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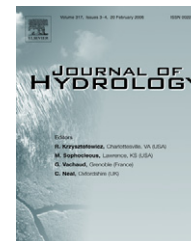
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## 2 On the application of scintillometry 3 over heterogeneous grids ☆

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### KEYWORDS

Scintillation;  
Eddy covariance;  
Heterogeneity;  
Aggregation;  
Structure parameter

**Summary** In this paper the applicability of the Monin–Obukhov similarity theory (MOST) over heterogeneous terrain below the blending height is investigated. This is tested using two large aperture scintillometers (LAS), in conjunction with aggregation schemes to infer area-averaged refractive index structure parameters. The two LAS were operated simultaneously over the oliveyard of Agdal, located near Marrakech (Morocco). The Agdal olive yard is made up of two contrasted fields, or patches. The two sites are relatively homogeneous, but differ strongly in characteristics (mainly soil moisture status, and, to a lesser extent, vegetation cover). The higher soil moisture in the northern site creates heterogeneity at the scale of the entire olive yard (i.e. at grid scale). At patch scale, despite the complexity of the surface (tall, sparse trees), a good agreement was found between the sensible heat fluxes obtained from eddy-covariance systems and those estimated from the LAS. At grid scale, the aggregated structure parameter of the refractive index, simulated using the proposed aggregation model, behaves according to MOST. This aggregated structure parameter of the refractive index is obtained from measurements made below the grid scale blending height, and shows that MOST applies here. Consequently, scintillometers can be used at levels below the blending height. This is of interest, since strictly respecting the height requirements poses tremendous practical problems, especially if one is aiming to derive surface fluxes over large areas.

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### Introduction

The structure parameter of the refractive index ( $C_n^2$ ) of air is a key parameter that characterizes the intensity of the turbulent fluctuations of the atmospheric refractive index. Using the scintillation technique, one can measure this parameter at spatial scales varying from several hundreds

☆ We, the authors, declare that the presented paper contains original work, is not being submitted elsewhere, and all authors agree to the contents and submission of the paper.

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18 of meters (e.g. displaced-beam laser scintillometer) up to  
19 10 km (e.g. extra large aperture scintillometer). Depending  
20 on the wavelength at which the scintillometer operates,  
21 knowledge of  $C_n^2$  permits the calculation of vertical fluxes  
22 of heat or water vapour from the earth's surface, which  
23 are required in many meteorological, hydrological and agri-  
24 cultural applications. These fluxes can be, and have been,  
25 measured using point-sampling measurement devices such  
26 as Bowen-ratio or eddy-covariance (EC) systems. However,  
27 for several applications, in particular large scale irrigation  
28 management or the validation of surface parameterization  
29 schemes in large-scale hydro-atmospheric models, grid-  
30 scale values are required. A network of point-sampling de-  
31 vices, such as eddy-covariance, can be used. However, the  
32 high cost and the requirement of continuous availability of  
33 well-trained staff to operate and maintain them has led  
34 the scientific community to look for alternative techniques  
35 to estimate area-averaged fluxes over large heterogeneous  
36 surfaces.

37 In this context, a number of different techniques have  
38 been introduced for research applications, such as a dis-  
39 persometer theodolite, displaced-beam laser scintillome-  
40 ters, microwave scintillometers and large or extra large  
41 aperture scintillometers (LAS, XLAS). In this study we focus  
42 on the scintillation technique. The principle of scintilla-  
43 tion consists of transmitting a beam of electromagnetic radi-  
44 ation and measuring the intensity variations of the received  
45 signal. Wang et al. (1978) have shown that the variance of  
46 the logarithm of the intensity fluctuations can be related  
47 to  $C_n^2$ , which, for scintillometers operating at visible or  
48 near-infrared wavelengths, can then be related to the struc-  
49 ture parameter of temperature,  $C_T^2$ , to derive the sensible  
50 heat flux through Monin–Obukhov similarity theory (MOST)  
51 (Wesely, 1976; Moene, 2003). Due to its ability to integrate  
52 atmospheric processes along a transect, varying from a few  
53 hundreds of metres up to a several kilometres, the scintilla-  
54 tion method is a promising approach for routine observa-  
55 tions of surface fluxes. Compared to e.g. eddy-covariance  
56 systems, the scintillometer is easy to install, relatively  
57 cheap and it is a practical method to obtain area-average  
58 surface fluxes over several kilometres. The instrument is  
59 capable of continuous measurements with minimum human  
60 intervention.

61 Over the last decade, several authors have proven the  
62 reliability of heat flux estimates from scintillometer over  
63 fairly homogeneous terrain (e.g. Green et al., 1994; de  
64 Bruin et al., 1995; Meijninger and de Bruin, 2000; Hoedjes  
65 et al., 2002). Recently, several investigations have demon-  
66 strated the potential of this method over moderately inho-  
67 mogeneous surfaces (Chehbouni et al., 1999, 2000b; Beyrich  
68 et al., 2002; Meijninger et al., 2002). However, a disadvan-  
69 tage of the method is that it requires the use the semi-  
70 empirical Monin–Obukhov similarity theory which might  
71 not be applicable over very complex surfaces (Lagouarde  
72 et al., 2002).

