be properly corrected. We therefore conducted laboratory tests, re-positioning the HMMS very quickly ( $< 1$  s) in two different environments possessing different conditions. This was carried out for temperature and humidity by re-locating between a large cold chamber and constant environmental conditions in a room, for long-wave radiation above two water bodies with different temperatures and for short-wave radiation with and without short-wave light. The CO<sub>2</sub> analyser was tested between nitrogen and a CO<sub>2</sub> calibration gas. A laboratory test for the O<sub>3</sub> analyser was not necessary because of the low time constant.

Table 3 gives the exact numbers obtained with the sudden change of the environmental conditions. The signal differences were used for the calculation of the time constant  $\tau_{63}$ , which indicates a change of the signal of 63 % of the final value (Fig. 3). For a better comparison, the signal difference is presented as the normalised difference between the initial value (0.0) and the final value (1.0). The calculation also served for the identification of possible hysteresis effects, which were found for the temperature and humidity sensor. For both sensors, the adaptation to changes in the input signal was faster for a positive signal difference ( $T$ : cold  $\rightarrow$  warm; RH: dry  $\rightarrow$  wet).

A value close to the final signal is measured after a sudden change of the input signal beyond five times the time constant (Foken, 2008). This delay causes, together with the speed of the HMMS ( $0.5 \text{ ms}^{-1}$ ), a spatial relocation of the measurement signal. The calculated values for the spatial relocation can be found in Table 3. The relocation for the sensors with an identified hysteresis can vary, depending on the way the change in the input signal occurs. This relocation can be corrected with the correction algorithm (see section below) or must be taken into account for the interpretation of the data.

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### 3.2 Application of the correction algorithm

The main focus of this work is, besides the technical presentation of the HMMS together with the exact determination of the individual response times, the inspection of the measured quantities. Here, the focus lies mainly on the forest edge: the transition area from the dense spruce forest to the open clearing (this transition area, and not the dense forest or the open clearing, is also the focus of all further investigations in the EGER IOP3 project). An abrupt change in the input signals of all quantities is observable mostly within a few meters distance of the forest edge. Because of the individual sensor response times and the motion of HMMS, the measured input signals lag behind the “true” input signal.

To correct the lag, or rather the dynamical errors in the measurements of the HMMS sensors, we use a correction algorithm of the recorded signal  $X_i$  with a linear adjustment after Eq. (6), a first-order differential equation. However, we are aware that at the measuring site, especially at the forest edge, the prevailing gradients are influenced by turbulence, with an increased number of coherent structures like sweeps and ejections (Eder et al., 2013), and also by small-scale heterogeneities. Within a short time, these structures can have an effect on the gradient, which leads to an overlapping of several different functions and to non-steady-state conditions. There is, for example, a generalised dynamic performance model (Brock and Richardson, 2001), which considers – beside a steady-state solution – a transient solution. Nevertheless, we confined ourselves to the correction algorithm which includes a linear adjustment, since the changes in the quantities caused by the transition from the forest to the clearing are significantly higher than the changes caused by fluctuations of small-scale structures, which have a purely random character.

For the correction, we examined the time series individually for every single run of the HMMS (forest to clearing, or back) and determined the starting point and the endpoint of the significant change and the gradient itself near the forest edge. Afterwards we corrected the measured values to the “true” measured values. After the correction, the

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final value of the signal will be reached earlier in time and also in spatial terms. The investigation of many runs showed us that this procedure is the best way to correct the measured values along the forest edge.

Because of the necessity of an individual determination of the linear function, we decided to correct only that data of measurements which are used for detailed studies of the micrometeorological phenomena near the forest edge. In the following we present two examples of the correction algorithm, and in Sect. 3.4 a daily cycle of all parameters which has not been corrected. Due to a lower spatial resolution of the figures the general information is not disturbed.

