Evaluation of MOST functions and roughness length parameterization on sensible heat flux measured by large aperture scintillometer over a corn field

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Abstract
As part of a comprehensive study investigating how subsurface drainage systems affect the energy and water balances on land surfaces, a large aperture scintillometer (LAS) was used to determine the sensible heat and momentum fluxes over a corn (Zea mays) field. To keep the flux footprint of the observation within the 22 ha field boundary, the LAS had to be placed at a height no greater than 1.8 m above displacement height. As a result, the surface layer was mostly near-neutral at the LAS path height. Sensible heat fluxes were derived from the LAS measurements (\(H_{\text{LAS}}\)) using four different Monin–Obukhov Similarity Theory (MOST) functions for temperature (\(f_T\)). While correlating well with the sensible heat fluxes measured by the Eddy covariance system (EC), the values of \(H_{\text{LAS}}\) were systematically higher if the rule of thumb formula for estimating the roughness length \((z_0)\) was used. The use of this rule of thumb formula led to higher estimates than the EC measurements of the frictional velocity \(u^*\), to which \(H_{\text{LAS}}\) is particularly sensitive under near-neutral conditions. With a modified formula for \(z_0\), a better agreement between \(H_{\text{LAS}}\) and \(H_{\text{EC}}\) is achieved for all the \(f_T\) functions tested. Using the \(f_T\) function (W71) proposed by Wyggaard et al. (1971) and the improved estimate of \(z_0\), \(H_{\text{LAS}}\) agreed with \(H_{\text{EC}}\) within 32 W m\(^{-2}\) and with a regression slope of 1.0 ± 0.05.

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1. Introduction

A wet weather cycle since 1993 has brought the groundwater level closer to the soil surface in many areas in the Red River of the North Basin. Subsurface drainage can be an effective way to maintain crop production in the areas with shallow groundwater or in North Dakota where subsurface drainage was installed.

Eddy covariance (EC) measures the sensible heat flux through the air temperature and vertical wind speed measurements, it relies on the validity of MOST for the calculation of surface fluxes. Therefore, for MOST-based estimates of fluxes to be reliable, a final test should be a comparison of heat fluxes derived from the scintillometry method with those measured independently, such as by an EC (De Bruin et al., 1993).

Comparisons of LAS and EC measurements have shown that the LAS works well not only over uniform landscape (e.g., McAneney et al., 1995) but also over heterogeneous surfaces (Chehabouni et al., 2000; Lagouarde et al., 2002b; Meinjinger et al., 2002b) and terrain of changing elevation (Hartogensis et al., 2003). LAS-derived surface heat fluxes have also been evaluated against other methods,
such as Bowen-ratio energy balance, satellite, or hydrologic models (e.g., Marx et al., 2008; Pauwels et al., 2008).

Some studies have reported the overestimates of the sensible heat flux by LAS over EC. De Bruin et al. (1995) found that the sensible heat fluxes measured by both EC and LAS over a vineyard in a dry area in Spain agreed well with each other if a reasonable estimate of frictional velocity was available. They also found an overestimate by LAS under neutral conditions. Chehbouni et al. (2000) found that their LAS-based sensible heat flux overestimated EC-based values by an average of 30 W m$^{-2}$ over grass and 40 W m$^{-2}$ over mesquite, respectively. They attributed this bias to the overestimation of momentum transfer by the LAS. Lagouarde et al. (2002a) found a systematic overestimation of $\pm$10% in LAS-measured sensible heat flux over a two-surface composite landscape as compared with reference values obtained by the EC, and they attributed this bias to the non-linearity in the integration weighting function for $C^\alpha$ along the LAS path length. In a comparison study of sensible heat flux by a LAS with an EC over an area of Amazonian rain forest and found the flux estimates by the EC are often lower than those by the LAS. The differences between the two measurements would decrease if the averaging periods for EC calculation increase. They attributed the overestimation to the spatial averaging effect of the LAS. Kleissl et al. (2008) reported that sensible heat flux by their three LAS instruments over the same path were 2–17% higher than those by the EC, and the inter-comparison studies (Hartogensis et al., 2008; Kleissl et al., 2008; Kleissl et al., 2009) showed that this systematic overestimation was due to electronic or optical problems in the Kipp & Zonen (the Netherlands) LAS instruments that they used. This performance problem, which also caused significant inter-LAS differences of up to 21%, however, was not found in the LAS instruments either by Scintec, Germany (Kleissl et al., 2009) or by Wageningen University, the Netherlands (Hartogensis et al., 2008), which were used in the other studies mentioned above.

In this study, the use of LAS was evaluated by comparing with the EC measurements over a corn field with subsurface drainage installed in southeast North Dakota, USA. Even though the field is relatively uniform with a single crop, this study differs from earlier experiments in two aspects. Environmentally, the recent wet weather cycle has caused significant rise in the water table, and many fields have subsurface drainage systems installed to mitigate flooding impact. However, the effect of these drainage systems on the surface heat and water fluxes is still unknown (Smits et al., 2010). Operationally, the small area of the field (~22 ha) where subsurface drainage was installed has restricted the size of the footprints of the EC and the LAS, which in turn limits the maximum heights of both instruments to ~1.8 m (relative to the zero-plane displacement). This posed a challenge: the dramatic increases in the height of corn during the growing season might change the surface condition that the LAS saw from within the surface layer initially to the roughness sublayer later. It was of interest to examine whether the change in surface conditions affected the estimate of sensible flux, because, theoretically, MOST only applies in the surface layer. Given these characteristics of our experiment, the objectives of this study include: (1) examine whether changing surface conditions affect the application of LAS in measuring sensible heat fluxes; and (2) test different MOST similarity functions to determine the one that is applicable for the experiment.