73 The main objective of this paper is to test the applicabil-  
74 ity of MOST at grid scale. The grid consists of two or more  
75 distinct fields (or patches) with different characteristics,  
76 creating a heterogeneous (grid) surface. This is tested by  
77 combining LAS measurements, over two individually homo-  
78 geneous patches with different characteristics, with aggre-  
79 gation schemes to derive a grid scale average refractive

index structure parameter,  $\langle C_n^2 \rangle$  (angular brackets denoting  
80 grid scale averages). The aggregation scheme is required  
81 since  $C_n^2$  is not linear. Regarding the aggregation issue, we  
82 have adopted the deterministic approach (Shuttleworth,  
83 1991; Arain et al., 1996; Noilhan and Lacarrere, 1995; Che-  
84 hbouni et al., 1995, 2000a; Lagouarde et al., 2002), which  
85 consists of deriving analytical relationships between local  
86 and effective (area-averaged) surface parameters by  
87 matching the model equations at different scales. In order  
88 to develop the aggregation scheme and to verify the appli-  
89 cability of the Monin–Obukhov similarity theory (MOST), a  
90 field experiment has been designed and carried out during  
91 the autumn of 2002 over the olive yard of Agdal in Morocco,  
92 within the framework of the SUDMED (Chehbouni et al.,  
93 2003) and IRRIMED projects (<http://www.irrimed.org>).  
94

95 This paper is organized as follows: in “Theoretical back-  
96 ground” section, the basic equations and the associated  
97 procedure that allow the estimation of sensible heat flux  
98 from the structure parameter of the refractive index of  
99 air are presented. An overview of the experimental design  
100 is outlined in “Experimental site and measurements” sec-  
101 tion. In “Aggregation procedures for obtaining grid aver-  
102 aged  $C_n^2$ ” section, we present the developed aggregation  
103 scheme to derive the area-averaged refractive index struc-  
104 ture parameter  $\langle C_n^2 \rangle$  over two adjacent olive tree fields un-  
105 der unstable conditions. In “Results and discussion”  
106 section, a comparison between LAS and EC derived mea-  
107 surements at both patch and at grid scales is presented  
108 (where patch scale refers to individual fields and grid scale  
109 to the ensemble of several (in our case two) fields). Finally,  
110 we conclude by discussing the accuracy of the suggested  
111 approach to estimate the area-averaged structure parame-  
112 ter of the refractive index and the applicability of MOST  
113 at grid scale using measurements made below the blending  
114 height.

## Theoretical background

The large aperture scintillometer (LAS) is a device that mea-  
115 sures the structure parameter of the refractive index of air.  
116 In the optical domain, this  $C_n^2$  depends mainly on tempera-  
117 ture fluctuations and, to a lesser effect, humidity fluctua-  
118 tions. Assuming that temperature and humidity fluctua-  
119 tions are perfectly correlated, Wesely (1976) showed  
120 that, to a good approximation, the temperature structure  
121 parameter  $C_T^2$  can be derived from  $C_n^2$  by:  
122  
123  
124

$$C_T^2 = C_n^2 \left( \frac{T^2}{\gamma p} \right)^2 \left( 1 + \frac{0.03}{\beta} \right)^{-2}, \quad (1)$$

125 where  $\gamma$  is the refractive index coefficient for air  
126 ( $7.8 \times 10^{-7} \text{ K Pa}^{-1}$ ), and  $\beta$  the Bowen ratio. The final bracket-  
127 ed term is a correction for the effects of humidity.  $C_n^2$  and  
128  $C_T^2$  are in ( $\text{m}^{-2/3}$ ) and ( $\text{K}^2 \text{ m}^{-2/3}$ ), respectively.  
129  
130

131 According to MOST, it is possible to link  $C_T^2$  and the tem-  
132 perature scale  $T_*$  for unstable conditions, i.e.,  $L < 0$  (de  
133 Bruin et al., 1993) using:  
134

$$\frac{C_T^2}{T_*^2 (z-d)^{-2/3}} = f((z-d)/L) = 4.9(1 - 9(z-d)/L)^{-2/3}, \quad (2)$$

135  $L$  is the Monin–Obukhov length defined as: 137

138

140 
$$L = -\frac{T_a u_*^2}{\kappa g T_*} \quad (3)$$

141 with  $\kappa = 0.41$ ,  $g = 9.81 \text{ m s}^{-2}$  and  $u_*$  is the friction velocity,  
142 given by:

143 
$$u_* = \kappa u [\ln((z-d)/z_0) - \psi((z-d)/L)]^{-1}, \quad (4)$$

146 where  $\psi$  is the integrated stability function (Panofsky and  
147 Dutton, 1984),  $z$  is the measurement height,  $d$  the displace-  
148 ment height and  $z_0$  is the roughness length.149 The sensible heat flux  $H$  ( $\text{W m}^{-2}$ ) is calculated iteratively  
150 using Eqs. (1)–(4) and the following relationship:

151 
$$H = \rho c_p u_* T_* \quad (5)$$

154 where  $\rho$  ( $\text{kg m}^{-3}$ ) and  $c_p$  ( $\text{J kg}^{-1} \text{K}^{-1}$ ) are the air density and  
155 specific heat capacity at constant pressure, respectively.