Figure 4 shows a nighttime series for air temperature (top) and relative humidity (bottom) of one complete run of the HMMS. The run led from the forest to the clearing (“Forward Direction” – 02:53–02:58 CET) and from the clearing back to the forest (“Backward Direction” – 02:58–03:03 CET). In the forest and in the clearing, measured (uncorrected) values (black solid lines) were almost constant, while near the forest edge there was an obvious steep gradient. For this case, the starting points and the endpoints of the respective in/decrease of the corresponding quantity were determined individually by visual inspection.

The grey lines in Fig. 4 indicate the corrected data of air temperature and relative humidity at the forest edge. They clearly show that a correction of the measured values is required in order to interpret the results of the measurements correctly. The relocation of the measured signal compared to the corrected measured signal is obvious and corresponds to the calculated relocation in Table 3. After the correction the “true” measured values for air temperature have almost the same values at the forest edge, while the gradient for the relative humidity starts in the backward direction much later than in the forward direction. Possible reasons could be (a) an effect caused by the hysteresis or (b) an abrupt change of the gradient affected by turbulent structures, or (c) a combination of both effects.

Figure 5 shows horizontal profiles of short-wave downwelling radiation ( $K_d$ ) and long-wave downwelling radiation ( $L_d$ ) during daytime of the 28 June around the forest edge.

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The significant change of  $K_{\downarrow}$  (top) occurred approximately 5 m north of the forest edge (position measured from starting point: 70 m) because the sun was shining into the first meters of the forest's understorey. In contrast, the significant change of  $L_{\downarrow}$  (bottom) lies exactly on the forest edge (position measured from starting point: 75 m). The profiles in Fig. 5a and c show the uncorrected measurements for  $K_{\downarrow}$  and  $L_{\downarrow}$ , respectively. Time constants of the sensors and the different driving direction of the HMMS led to the zig-zag pattern of the uncorrected measurement data. To correct radiation measurements between 14:00 and 18:00 CET of 28 June 2011, we considered corresponding response times (4 s, see Table 3), defined starting and end points of the linear gradient and calculated the “true” data assuming a linear gradient of radiation data between starting and end point. The dynamical error corrected horizontal radiation profiles, shown in Fig. 5b ( $K_{\downarrow}$ ) and 5d ( $L_{\downarrow}$ ), are nearly free of the zig-zag pattern.

### 3.3 Radiation induced error in CO<sub>2</sub> measurements

Due to the small time constants ( $\tau_{63} < 1$  s, see Table 3), there is no need for a response time induced error correction of the CO<sub>2</sub> and O<sub>3</sub> measurements. Whereas the O<sub>3</sub> measurements, which – with the exception of the mentioned connection problems – were of high accuracy, we observed substantial problems in the CO<sub>2</sub> measurements during daytime. Because of a late delivery of the CO<sub>2</sub> analyser shortly before the start of the project, we had no chance to check the analyser against different influences. Laboratory tests after the project have shown that the CO<sub>2</sub> concentration can be kept at a constant level as long as the analyser is not exposed to direct sunlight, and immediately drifts down if the analyser is subjected to direct sunlight. Because of this we had to discard the CO<sub>2</sub> measurements during daytime, whereas the measured values recorded during nighttime coincide with other CO<sub>2</sub> measurements near the HMMS track. Since larger spatial differences in CO<sub>2</sub> measurements occur mainly during nighttime, this is not a significant limitation in the applicability of the HMMS system. However, in subsequent projects we should consider the use of a different analyser.



The increase of temperature in the morning starts at the clearing significantly earlier than in the forest. And also the decrease in the evening starts earlier at the clearing.

The relative humidity (Fig. 6f) is, at nighttime, higher on the clearing than in the forest and at daytime this is reversed. The decrease after the sunrise is significantly earlier at the clearing than in the forest. Also, the increase in the evening starts earlier at the clearing.

The CO<sub>2</sub> concentration (Fig. 6g) has its maximum in the early morning and early evening under very stable situations. Here the higher values are at the clearing, and also during nighttime the higher values can be found at the clearing. Because of the radiation induced errors in the CO<sub>2</sub> concentration measurements, we have shown only measured values during night.

Unfortunately there are bigger gaps in the profile of the O<sub>3</sub> concentration (Fig. 6h), due to the mentioned connection problems, but the increase in the afternoon is still clearly visible.