## 2. Experiment and theory

### 2.1. Descriptions of the site and the instruments

The test site (Fig. 1) is located near the border of North Dakota, South Dakota and Minnesota at Fairmount, North Dakota, USA (46.00895°N, 96.60568°W), with an elevation of 296 m above sea level. The climate is typical continental, with an annual mean temperature of 6°C, mean precipitation of 330–717 mm and mean potential evapotranspiration of 1030–1307 mm (NDAWN, 2009). The average frost-free days are 137. The prevailing winds during the growing season are either northerly or southerly. The field has an area of 44 ha, of which 22 ha had subsurface drainage system (orange lines in Fig. 1) installed in August 2002 at a mean depth of 1.1 m. In 2008, corn (Zea mays) was planted on April 19 but did not germinate until June 1 because snow storms occurred during late April and early May. In 2009, corn was not planted until May 17 because of early-spring flooding in the area and germinated around May 27.

One EC system was installed in the drained field in both years, and a second EC system was installed in the undrained field in 2009. The EC systems operated from June 10 to October 19, 2008 and from June 2 to October 20, 2009. The configurations for the two EC systems were the same, and each consisted of the following instruments: CSI CSAT3 3D sonic anemometer, CSI KH20 krypton hygrometer, Li-Cor 7500 gas analyzer, Texas Electronics TE525WS tipping bucket, Kipp & Zonen CNR1 net radiometer in 2008 and REBS Q1.1 net radiometer in 2009, Vaisala HMP45C temperature/relative humidity sensor, Hukseflux HP010SC self-calibrating soil heat flux plate, TC4V averaging soil thermocouple probe, and CS616 water content reflectometer. In this study, only the measurements by the EC in the drained field were used. The EC data were recorded every 30 min. In deriving sensible and latent heat fluxes from the EC several standard procedures were followed (Jia et al., 2009), including coordinate rotation correction to force average vertical velocity to zero (Sumner, 2001), sonic temperature to air temperature correction (Paw et al., 2000; Schotanus et al., 1983), the Webb correction to adjust for temperature-induced fluctuations in air density (Webb et al., 1980), oxygen correction accounting for the hygrometer sensitivity to oxygen (Tanner and Green, 1989), and the Horst correction accounting for the separation between sonic and krypton hygrometer (Horst, 2003). The
Bowen-ratio method was used to close the surface energy balance (Twine et al., 2000; Wilson et al., 2002).

A BLS900 (Scintec, Germany) was deployed in 2008 and 2009 (see Table 1 for dates and times of deployment). The pulse repetition rate of the LAS was set at 5 Hz in 2008 and 125 Hz in 2009. The LAS data were recorded every 1 min, and later the values of \( C_2^2 \) were averaged into 30-min intervals for comparison with the EC data. The setup of the BLS900 differed slightly between the two years in orientation and path length, but the location of the EC system was fixed approximately in the middle of the BLS900 path (Fig. 1). The path length was 584 m in 2008 and 610 m in 2009. The heights of the EC and the LAS were adjusted depending on the growth of the corn, and Table 1 lists the heights for the EC (\( z_{EC} \)), the LAS (\( z_{LAS} \)) and the crop (\( h \)) at the dates and times when the BLS900 was deployed. The effective height of the LAS above the crop (\( z_{LAS} - h = 0.67 \) m) was relatively short, ranging from 0.9 to 1.83 m. As explained below, this is mainly constrained by the footprint. Since the height of the corn were rather uniform, with variations of <5%, the LAS beam height was assumed to remain constant along the path, and the uncertainty in the derived sensible heat flux due to this assumption should be <2% (Hartogensis et al., 2003).

### 2.2. Theoretical basis for the large aperture scintillometer

Wang et al. (1978) provided a theoretical description of the LAS by relating the variance of logarithmic light intensity (\( \langle l \rangle \)) received by the receiver (\( I_{in} \)) to the outer scale of the turbulence (\( C_2^2 \)),

\[
\langle C_2^2 \rangle = \frac{1.12 \sigma_{ln}^2 D^{2/3} T^{-1}}{(2)}
\]

where \( D \) is the diameter of the aperture (15 cm for BLS900) and \( T \) the path length between the transmitter and the receiver. The brackets in Eq. (1) denote the average along the path length of the LAS. Theoretically, the real part of the refractive index of air and hence \( C_2^2 \), is a function of temperature, humidity, and pressure. The fluctuation of \( C_2^2 \) due to pressure is small in comparison to that due to temperature and humidity. In the visible and near infrared wavelengths, the contribution to \( C_2^2 \) by temperature dominates; however, the contribution due to humidity is not insignificant and therefore a correction for \( C_2^2 \) needs to be applied to derive \( C_2^2 \). Following Wesely (1976a),

\[
\Delta_1 = \left( \frac{A_1 T^2}{P} \right)^{-2} \langle C_2^2 \rangle f_{BR}
\]

where \( A_1 = -7.87 \times 10^{-7} \) K Pa\(^{-1}\), \( P \) is the pressure in Pa, \( T \) the temperature in K, and \( f_{BR} \) the correction factor due to humidity. For a detailed derivation of \( f_{BR} \), see Moene (2003). Assuming the fluctuations of temperature and humidity are perfectly correlated,

\[
f_{BR} = (1 + 0.03 \beta^{-1})^{-2}, \quad (3)
\]

where \( \beta \) is the Bowen-ratio, the ratio between sensible and latent heat fluxes.