## 156 Experimental site and measurements

157 The experiment was carried out in the fall of 2002, between  
158 day of year (DOY) 295 and 306 (22nd October–2nd Novem-  
159 ber) at the 275 ha Agdal olive orchard, which is located to  
160 the southeast of the city of Marrakech, Morocco ( $31^\circ 36' \text{N}$ ,  
161  $07^\circ 59' \text{W}$ ). The climate is semiarid Mediterranean. Precipita-  
162 tion falls mainly during winter and spring, from the begin-  
163 ning of November until the end of April, with an average  
164 yearly rainfall of 175–250 mm. The atmosphere is very  
165 dry, with an average humidity of 50%, and the potential  
166 evaporation is very high (1600 mm per year), greatly  
167 exceeding the annual rainfall. The experimental area is di-  
168 vided in two fields, which are referred to as the southern  
169 site and the northern site. The average height of the olive  
170 trees is 6.5 m in the southern and 6 m in the northern site.  
171 The vegetation is more homogenous in the southern site  
172 than in the northern site, as can be seen in Fig. 1, with an  
173 average vegetation cover of approximately 55% in the south-  
174 ern site and 45% in the northern site, as obtained from hemi-  
175 spherical canopy photographs (using a Nikon Coolpix 950<sup>®</sup>  
176 with a FC-E8 fish-eye lens converter, field of view  $183^\circ$ ).  
177 The period of the experiment was chosen in order to have  
178 a distinct difference between the two sites in term of soil  
179 moisture. The southern site was dry and the northern site  
180 had just been irrigated. Fig. 2 shows the evolution of the  
181 volumetric water content throughout the experiment. From  
182 Fig. 2, it is clear that the grid, comprised of the northern  
183 and southern sites, is heterogeneous.

184 Both sites were equipped with a set of standard meteor-  
185 ological instruments to measure wind speed and direction  
186 (Young Wp200) and air temperature and humidity, using  
187 HMP45AC temperature and humidity probes (Vaisala) at  
188 9 m. Furthermore, net radiation in the southern site was  
189 measured using a CNR1 (Kipp and Zonen) installed at 8 m  
190 and Q7 net radiometer (REBS) at 7 m. In the northern site  
191 the net radiation was measured with a Q6 net radiometer  
192 (REBS) at 8 m. Net radiation over the soil in both fields  
193 was measured by a Q7 at 1 m. Soil heat flux was measured  
194 at three locations at a depth of 0.01 m using soil heat flux  
195 plates (Hukseflux). The first was located below the canopy  
196 close to the trunk of a tree, in order to be not exposed to  
197 solar radiation; the second was exposed directly to solar  
198 radiation, and the third was installed in an intermediate po-  
199 sition, partly sunlit, partly shaded. An average of these

three measurements was calculated to obtain a representa-  
200 tive value. Soil moisture was measured at different depths  
201 (0.05, 0.1, 0.2, 0.3 and 0.4 m) using 5 CS616 water content  
202 reflectometers (Campbell Scientific Ltd.). All meteorologi-  
203 cal measurements were sampled at 1 Hz, and 30 min aver-  
204 ages were stored. The prevailing wind direction is from  
205 the northwest.  
206

In both the northern and the southern site, EC systems  
207 were installed to provide continuous measurements of the  
208 vertical fluxes of heat, water vapour and  $\text{CO}_2$  at a height  
209 of 8.8 and 8.7 m for the southern and northern sites, respec-  
210 tively. The EC systems consisted of a 3D sonic anemometer  
211 (CSAT3, Campbell Scientific Ltd.) and an open-path infrared  
212 gaz analyzer (Li7500, Licor Inc.). Raw data were sampled at  
213 a rate of 20 Hz and were recorded using CR23X dataloggers  
214 (Campbell Scientific Ltd.) which were connected to portable  
215 computers to enable storage of large raw data files. The  
216 half-hourly values of fluxes were later calculated off-line  
217 after performing coordinate rotation, frequency correc-  
218 tions, correcting the sonic temperature for the lateral  
219 velocity and presence of humidity, and the inclusion of  
220 the mean vertical velocity according to Webb et al.  
221 (1980). Data from the eddy-covariance system were pro-  
222 cessed using the software 'ECPack' developed by the Mete-  
223 orology and Air Quality group, Wageningen University  
224 (available for download at <http://www.met.wau.nl/>).  
225

Air pressure was measured in the southern site using the  
226 pressure sensor of the Li7500 infrared gas analyzer, and on  
227 the northern site using a pressure sensor (Vaisala PTB101B).  
228 1 min averages were recorded on the dataloggers.  
229