## 4 Conclusions

Regarding the technical aspects of the HMMS, we can affirm that the drive mechanism with the garden railway system was uncomplicated in terms of the system integration and the control by the HMMS software, and also the application during dry conditions was uncomplicated. In spite of that, we had several problems with the rail system during the project: under wet conditions the climbing ability of the HMMS was lost; however measurements had to be stopped under these conditions anyway, because of the insufficient waterproofness. And the relatively high coefficient of thermal expansion of brass caused problems in the smooth driving of the HMMS. While during temperatures above 20 °C wave formations in the total rail system could be observed, leading to a halting system, there were during night/early morning (cold temperatures,  $T < 10\text{ °C}$ ) gaps between the 2 m long rail segments observable. If the gap occurred in the first 25 m (Position: 0 to 25 m) or in the last 25 m (Position: 125 to 150 m), this led to

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powerless rail segments and a stopped HMMS system, due to the chosen feed points for the power (see Sect. 2.1.1). Those problems led to a high variability in the durations for a single run of the HMMS. During a subsequent project with the HMMS, which was conducted in summer 2012, we used modified connectors between the rail segments, which resulted in a significant improvement in the rail system. And also a feed in of power up to the end was used to avoid powerless rail segments. Regarding the drive mechanism (here: especially the inner workings of the engines) we were surprised that the engines kept up the 250 h of operating time during EGER IOP3 and that maintenance was only necessary after the end of the project. But an ageing of the engines was already observable over time, which resulted in longer run duration times. We had expected a substantially shortened lifespan of the engines, because the total weight of the HMMS was almost 10 times greater than the original weight of the garden railway locomotive, resulting in a higher axial load and consequently more stress for the engines. A more robust drive system, like e.g. Oncley et al. (2009) used with cables and steel wheels is certainly more uncomplicated in terms of consistency and durability, but on the other side the development effort and financial input is substantial larger.

The set of devices, used for the control of the HMMS, as well as the data acquisition was nearly unproblematic. The HMMS software was together with the DAQ device a perfect interface between the sensors and the data acquisition and also between the determination of position (bar codes) and the HMMS speed and driving direction system. Only the bar code scanner had during humid conditions (morning fog) off an on some failed readings, because of dew on the codes and the sensor's glass and during sunny days the scanner had to be shadowed to avoid failed readings.

In the case of the sensor system on the HMMS, most sensors (CMP3/CGR3, HMP155, O<sub>3</sub> analyser) are frequently used in meteorological measurements and as a consequence, the application was quite simple and the results were adequate. Because of the low accuracy ( $\pm 40$  ppm) and the radiation induced errors in the CO<sub>2</sub> concentration measurements, we should consider a change to a more accurate sensor, or protect the sensor with a housing and cooling system. This could in turn lead



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for their fast ozone analyser, which they lent us for the EGER IOP3 project in summer 2011. Especially their modifications for a smaller and lighter ozone analyser make it possible to measure ozone gradients with the HMMS. We also want to thank the company SICK Vertriebs-GmbH, in particular M. Clement, for the gift of the bar code scanners, and we are also grateful for his fast support. Furthermore, we would like to thank L. Heymann from the Chair of Applied Mechanics and Fluid Dynamics from the University of Bayreuth, who helped us determine the flow rate inside the radiation shielded tube of the HMP155. Qianqian Liu helped us manage the measurements with the HMMS during the project. And we want to thank all other PhD students of the Department of Micrometeorology, student helping assistants and G. Müller from BayCEER for helping us with the construction of the wooden substructure of the HMMS track.

The EGER IOP3 project was funded by the German Science foundation (DFG) under the contract numbers DFG projects: PAK 446 (FO 226/21-1, ME 2100/5-1, RA 617/23-1 and HE 5214/4-1). The funding of the HMMS was realised by the University of Bayreuth and the Max Planck Institute for Chemistry, but not within PAK 446. This publication is funded by the German Research Foundation (DFG) and the University of Bayreuth in the funding programme Open Access Publishing.