The value of \( A_1 \) in Eq. (2) and the value 0.03 in Eq. (3) given by Wesely (1976a) were estimated for the wavelength of 600 nm. Our calculation using the recent formula of the refractive index of air (Ciddor and Hill, 1999) showed that \( A_1 \) varies 1% from \(-7.87 \times 10^{-7} \) to \(-7.80 \times 10^{-7} \) K Pa\(^{-1}\) between 600 and 880 nm, and the value 0.03 varies about 10% with both wavelength (600–880 nm) and temperature (0–30 °C) but the resulting change in \( f_{BR} \) is less than 1%.

According to MOST, which relates surface fluxes to statistics of scalar quantities that are conserved during advection (Hill, 1997), \( C_2 \), made dimensionless with the temperature scale \( \theta \), is a universal function of the stability parameter \( \zeta \):

\[
\frac{C_2^2 \ln \left( \frac{z_{LAS} - d_0}{z_{MO}} \right)^{2/3}}{T^2} = \frac{f_T}{f_T(z_{LAS} - d_0)} = f_T(z_{MO})
\]

where \( z_{LAS} \) is the height of the LAS beam above the ground, \( d_0 \) the zero-displacement height, and \( z_{MO} \) the Obukhov length. \( T \) is related to the sensible heat flux, \( H \) (e.g., De Bruin et al., 1993):

\[
T_s = \frac{-H}{\rho_a c_p u^*}
\]

where \( \rho_a \) and \( c_p \) are the density and specific heat at constant pressure for air, respectively, and \( u^* \) is the frictional velocity. The Obukhov length, \( z_{MO} \), is defined as:

\[
l_{MO} = \frac{u^* T}{g \theta (1 + \gamma_{BR})}
\]

where \( g \) is the acceleration due to gravitation, \( \kappa \) the von Karman’s constant (0.4), and \( \gamma_{BR} \) the correction due to the buoyancy effect of humidity (e.g., Brutsaert, 1982).

\[
l_{BR} = \frac{0.61 c_p T}{\rho_f u^*}
\]

where \( L_p \) is the latent heat for vaporization. By definition, the temperature involved in estimating Obukhov length is the virtual temperature—the temperature that dry air would have if its pressure and density were equal to those of moist air (e.g., Garratt, 1992). Therefore, if the actual temperature is used, as in Eq. (6), the correction of \( L_{MO} \) is needed for moist air. The histogram of Bowen-ratio (\( \beta \)) (Fig. 2) estimated from the EC measurements of sensible and latent heat fluxes shows that often \( \beta < 0.5 \) during the experiment, suggesting that the field was wet and therefore the humidity corrections of \( f_{BR} \) and \( g_{BR} \) need to be applied.

Since a LAS only provides estimates of \( C_2^2 \) and hence \( T_s \), an additional expression to solve for \( u^* \) is needed to calculate the sensible heat flux from Eq. (5). Measurements of wind speed, \( u \), at a fixed height of \( z_a \) are used to estimate \( u^* \) with the following flux profile relationship:

\[
u = k u \left( \ln \left( \frac{z_a - d_0}{z_a} \right) - \psi_m \left( \frac{z_a - d_0}{L_{MO}} \right) + \psi_m \left( \frac{z_a}{L_{MO}} \right) \right)^{-1}
\]
where \( z_0 \) is the roughness length for momentum and \( \psi_0 \) the stability correction for the transfer of momentum, which for unstable conditions (\( \zeta < 0 \)) is defined as \( \psi_m(\zeta) = 2\ln[1 + x]/2] + \ln[1 + x^2]/2 - 2\arctan(x) + \pi/2 \), with \( x = (1 - 16\zeta)^{1/4} \), and \( \psi_m(\zeta) = -5\zeta \) for stable condition (\( \zeta > 0 \)). Because the data for \( u \) were taken from the sonic anemometer used for the EC measurements, \( z_0 \) is at the same height as \( z_{EC} \) in Table 1. Eqs. (4)–(8) are then solved iteratively to find \( H \).

Several forms of the universal function for temperature, \( f_T \), have been proposed (e.g., Brutsaert, 1982; Hill, 1997). Asanuma and Iemoto (2007), denoted hereafter as W71, TG92, and AI07 are quite different from W71 with slight modifications; (3) TG92 and AI07 are quite different from W71 and DB95. The former two studies included the von Karman's constant in their estimate of \( \zeta \), while the latter two did not.

The authors did not provide the values for unstable conditions. Following DB95, they are assumed to be constant with a value determined using the unstable condition function with \( \zeta = 0 \).