The LAS operated in this study were built by the Mete-  
230 orology and Air Quality Group (Wageningen University, the  
231 Netherlands). These instruments have been constructed  
232 according to the basic design described in Ochs and Wilson  
233 (1993). They have an aperture size of 0.15 m and the trans-  
234 mitter operates at a wavelength of 0.94  $\mu\text{m}$ . At the receiver,  
235  $C_n^2$  is sampled at 1 Hz and averaged over 1 min  
236 intervals by a CR510 datalogger. Two identical LAS were  
237 used in this experiment. The first was installed over the  
238 southern site, perpendicular to the dominant wind direc-  
239 tion, over a pathlength of 1050 m (denoted LAS<sub>s</sub>). The trans-  
240 mitter was mounted on a tripod installed on a roof, located  
241 on the southwest corner of the southern site, while the re-  
242 ceiver was mounted on a 15 m high tower that was posi-  
243 tioned next to the road that separates the two sides of  
244 the orchard. The second LAS was installed over the northern  
245 site, the orientation of this LAS was almost parallel to the  
246 dominant wind direction, and it measured over a pathlength  
247 of 1070 m (denoted LAS<sub>n</sub>). The receiver was installed on the  
248 same tower as the receiver of LAS<sub>s</sub>. The transmitter was  
249 mounted on a tripod installed on a roof located near the  
250 northern corner of the northern site. The setup of the  
251 receivers on the 15 m tower was such that the two signals  
252 did not interfere. The average heights of the LAS transects  
253 were 14 m for the southern site and 14.5 m for the northern  
254 site.  
255

From Fig. 1 it can be seen that the two experimental  
256 sites, especially the northern site, are not completely  
257 homogeneous; intersecting dirt roads and missing trees  
258 cause a certain degree of heterogeneity. However, consid-  
259 ering the horizontal scale of these heterogeneities, the  
260 experimental setup of both the EC systems and the LAS  
261

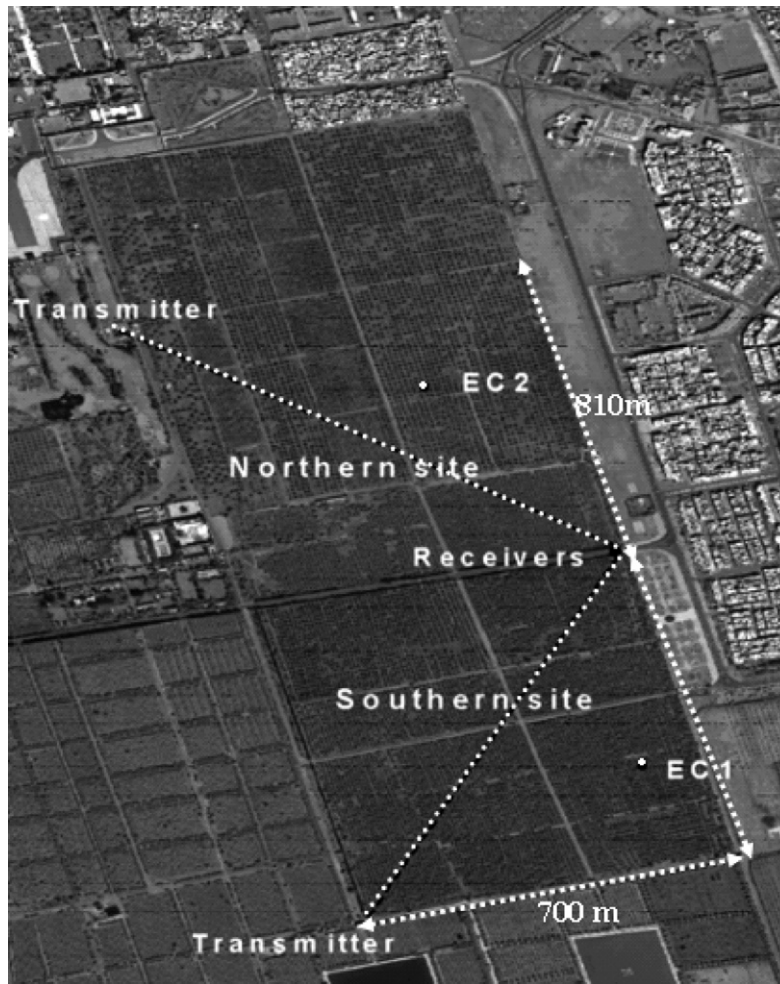


Figure 1 Overview of the experimental site (Quickbird image).