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**Table 2.** Sensors mounted on the HMMS are two pyranometers (down- and upwelling,  $K_{\downarrow}, K_{\uparrow}$ ), two pyrgeometers (down- and upwelling,  $L_{\downarrow}, L_{\uparrow}$ ), a temperature ( $T$ ) and relative humidity sensor (RH), a  $\text{CO}_2$  analyser ( $\text{CO}_2$ ), and an  $\text{O}_3$  analyser ( $\text{O}_3$ ). The accuracies are taken from the manufacturers' information.

Parameter	Sensor	Accuracy	Remark
$K_{\downarrow}$	Kipp & Zonen CMP3	$< 15 \text{ W m}^{-2}$	Amplifier used (Factor: 50-fold)
$K_{\uparrow}$	Kipp & Zonen CMP3	$< 15 \text{ W m}^{-2}$	Amplifier used (Factor: 100-fold)
$L_{\downarrow}$	Kipp & Zonen CGR3	$< 15 \text{ W m}^{-2}$	Amplifier used (Factor: 500-fold); optional PT-100 temperature sensor
$L_{\uparrow}$	Kipp & Zonen CGR3	$< 15 \text{ W m}^{-2}$	Amplifier used (Factor: 500-fold); optional PT-100 temperature sensor
$T$	Vaisala HMP155	$\pm 0.1 \text{ K}$	Radiation shield and ventilated with $4 \text{ m s}^{-1}$
RH	Vaisala HMP155	$\pm 1 \%$	Radiation shield and ventilated with $4 \text{ m s}^{-1}$
$\text{CO}_2$	Edinburgh Instruments Gascard <sup>®</sup> NG $\text{CO}_2$ 1000 ppm	$\pm 40 \text{ ppm}$	Vacuum pump DC24/16F (Flow rate: $1.2 \text{ L min}^{-1}$ )
$\text{O}_3$	Enviscope $\text{O}_3$ analyser	$\sim 0.09 \text{ ppbv}^*$	Vacuum pump DC24/80L (Flow rate: $3.0 \text{ L min}^{-1}$ )

\* Accuracy at a measuring frequency of 1 Hz and a mixing ratio of 50 ppbv (1 ppbv = mixing ratio of  $10^{-9}$ ).

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**Table 3.** Results of calculation of the sensor response time with the given signal differences  $\Delta X_i$  in the laboratory test and its consequences on the location of the measured data. The spatial relocation is shown for a positive or negative signal difference, with the possible affect of hysteresis. For the sensors used see Table 2.

Parameter	Signal difference $\Delta X_i$	$\tau_{63}$	Delay time	Hysteresis	Spatial relocation for $0.5 \text{ ms}^{-1}$	
					$+\Delta X_i$	$-\Delta X_i$
$K_{\downarrow}, K_{\uparrow}$	$350 \text{ W m}^{-2}$	$4 \text{ s}^{\text{a}}$	–	no	12 m	12 m
$L_{\downarrow}, L_{\uparrow}$	$150 \text{ W m}^{-2}$	$4 \text{ s}^{\text{a}}$	–	no	14 m	14 m
$T$	5 K	$12 \text{ s}^{\text{b}}$	–	yes	21 m	19 m
RH	15 %	$20 \text{ s}^{\text{a}}$	–	yes	23 m	20 m
$\text{CO}_2$	480 ppm	$< 1 \text{ s}^{\text{a}}$	$0.2 \text{ s}^{\text{d}}$	no	3 m	3 m
$\text{O}_3$	–	$< 0.1 \text{ s}^{\text{c}}$	$0.5 \text{ s}^{\text{d}}$	no	0.5 m	0.5 m

<sup>a</sup> In agreement with the data given by the manufacturer.

<sup>b</sup> 8 s shorter than data given by the manufacturer due to sensor modification.

<sup>c</sup> Developed for high frequency measurements (50 Hz),  $\tau_{63}$  is negligible (no laboratory test conducted).

<sup>d</sup> Delay time caused by the inlet length.