In this study, the universal functions proposed by Wyngaard et al. (1971), Thiermann and Grassl (1992), De Bruin et al. (1995), and Asanuma and Iemoto (2007), denoted hereafter as W71, TG92, DB95, and AI07, respectively, were evaluated. The details of these functions are listed in Table 2 and their variations with \( \zeta \) are shown in Fig. 3. Note that the coefficients for W71, TG92 and AI07 were adjusted from their original values. The reasons for evaluating these functions are: (1) W71 was developed based on the data over a flat field with uniform wheat stubble in southwestern Kansas (Kaimal and Wyngaard, 1990) and has been widely used; (2) DB95 represents one of those variations of W71 (e.g., Andreas, 1988; Hill et al., 1992) that were derived from W71 with slight modifications; (3) TG92 and AI07 are quite different from W71 and DB95 in analytical forms and performed well in recent studies (Asanuma and Iemoto, 2007; Savage, 2009); and (4) most importantly, these four functions cover a wide range of possible values for the MOST universal functions. Wyngaard et al. (1971) showed that under unstable conditions when free convection prevails, \( f_T \) is proportional to \( \zeta^{-2/3} \). The four \( f_T \)s roughly follow \( \zeta^{-2/3} \) when \( \zeta < -0.5 \) (Fig. 3).

Both \( d_0 \) and \( z_0 \) are empirical parameters. From the mass conservation principle, the values of \( d_0 \) and \( z_0 \) are such that the logarithmic wind profile, \( \ln(z_u - d_0)/z_0 \), extrapolated to \( z_u = d_0 + z_0 \), transports the same amount of mass as the actual wind profile (De Bruin and Moore, 1985). Experiments showed that \( d_0 \) and \( z_0 \) vary with both vegetation heights (De Bruin and Moore, 1985) and wind speeds (Molion and Moore, 1983). However, \( d_0 \) and \( z_0 \) are typically modeled as a function of vegetation height (\( h \)) only (e.g., Garratt, 1992):

\[
\frac{d_0}{h} = \frac{2}{3} \tag{9}
\]

and

\[
\frac{z_0}{h} = 0.1 \tag{10}
\]

Eqs. (9) and (10) are often called the rule of thumb estimates. Hoedjes et al. (2007) discussed the diurnal change of \( d_0 \) and its effect on the estimate of sensible heat flux from LAS measurements. They found an overestimate for low sensible heat fluxes and an underestimate for high sensible heat fluxes.

Few studies have reported the effect of uncertainties in \( z_0 \) on the estimate of sensible heat flux from LAS. The sensitivities of \( u_*, T \) and \( H \) to uncertainties in \( z_0 \) are analyzed using the data measured in the experiment (Fig. 4). For the uncertainty in \( z_0 \), measured as a ratio of the assumed value to the “true” value, varying from 0.1 to 10, \( T \) varies <5% but \( u_* \) varies from an underestimate of −100% to an overestimate of 100%. Since \( T \) is not sensitive to \( z_0 \), the errors...
in $H_{\text{LAS}}$ due to $z_0$ uncertainty are primarily propagated through the errors in $u^*$.  

23. Footprint

To compare the fluxes measured by the two systems, LAS and EC need to be set up in such a way that the majority of their respective source areas (footprint) overlap (e.g., Meijninger et al., 2002b; Von Randow et al., 2008). Following Meijninger et al. (2002b), the areal footprint for the LAS ($f_{\text{LAS}}$) is a combination of the spatial weighting function $W_{\text{LAS}}$ along the path length of the LAS (Clifford et al., 1974; Wang et al., 1978) and the footprint of the air plume ($f_{\text{air}}$) passing through the LAS path during the period of averaging (Hsieh et al., 2000). The weighting function, $W_{\text{LAS}}$, is bell-shaped, with its center in the middle of the path and approaching zero toward both ends. This explains that EC is typically placed in the middle of the LAS path for comparisons (Fig. 1). The areal footprint for EC ($f_{\text{EC}}$) is a combination of $f_{\text{air}}$ and the weighting along the cross-wind direction ($W_{\text{EC}}$), which is often assumed to follow a normal distribution with a standard deviation proportional to the ratio of the standard deviation of the wind speeds in the cross-wind direction to the mean wind speed in the streamwise direction, and to the travel distance of the air from upwind to the EC (e.g., Hoedjes et al., 2007; Von Randow et al., 2008). The footprint of the passing air plume ($f_{\text{air}}$) was developed for scalar fluxes, and it is assumed to apply to $C_r^2$ as well.

The areal footprints for the LAS ($f_{\text{LAS}}$) and the EC ($f_{\text{EC}}$) are shown in Fig. 1 for $h_{\text{EC}} = -70$ m, $z_0 = 0.04$ m, and $z - d_0 = 1.8$ m. The values for $h_{\text{EC}}$ and $z_0$ are approximately the medians for their respective variations, and the footprint would increase with a decrease in either $h_{\text{EC}}$ or $z_0$. Given the ranges of variations observed for $h_{\text{EC}}$ and $z_0$ during the experiment, we estimated that the effective heights $z - d_0$ for both the instruments should be $<1.8$ m in order for $80\%$ of their footprints to stay within the area where the sub-surface drainage system was installed. This is the major constraint that restricted the height of the two instruments. The footprint in Fig. 1 is for a northerly wind, but it can be expected that the footprint area would be mostly within the field boundary for other wind directions as well.