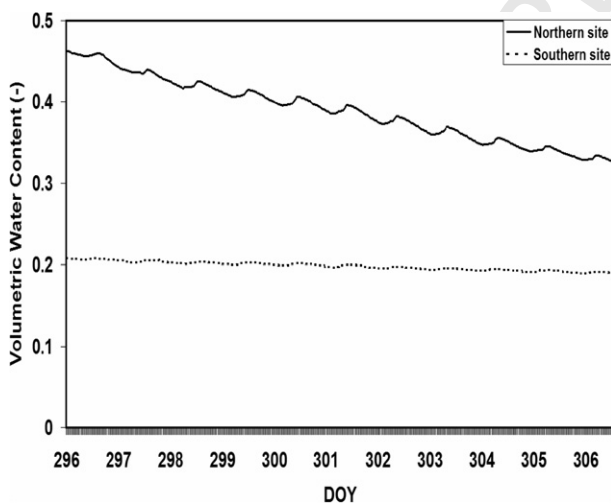


Figure 2 Evolution of the volumetric water content during the experimental period for the southern site (dotted line) and northern site (solid line).

is generally accepted to be applicable (Meijninger et al., 2002). In this study, patch scale refers to either northern or southern site, whereas grid scale refers to the entire oliveyard (or, the ensemble of northern and southern sites).

### Aggregation procedures for obtaining grid averaged $C_n^2$

Due to the non-linearity of  $C_n^2$ , the grid-scale average refractive index structure parameter  $\langle C_n^2 \rangle$  cannot be obtained as a weighted average of the patch-scale  $C_n^2$  values. Two alternative approaches are described in this section: the effective approach (denoted by subscript 'eff') and the aggregational approach (denoted by subscript 'agg'). In the effective approach, values of  $\langle C_n^2 \rangle_{\text{eff}}$  are obtained through the combination of eddy correlation based measurements of  $H$ ,  $L_v E$ , and  $u$ , and MOST. In the aggregated approach,  $\langle C_n^2 \rangle_{\text{agg}}$  is obtained through a combination of MOST, an aggregation scheme and the LAS-based patch-scale measurements of  $C_n^2$ .

### Effective approach

The effective approach consists of deriving an area-averaged  $C_n^2$  from eddy-covariance measurements. This  $\langle C_n^2 \rangle_{\text{eff}}$  is obtained by inverting Eqs. (1)–(5) using grid

are believed to be at or above the blending height, or the height at which the turbulent signatures of the individual heterogeneous structures are mixed, and above which MOST

286 scale averages of sensible and latent heat fluxes and friction  
287 velocity.  $\langle H_{EC} \rangle_{\text{eff}}$  and  $\langle LvE_{EC} \rangle_{\text{eff}}$  are obtained as a simple lin-  
288 ear weighted average of the fluxes measured at both sites.  
289 The effective friction velocity,  $\langle u_{*EC} \rangle_{\text{eff}}$ , is obtained by  
290 applying the matching rule to momentum fluxes (Chehbouni  
291 et al., 1999):  
292

$$294 \langle u_{*EC} \rangle_{\text{eff}} = \left( \sum f_{iEC} u_{*iEC}^2 \right)^{0.5}, \quad (6)$$

295 where  $f_{iEC}$  is the fraction of the surface covered by the  
296 patch  $i$ . Since the eddy-covariance systems at both northern  
297 and southern sites were installed at approximately the same  
298 height above the vegetation, we found it safe to assume  
299  $f_{iEC} = 0.5$ , since the size of the area from which the mea-  
300 sured flux emanates will be roughly the same for each site.

### 301 Aggregational approach

302 The second approach consists of estimating a grid scale  
303 average  $C_n^2$  from the LAS measurements. This  $\langle C_{nLAS}^2 \rangle_{\text{agg}}$  is  
304 obtained using  $C_{ns}^2$  and  $C_{nN}^2$  in combination with the aggrega-  
305 tion scheme described in this section. After obtaining a  
306 patch scale sensible heat flux from each LAS (using Eqs.  
307 (1)–(5)), a grid-scale sensible heat flux can be obtained as  
308 follows:  
309

$$311 \langle H \rangle = f_c H_{LAS-S} + (1 - f_c) H_{LAS-N}, \quad (7)$$

312 where subscripts S and N indicate variables associated with  
313 the southern or northern site, respectively, and  $f_c$  is the  
314 fraction of the southern area in the entire grid surface.  
315 The value of  $f_c$  is further discussed in “grid scale” section  
316 Eqs. (6) and (7) can be simplified as:  
317

$$319 \langle u_* T_* \rangle = f_c u_{*S} T_{*S} + (1 - f_c) u_{*N} T_{*N}, \quad (8)$$

$$321 \langle u_*^2 \rangle = f_c u_{*S}^2 + (1 - f_c) u_{*N}^2. \quad (9)$$

322 According to Monin–Obukhov similarity theory and using the  
323 scaling constants found by de Bruin et al. (1993):  
324

$$326 \frac{C_n^2(z-d)^{2/3}}{T_*^2} = 4.9 \left( 1 - 9 \frac{(z-d)}{L} \right)^{-2/3}. \quad (10)$$

327 By substituting Eq. (1) into Eq. (10) and Eq. (10) into (8), Eq.  
328 (11) can be obtained:  
329

$$331 \langle C_{nLAS}^2 \rangle_{\text{agg}} = \langle y \rangle^{-1} (y_S C_{ns}^2 + y_N C_{nN}^2) \quad (11)$$