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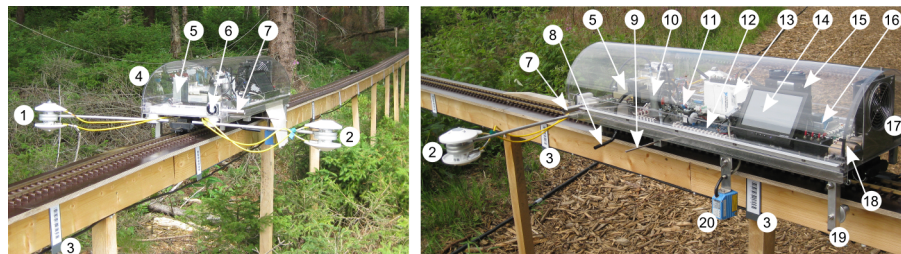
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**Fig. 1.** Front and lateral view of the HMMS. Specifications of the numbers are in Table 1.

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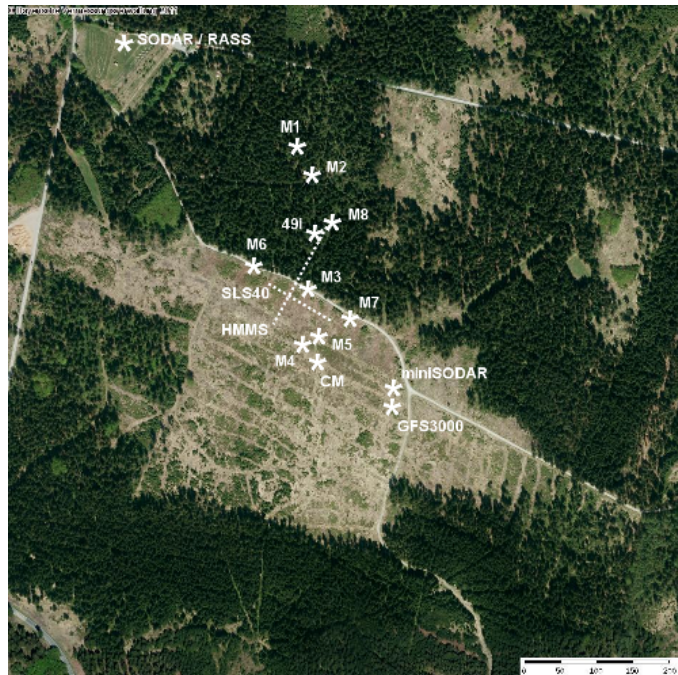
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**Fig. 2.** Top view of the investigation site of the EGER IOP3 project in summer 2011, with all measuring points and exact positions of the main tower M1 (32 m), the turbulence tower M2 (36 m), the forest edge tower M3 (41 m), the turbulence mast M4 (5.5 m), the mast for the Modified Bowen-Ratio Method M5 (3.1 m), the turbulence masts M6–M8 (5.5 m), the mast for chemical measurements CM (2 m), the Laser-Scintillometer SLS-40, the Horizontal Mobile Measuring System HMMS, the ozone monitor “49i”, SODAR/RASS, miniSODAR, and the GFS3000 (leaf gas exchange measurements). The map is oriented to the north. Aerial image taken from Bayerische Vermessungsverwaltung, URL: <http://geoportal.bayern.de/bayernatlas?base=910>.