24. Roughness sublayer

Conceptually, the lower part of the atmospheric boundary layer over the rough land surface is partitioned into a roughness sublayer immediately above the surface and an overlying surface sublayer (Garratt, 1992). The success of deriving sensible heat flux from a LAS requires the instrument to be operating in the surface layer where the fluxes (sensible, humidity, and momentum) can be scaled following MOST. Garratt (1978) estimated that the roughness sublayer (reference to zero-plane displacement) over sparsely distributed trees and shrubs extended up to $20–80$ times of $z_0$, which is about $2–8$ times the crop height according to Eq. (10). Over Amazonian forest, Von Randow (2006) obtained $8–10$ times of $z_0$. For maize ($Z. mays$), Cellier and Brunet (1992) obtained about $15$ times of $z_0$. These differences in the reported values are expected because the length of the roughness layer also depends on the spacing (or density) of the canopy (Garratt, 1980). The ratios of $(z_{\text{LAS}} - d_0)/z_0$ estimated from Table 1 and Eq. (10) show that, except for the early growing seasons, the ratios were less than $10$ (Fig. 5). This was a concern for the LAS operation because MOST is violated in the roughness sublayer (e.g., Möldner et al., 1999; Thom et al., 1975). To evaluate whether this transition had occurred, the LAS measurements needed to be compared against a MOST-independent observation, such as EC, which measures the surface fluxes directly and does not depend on the validity of MOST (Möldner et al., 1999). This is also the corner-stone of this study.

Table 3

<table>
<thead>
<tr>
<th>$r$, RMSD*, MAPD, S</th>
<th>DB95</th>
<th>W71</th>
<th>TG92</th>
<th>AK07</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.87, 61, 0.67, 1.38 ± 0.07</td>
<td>0.87, 59, 0.65, 1.37 ± 0.07</td>
<td>0.87, 42, 0.52, 1.39 ± 0.06</td>
<td>0.87, 54, 0.59, 1.32 ± 0.04</td>
</tr>
<tr>
<td>2</td>
<td>0.86, 62, 0.39, 1.01 ± 0.05</td>
<td>0.86, 31, 0.37, 1.00 ± 0.05</td>
<td>0.86, 31, 0.35, 0.86 ± 0.04</td>
<td>0.86, 30, 0.36, 0.95 ± 0.04</td>
</tr>
</tbody>
</table>

* RMSD has unit of W m$^{-2}$. 

Fig. 4. Mean ± one standard deviation of the relative differences in $u^*$, $T^*$, and $H_{\text{LAS}}$ estimated over the experiment as a function of the uncertainty in $z_0$. Uncertainty in $z_0$ is evaluated as a ratio of the assumed value to the “true” value of $z_0$. The relative difference in $u^*$ ($T^*$ or $H_{\text{LAS}}$) is calculated as: (value of $u^*$ ($T^*$ or $H_{\text{LAS}}$) estimated using the assumed value of $z_0$/value of $u^*$ ($T^*$ or $H_{\text{LAS}}$) estimated using the “true” value of $z_0$) - 1.

Fig. 5. The ratios of $(z - h_0)/z_0$ as a function of $h$. The values of $z_0$ were estimated using Eq. (10) (crosses) and Eq. (11) (squares), respectively. The horizontal dashed line represents a constant ratio of 20 and solid line a ratio of 10.
3. Results and discussion

The algorithm presented above will hereafter be referred to as Algorithm 1, which was then modified using an improved estimate of $z_0$ (Eq. (11)). The modified algorithm will be referred to as Algorithm 2. Both algorithms were applied to derive the sensible heat fluxes from the LAS measurements. For each algorithm, different MOST universal functions ($f_T$) listed in Table 2 were tested. The performance of the various LAS algorithms with different $f_T$ functions were evaluated by comparing the sensible heat flux derived by the LAS ($H_{LAS}$) and the EC ($H_{EC}$) in terms of correlation coefficient ($r$), root mean square difference (RMSD), mean absolute percentage difference (MAPD), and zero-intercept regression coefficient or slope, $S$, as in $T_{LAS} = S \times T_{EC}$.

### Table 4
Comparison of $T^*$ between the estimates by the EC and the LAS using different $f_T$ functions (column-wise) and different LAS algorithms (row-wise) in terms of correlation coefficient ($r$), root mean square difference (RMSD), mean absolute percentage difference (MAPD), and zero-intercept regression coefficient or slope, $S$, as in $T_{LAS} = S \times T_{EC}$.

<table>
<thead>
<tr>
<th>$r$, RMSD*, MAPD, S</th>
<th>DB95</th>
<th>W71</th>
<th>TG92</th>
<th>AL07</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.85, 4.8, 0.32 0.99 ± 0.05</td>
<td>0.86, 7.0, 0.31 0.98 ± 0.05</td>
<td>0.86, 5.1, 0.29 0.85 ± 0.04</td>
<td>0.86, 4.7, 0.30 0.89 ± 0.04</td>
</tr>
<tr>
<td>2</td>
<td>0.86, 5.2, 0.35 1.02 ± 0.05</td>
<td>0.85, 4.9, 0.33 1.00 ± 0.05</td>
<td>0.85, 5.1, 0.30 0.86 ± 0.04</td>
<td>0.85, 4.8, 0.32 0.95 ± 0.04</td>
</tr>
</tbody>
</table>

* RMSD has a unit of 0.01 °C.