332 with:

$$334 y_X = (f_X) \frac{u_{*X} \left( 1 + \frac{0.03}{\beta_X} \right)^{-2} (z_X - d_X)^{2/3}}{T_{*X} \left( 1 - 9 \frac{(z_X - d_X)}{L_X} \right)^{-2/3}}, \quad (12)$$

335 where  $X$  is either S, N or indicating the grid-scale average  
336 (angular brackets), and  $f_X = 1$  for  $\langle y \rangle$ ,  $f_X = f_c$  for  $y_S$  and  
337  $f_X = (1 - f_c)$  for  $y_N$ . Using once again the principle that con-  
338 sists of formulating grid-scale surface fluxes using the same  
339 equations that govern the patch-scale behaviour, but whose  
340 arguments are the aggregate expressions of those at the  
341 patch-scale (Chehbouni et al., 2000a),  $\langle L \rangle$  is derived from  
342 the area-average sensible heat flux and friction velocity as :

$$344 \langle L \rangle = \frac{-\rho c_p T_a \langle u_* \rangle^3}{kg \langle H \rangle}, \quad (13)$$

$\langle \beta \rangle$  is the grid-scale average Bowen ratio, defined as:

$$\langle \beta \rangle = \frac{\langle H \rangle}{\langle LvE \rangle}, \quad (14)$$

where  $\langle LvE \rangle$  is defined analogous to  $\langle H \rangle$  in Eq. (7), with  
patch scale values of  $LvE$  obtained as the resultant of the  
energy balance ( $LvE_{LAS} = R_n - G - H_{LAS}$ ).

On the other hand, one should mention that aggregation  
procedures based on the flux matching rules do not deal di-  
rectly with the primary surface variables, such as roughness  
length and displacement height. In this context, and accord-  
ing to previous study (Shuttleworth, 1988; Lagouarde et al.,  
2002), a semi-empirical approach is generally used. It stipu-  
lates that “the effective area-average value of land surface  
parameters is estimated as a weighted average over the  
component cover types in each grid through that function  
involving the parameter which most succinctly expresses  
its relationship with the associated surface flux”. Subse-  
quently, in this context, the grid scale average displace-  
ment height,  $\langle d \rangle$ , and roughness length,  $\langle z_0 \rangle$ , are  
expressed as:

$$\langle d \rangle = f_c d_S + (1 - f_c) d_N \quad (15)$$

and

$$\left( \ln \left( \frac{z - \langle d \rangle}{\langle z_0 \rangle} \right) \right)^2 = f_c \left( \ln \left( \frac{z - d_S}{z_{0S}} \right) \right)^2 + (1 - f_c) \times \left( \ln \left( \frac{z - d_N}{z_{0N}} \right) \right)^2. \quad (16)$$

Here  $z_{0S}$  and  $z_{0N}$  represent the roughness length for the  
southern and northern sites, respectively, each of which is  
estimated as a fraction of the vegetation height (rule of  
thumb).

## 374 Results and discussion

In this section, the closure of the energy balance of the  
eddy-covariance data is analysed, followed by a comparison  
between sensible heat fluxes measured by the EC systems  
and by the LAS at patch scale. Thereafter we test the appli-  
cability of MOST at grid scale when measurements are made  
below the so-called blending height, followed by a compar-  
ison of  $\langle C_{nLAS}^2 \rangle_{\text{agg}}$  and  $\langle C_{nEC}^2 \rangle_{\text{eff}}$  as well as a comparison be-  
tween the LAS based and EC-based area-averaged sensible  
heat flux. Note that only unstable conditions ( $\frac{(z-d)}{L} < 0$ ) are  
considered in this study.

### 385 Energy balance closure

As a measure of how the energy balance was closed in our  
observations, the sum of the latent ( $LvE$ ) and sensible ( $H$ )  
heat fluxes derived from the EC system is balanced by the  
available energy (net radiation ( $R_n$ ) minus soil heat flux  
( $G$ )). The energy balance closure depends both on the  
eddy-covariance measurements and the ability to ade-  
quately quantify the available energy over an area represen-  
tative of the flux source area. Most results in the literature  
have shown the sum of sensible and latent heat fluxes mea-  
sured by eddy-covariance to underestimate the available  
energy (Twine et al., 2000; Hoedjes et al., 2002; Testi  
et al., 2003).