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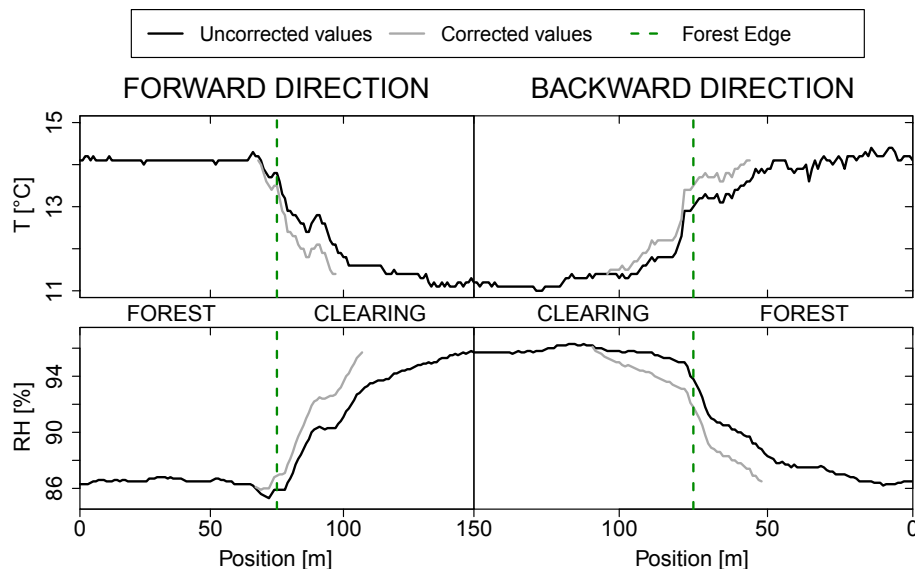
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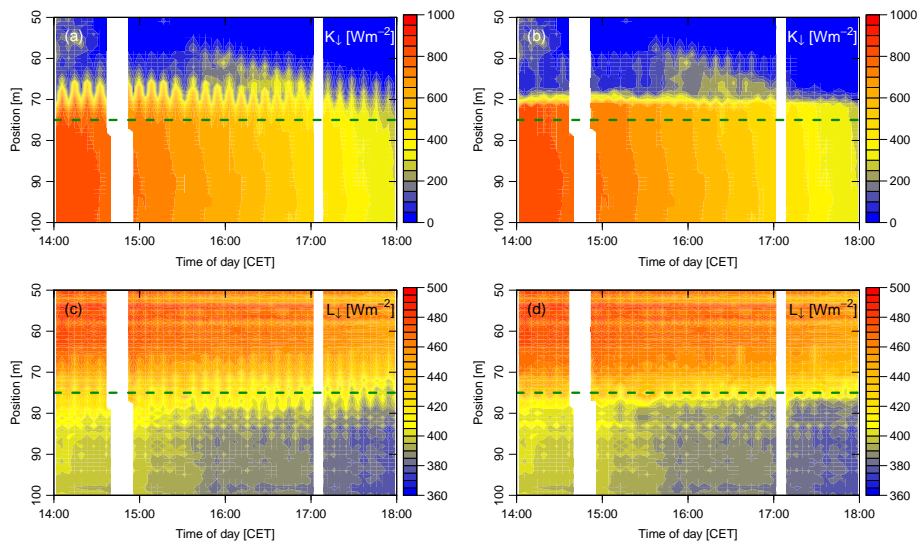
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**Fig. 4.** Example time series of temperature (top) and relative humidity (bottom) for one complete run of the HMMS during nighttime of 28 June 2011. The runtime was 02:53–02:58 CET in forward direction and 02:58–03:03 CET in backward direction. The forest edge is indicated by the vertical green dotted line. The time series shows the uncorrected measured values (black solid line) and, at the forest edge, the corrected gradient (grey solid line).