3.1. $H_{LAS}$ using the rule of thumb estimate of $z_0$

$H_{EC}$ (black curve in Fig. 6) shows the typical pattern of variation in sensible heat flux on clear days: increasing as the surface heated in the morning (e.g., on August 6, 2008 and June 30, 2009) and decreasing as the surface cooled in the afternoon (e.g., on July 13, 2008 and September 26, 2009). The sudden drops in sensible heat flux in the mid-day of August 6, 2008 and July 8, 2009 were due to the presence of clouds.

$H_{LAS}$, derived using Algorithm 1, is plotted in Fig. 6 as solid curves of different colors that correspond to different $f_T$ functions. Overall, $H_{LAS}$ and $H_{EC}$ correlate with each other very well ($r > 0.85$) regardless of which $f_T$ function is used. TG92-based $H_{LAS}$ compared best with $H_{EC}$ (RMSD = 43 W m$^{-2}$) and $H_{LAS}$ based on DB95 and W71 showed the largest difference with $H_{EC}$ (RMSD > 60 W m$^{-2}$). The average RMSD in $H_{LAS}$ among different $f_T$ functions is 23 W m$^{-2}$, which is less than half of the RMSDs between $H_{LAS}$ and $H_{EC}$.

### Table 5
Same as Table 4 but for $u_*$. Since the estimates of $u_*$ among different $f_T$ functions are almost the same (varying <1%, Fig. 9b), only the values for W71 are shown.

<table>
<thead>
<tr>
<th>$r$, RMSD*, MAPD, S</th>
<th>W71</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.78, 0.21, 0.44, 1.37 ± 0.07</td>
</tr>
<tr>
<td>2</td>
<td>0.77, 0.08, 0.16, 0.98 ± 0.05</td>
</tr>
</tbody>
</table>

* RMSD has a unit of m s$^{-1}$.

Fig. 6. Comparison of $H_{EC}$ (black curve) and $H_{LAS}$ derived using Algorithm 1 (solid lines) and Algorithm 2 (dotted lines). Different colors for $H_{LAS}$ correspond to different $f_T$ functions being used (the same color scheme as Fig. 3). The top row shows the results for 2008 and bottom for 2009. The dates (month/day) are indicated at the top of each panel. Note, the scales for x- and y-axis are different among different panels. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)
Fig. 7. Comparison of $T^*$ (a) and $u^*$ (b) estimated from the EC and the LAS. In (a) $T^*$ by LAS was estimated using Algorithm 1 with $f_T$ functions of W71 and TG92. In (b) $u^*$ by LAS was estimated using Algorithms 1 and 2 all with $f_T$ function of W71.

Apparently, the differences in the universal functions alone cannot account for all the differences between the two measurements and $H_{\text{LAS}}$ by Algorithm 1 is systematically greater than $H_{\text{EC}}$ by 47–66% ($S$ from 1.19 to 1.38).

Table 4 shows that the estimates of $T^*$ by Algorithm 1 agreed well with the EC measurements with the exception for TG92, the use of which led to lower values of $T^*$ ($S = 0.85 \pm 0.04$ for TG92 vs. $S = 0.94–0.99 \pm 0.05$ for the other $f_T$ functions). The estimates of $T^*$ by the LAS using W71 and TG92 are compared with $T^*$ by the EC in Fig. 7a. On the other hand, the choice of $f_T$ functions barely affects the estimate of $u^*$ (Fig. 8b) and Table 5 shows that Algorithm 1 overestimated the $u^*$ derived from EC measurements by an average of 0.2 m s$^{-1}$. Fig. 7b compares the estimates of $u^*$ by the LAS and the EC. The combination of Tables 4 and 5 and Fig. 7 suggests that the overall overestimation of $H_{\text{LAS}}$ relative to $H_{\text{EC}}$ was largely due to the systematically higher estimates of $u^*$ by the LAS as compared to the measurements by the EC.

Studies by De Bruin et al. (1995) and Chehbouni et al. (2000) attributed the overestimation of $H_{\text{LAS}}$ over $H_{\text{EC}}$ to the overestimation of momentum transfer by the LAS. In Chehbouni et al. (2000), the LAS was placed about 4 and 10 m above the grass patch and the mesquite patch, respectively. Using the $f_T$ function of DB95, they found that $u^*$ was overestimated by the LAS in both fields, with RMSD = 0.21 and 0.28 m s$^{-1}$ and $S = 1.16$ and 1.35, respectively, which are comparable to our overestimates of $u^*$ (RMSD = 0.21 m s$^{-1}$ and $S = 1.37$ for DB95). The resulting overestimates of $H_{\text{LAS}}$ in their study were 30–40 W m$^{-2}$, which, however, is less than the overestimate of 62 W m$^{-2}$ in our study. This is probably because the surface layer in which the LAS was deployed was mostly near-neutral during our experiments ($\zeta < -0.1$, Fig. 2). Under near-neutral conditions, the sensitivity of $H_{\text{LAS}}$ to $u^*$ is the largest while it is minimum or negligible under strongly convective conditions (Asanuma and Iemoto, 2007).