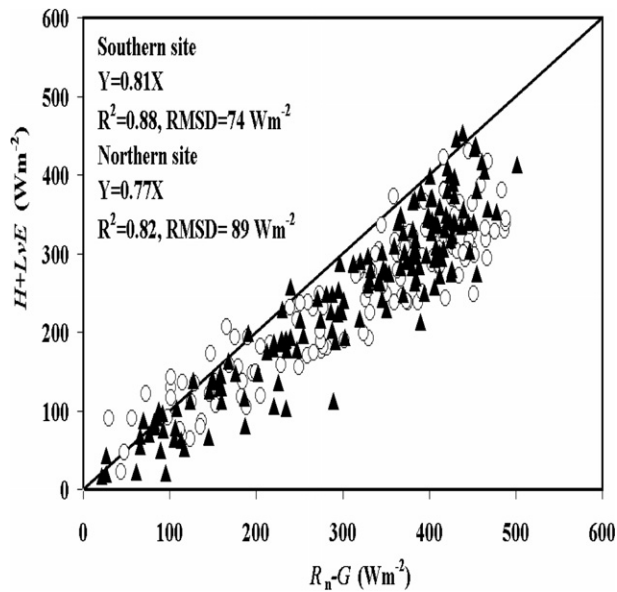


Figure 3 Comparison of half-hourly values of  $H + L_vE$  and  $R_n - G$  under unstable conditions, for northern site (triangles) and southern site (circles).

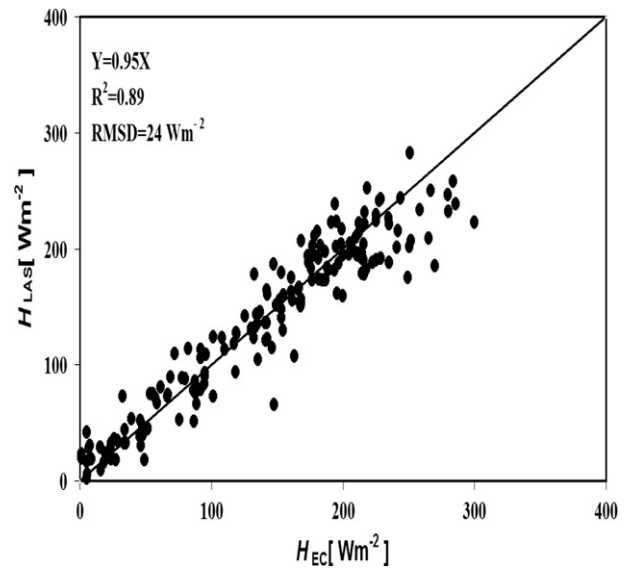


Figure 4a Comparison of  $H_{LAS}$  and  $H_{EC}$  during unstable conditions for the southern site.

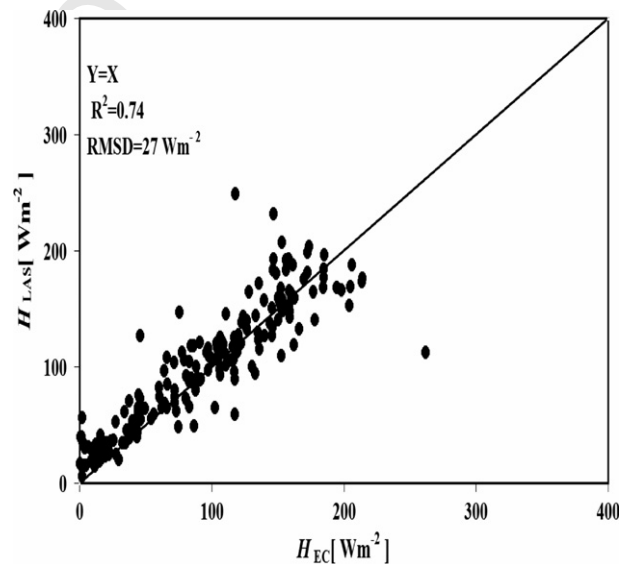


Figure 4b Comparison of  $H_{LAS}$  and  $H_{EC}$  during unstable conditions for the northern site.

398 Fig. 3 shows the plots of  $R_n - G$  against  $H + L_vE$  for the  
399 southern and northern sites. The linear regression (forced  
400 through the origin) yields ( $W m^{-2}$ )  $H_S + L_vE_S = 0.81(R_{nS} - G_S)$ ,  
401  $R^2 = 0.88$  and the root mean square difference  
402 (RMSD) =  $74 W m^{-2}$  for the southern site, and  
403  $H_N + L_vE_N = 0.77(R_{nN} - G_N)$ ,  $R^2 = 0.82$  and RMSD =  $89 W m^{-2}$   
404 for the northern site. Several reasons can be suggested to  
405 explain the lack of energy balance closure, for example  
406 underestimation of the fluxes measured with the eddy-  
407 covariance system, which might be due to the attenuation  
408 of the true turbulent signals at sufficiently high and low fre-  
409 quencies (e.g., Moore, 1986) or the differences in source  
410 area for convective fluxes and available energy. Addition-  
411 ally, energy storage within the olive tree biomass and in  
412 the air column beneath the net radiation measurement is  
413 not included in the energy balance. Scott et al. (2003) esti-  
414 mated the energy storage within the biomass in similar eco-  
415 systems to be about 5–10% of the available energy, which  
416 might explain some of the lack in energy balance closure.  
417 However, when compared to results reported in other  
418 experimental studies (the average error in closure ranges  
419 from 10% to 30% according to Twine et al., 2000), the energy  
420 balance closure obtained here can be considered  
421 acceptable.