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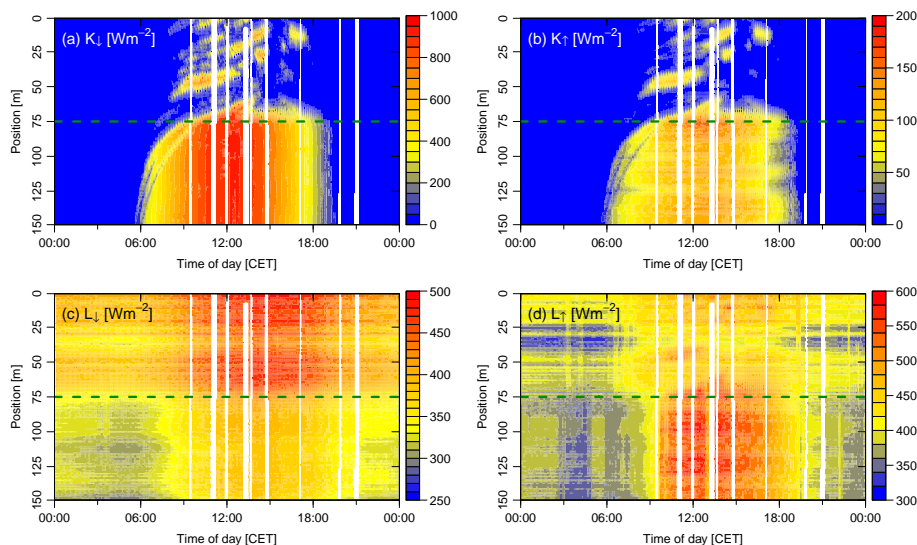
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**Fig. 5.** Detailed horizontal profiles during daytime of 28 June 2011 at the forest edge (horizontal green dotted line), uncorrected profiles for short-wave downwelling radiation  $K_{\downarrow}$  **(a)** and long-wave downwelling radiation  $L_{\downarrow}$  **(c)**, and in both cases response time corrected profiles **(b, d)**. Position shows distance from starting point in meters, starting in the forest (50 m) and ending at the clearing (100 m).

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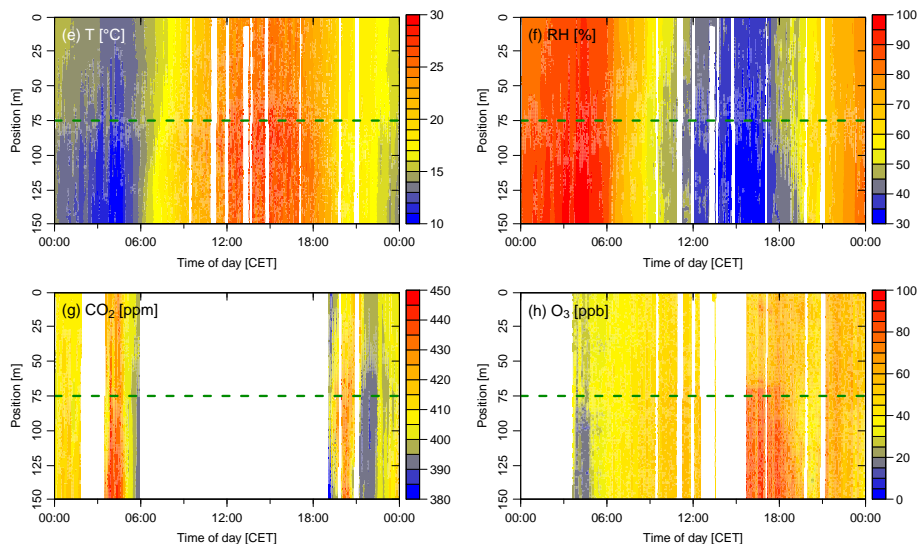


**Fig. 6.** Complete horizontal profile for the whole of 28 June 2011 for all measured quantities. **(a)** shows the downwelling short-wave radiation ( $K_{\downarrow}$ ) and **(b)** the upwelling short-wave radiation ( $K_{\uparrow}$ ). **(c)** shows the downwelling long-wave radiation ( $L_{\downarrow}$ ) and **(d)** the upwelling long-wave radiation ( $L_{\uparrow}$ ). Remark: the scaling of the four radiation components is different in the four graphs. Position shows distance from the starting point in meters, with the starting point in the forest (0 m), forest edge (75 m, horizontal green dotted line) and endpoint at the clearing (150 m).

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**Fig. 6.** Complete horizontal profile for the whole of 28 June 2011 for all measured quantities. **(e)** shows the temperature ( $T$ ) and **(f)** the relative humidity (RH). **(g)** shows the carbon dioxide concentration ( $\text{CO}_2$ ) and **(h)** the ozone concentration ( $\text{O}_3$ ). Position shows distance from the starting point in meters, with starting point in the forest (0 m), forest edge (75 m, horizontal green dotted line) and endpoint at the clearing (150 m).

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