3.2. $H_{\text{LAS}}$ using the improved estimate of $z_0$

The rule of thumb estimates for the roughness length, $z_0$ (Eq. (10)), and the zero-displacement height, $d_0$ (Eq. (9)) were used to calculate $u^*$. Since $d_0/h$ was less sensitive to the nature of the surface or to other factors than $z_0/h$ (Munro and Oke, 1975), Eq. (9) was found to be fairly representative for natural crop covered surfaces, while the discrepancy for Eq. (10) was significant (Brutsaert, 1982). Assuming that the rule of thumb estimate of $d_0$ still applies, $z_0$ was estimated using Eq. (8) with the measurements of $u$ and $u^*$ from the EC. Garratt (1980) used a similar approach to estimate $z_0$ and found it was less sensitive to the variations in $d_0$ and to the correction that was needed if the measurements were in the roughness sublayer.

The ratio of roughness length to crop height, $z_0/h$, is shown in Fig. 9 as a function of $h$. The values of $z_0/h$ are not a constant as it had been assumed in Eq. (10); instead, it varied for both short term (intraday variation due to wind speeds) and long term (due to crop height) as can be expected theoretically. Bending of crop under the wind stress will change $z_0$ (Monin, 1970). As corns grow taller, the canopy also becomes denser. The increase in density will
increase the drag, hence \( z_0 \); but as corn becomes extremely dense, the flow may actually skim over the top of the crop without entering the space below, so that the effective roughness length decreases (Brutsaert, 1982).

The use of the rule of thumb formula (Eq. (10)) in our experiment overestimated the roughness length for corn, especially during the early stages of growth (Fig. 9). For corn, a mean value of 0.08 for \( z_0/h \) was reported in Garratt (1992) and 0.06 in Jacobs and Van Boxel (1988). From the data presented in De Bruin and Moore (1985), \( z_0/h \) was found to be 0.04–0.07 for tall vegetation. These values are within the range of variations shown in Fig. 9. To the first approximation, a linear best fit applied to Fig. 9 gave:

\[
\frac{z_0}{h} = 0.02h + 0.02. 
\]

(Eq. (11)) will be called the improved estimates of \( z_0 \) and is used to replace Eq. (10) in Algorithm 2. Note the first 0.02 in Eq. (11) has a unit of m\(^{-1}\).

We should stress here that evaluating how roughness length varies with crop height was never planned for the experiment and is outside the scope of the study. We caution against the extended use of Eq. (11). Instead, Eq. (11) and Fig. 9 are presented in this study simply to show that the rule of thumb formula for \( z_0 \) has considerable uncertainty which, as shown in Fig. 4, can propagate through the LAS algorithm and affect the estimate of \( H_{\text{LAS}} \).

Because Eq. (11) was derived from the EC measurements of \( u^* \), we now see a much better match between the LAS and EC data of \( u^* \) (Fig. 7b), with RMSD decreasing from 0.21 to 0.08 m s\(^{-1}\) and \( S \) improving from 1.37 \( \pm \) 0.08 to 0.98 \( \pm \) 0.06 (Table 5). On the other hand, the corresponding changes in \( T_r \) are only 2% on average, which can be expected from Fig. 4 and is insignificant given the inherent uncertainties in the estimate of \( T_r \). The \( H_{\text{LAS}} \) estimated using Algorithm 2 compared better with \( H_{\text{EC}} \) than Algorithm 1 (Fig. 5). For all the \( f_T \) functions, the values of RMSDs for \( H \) are <33 W m\(^{-2}\) and of \( S \) range from 0.86 to 1.02 \( \pm \) 0.05 (Table 3).

### 3.3. Effect of MOST universal function for temperature

Which of the four \( f_T \) functions evaluated produces the best estimates of \( H, T_r \), and \( u^* \) depends on the \( z_0 \) formula (Eq. (10) or (11)) used to derive \( u^* \) in the LAS algorithm. While Table 3 shows that an improved estimates of \( u^* \) can enhance the accuracy of \( H_{\text{LAS}} \) estimates, DB95, W71, TG92 and AI07 all seemed to be applicable within the experiment and algorithm uncertainties. When using Eq. (11), W71 performed the best. The \( H_{\text{LAS}} \) estimated using W71 agreed with \( H_{\text{EC}} \) within 32 W m\(^{-2}\) and with a slope of 1.0 \( \pm \) 0.05. W71 was based on the observations over a flat field with uniform wheat stubble in Kansas plains (Wyngaard et al., 1971). Hill and Ochs (1992) commented that W71 fitted better to the Kansas data at the near-neutral conditions. This may explain why our \( H_{\text{LAS}} \) based on W71 compared best with \( H_{\text{EC}} \). On the other hand, Hill et al. (1992) found little sensitivity to the form of \( f_T \) of \( H_{\text{LAS}} \) measured over a flat and homogeneous mesa with short grasses. However, their data were obtained for \( \zeta < -0.1 \), mostly outside the stability range that our dataset can verify.

The differences in \( T_r, u^* \), and \( H_{\text{LAS}} \) estimated using Algorithm 2 with DB95, TG92, and AI07 relative to those with W71 are shown in Fig. 8a–c, respectively, as a function of the stability parameter \( \zeta \). Different \( f_T \) functions mainly affect the estimate of \( T_r \) (Fig. 8a) and have an effect of less than 1% on the estimate of \( u^* \) (Fig. 8b). Therefore, the final effect of \( f_T \) on \( H_{\text{LAS}} \) is primarily propagated through \( T_r \). Within the stability range observed during the experiment, \( H_{\text{LAS}} \) derived using DB95 and AI07 agreed within 10±% with \( H_{\text{EC}} \) using W71, while \( H_{\text{EC}} \) using TG92 underestimated \( H_{\text{LAS}} \) using W71 by 15% on average. Savage (2009) found that the use of TG92 produced the best agreement between his estimates of \( H_{\text{LAS}} \) and \( H_{\text{EC}} \) over a mixed grassland and relative to TG92 the differences in \( H_{\text{LAS}} \) were 10–20% for W71 and 15–30% for DB95. These are similar to the ranges of variations observed in our experiment (Fig. 8c).

### 3.4. Effect of humidity on stability

The humidity correction was applied because the field was relatively wet and the heat flux was dominated by the latent heat transfer (Fig. 2). The humidity correction using the Bowen-ratio involves two parts: the effect of humidity fluctuations on refractive index fluctuations (Eqs. (2) and (3)) and the effect of humidity on the stability (Eqs. (6) and (7)). The former has been studied in detail (Moene, 2003; Wesely, 1976a) and explicitly applied over relatively wet areas (e.g., Asanuma and Iemoto, 2007; Meijninger et al., 2002a; Pauwels et al., 2008; Von Randow et al., 2008). On the other hand, the latter has been seldom mentioned, even though it might be applied implicitly (De Bruin, personal communication). It would be of interest to examine its impact on the estimate of \( H_{\text{LAS}} \).

Neglecting the correction of the humidity–stability effect (Eq. (7)), \( L_m0 \) would be overestimated, and the overestimate is about 27% for \( \beta = 0.3 \) (the mode value of Bowen-ratio distribution in Fig. 2). The overestimation in \( L_m0 \) causes an underestimation in \( H_{\text{LAS}} \), whose magnitudes increase with decreasing sensible heat flux, ranging from <1% for \( H_{\text{LAS}} < 200 \text{ W m}^{-2} \) to up to 10% for \( H_{\text{LAS}} < 100 \text{ W m}^{-2} \) under our experimental conditions (squares in Fig. 10). While much less than the errors (crosses in Fig. 10) induced for neglecting the correction of the humidity–index effect (Eq. (3)), the humidity–stability effect on \( H_{\text{LAS}} \) estimate is not negligible, particular under wet conditions with small sensible heat flux.

### 3.5. Roughness sublayer

There was a concern that the combination of the two factors, the relative short clearance of the LAS above the crop constrained by the field size and the footprints and the rapid growth of the crop during the experiment, might reduce the atmospheric layer that the LAS operated from surface layer initially to roughness sublayer later (Fig. 5). If this had happened, \( H_{\text{LAS}} \) would underestimate the sensible heat flux because in the roughness sublayer both Eddy diffusivity and conductivity increase relative to the surface layer leading to enhanced momentum and scalar fluxes (Garratt, 1978; Molder et al., 1999; Simpson et al., 1998; Thom et al., 1975). This is contrary to our results, which have shown \( H_{\text{LAS}} \) overestimat-
Fig. 10. The two effects of the humidity corrections (refractive index and stability) on the estimate of $H_{\text{LAS}}$ are evaluated separately. Relative difference is calculated as: $|H_{\text{LAS}} \pm \text{humidity index correction}| / H_{\text{LAS}}$.

Fig. 11. $H_{\text{LAS}}$ estimated using Algorithm 2 with $f_2$ function of W71 as a function of $z - d_0$.

4. Conclusions

A LAS and an EC system were deployed in a corn field with subsurface drainage installed during the growing seasons of 2008 and 2009. To ensure the footprints of the two systems stayed within the field boundary ($\sim 22$ ha), their effective heights needed to be $< 1.8$ m. Because of the shorter clearance above the crop, the surface layer was mostly near-neutral at the LAS path height. This posed two challenges for deriving the sensible heat fluxes from the LAS: a more accurate estimate of $u^*$ is required for $H_{\text{LAS}}$ to be reliable (De Bruin et al., 1995) because $H_{\text{LAS}}$ is more sensitive to the uncertainty in $u^*$ under near-neutral conditions (Asanuma and Lemoto, 2007) and the rapid increase in height of the crop might further reduce the LAS to the roughness sublayer, where MOST is violated.

Comparisons of $H_{\text{LAS}}$ and $H_{\text{EC}}$ showed that the LAS, tested with four different $f_2$ functions, systematically overestimated the sensible heat flux by $40–60$ W m$^{-2}$. The overestimation was primarily due to the overestimate of $u^*$, which was estimated using the rule of thumb formula for the roughness length $z_0$. With an improved estimate of $z_0$, $H_{\text{LAS}}$ and $H_{\text{EC}}$ agreed within $32$ W m$^{-2}$ with a regression slope of $1.00 \pm 0.05$. This confirmed that the LAS, despite its lower clearance, did operate in the surface layer. This also emphasizes the importance of obtaining reliable estimates of $u^*$ in deriving sensible heat fluxes from scintillometry measurements, particularly under near-neutral conditions.

The MOST similarity functions are empirically determined and the differences among them can significantly impact the estimate of sensible heat flux. Therefore, it is important to identify a suitable $f_2$ function that applies. Among the four $f_2$ functions tested, W71 (Wyngaard et al., 1971) applies best to our experiment. Under wet conditions, the correction needs to be applied to account for not only the effect of humidity fluctuations on refractive index fluctuations, but also the effect of humidity on stability (buoyancy). Without corrections, the latter effect can cause an underestimate of $H_{\text{LAS}}$ up to 10%.

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