#### 422 Patch scale

423 In Figs. 4a and 4b the sensible heat fluxes obtained from the  
424 LAS ( $H_{LAS}$ ) are compared, under unstable conditions, to  
425 those measured with eddy-covariance ( $H_{EC}$ ) for the southern  
426 and northern sites, respectively. For the southern site, linear  
427 regression (forced through the origin) yields ( $W m^{-2}$ ):  
428  $H_{LAS,S} = 0.95H_{EC,S}$ ,  $R^2 = 0.89$  and RMSD =  $24 W m^{-2}$ , and  
429  $H_{LAS,N} = H_{EC,N}$ ,  $R^2 = 0.74$  and RMSD =  $27 W m^{-2}$  for the north-  
430 ern site. The contrast between the two sites in terms of  
431 water availability (irrigation) can clearly be seen in these

figures. Sensible heat flux values over the southern site 432  
are considerably higher than those over the northern site. 433  
In the southern site, the maximum value of  $H$  was around 434  
 $300 W m^{-2}$ , while for the northern site the maximum was 435  
around  $200 W m^{-2}$ . The comparison shows a better agree- 436  
ment for the southern site than for the northern site. There 437  
are several explanations for the scatter in Figs. 4a and 4b. 438  
During some of the intervals used in this study, conditions 439  
were partly cloudy. Additionally, an irrigation event had ta- 440  
ken place just before the experiment, with irrigation reach- 441  
ing the location of the EC-system on DOY 291. This caused 442  
heterogeneity in terms of soil moisture in the northern site 443  
during the experimental period. The impact of this hetero- 444  
geneity is amplified by the differences in the source area of 445

446 the LAS and that of the EC system. Indeed, due to the flood  
447 irrigation method employed in the site, it takes approxi-  
448 mately 15 days to irrigate the entire field. During this peri-  
449 od, the source area of the EC might be wet (dry) while a  
450 significant portion of that of the LAS is dry (wet).

#### 451 Grid scale

452 In order to derive fluxes from LAS one has to rely on the  
453 Monin–Obukhov similarity theory (MOST). Since MOST re-  
454 quires horizontal homogeneity, the question is whether this  
455 theory still applies under heterogeneous conditions. Addi-  
456 tionally, the measurements should be made above the  
457 blending height, which depends according to Wieringa  
458 (1986) on the friction velocity, wind speed and the horizon-  
459 tal length scale of the heterogeneities. Under the prevailing  
460 conditions over our study site, the average blending height  
461 was at about 26 m at the grid scale. Unfortunately, the  
462 operational deployment of the instruments at such height  
463 is not feasible. It is therefore of interest to investigate  
464 whether MOST holds under conditions of horizontal hetero-  
465 geneity (at grid scale) where the measurements are made  
466 below the blending height.

467  $\langle C_{nLAS}^2 \rangle_{agg}$  has been obtained assuming the linearity of scal-  
468 ars fluxes derived from the LAS (sensible heat and momen-  
469 tum fluxes over each field) using Eq. (11). In contrast to  
470 Lagouarde et al. (2002), who simulated values of  $\langle C_n^2 \rangle$  over  
471 a two-surface composite landscape by weighting values of  
472  $C_n^2$  computed for each field from the sensible heat flux  
473 (eddy-covariance) according to the scintillometer weighting  
474 function, here  $\langle C_{nLAS}^2 \rangle_{agg}$  was directly derived using  $C_n^2$  from  
475 the LAS using Eq. (11) so that the non-linearity of  $C_n^2$  is  
476 avoided in the calculation of  $\langle C_{nLAS}^2 \rangle_{agg}$ .

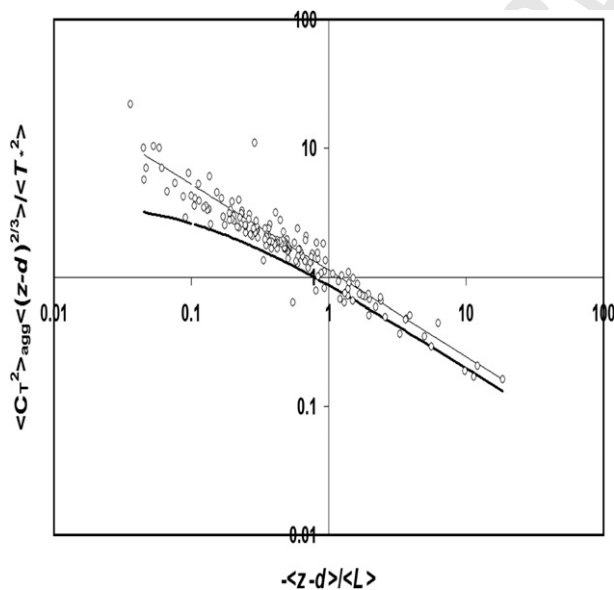


Figure 5  $\langle C_T^2 \rangle_{agg} \langle (z-d)^{2/3} \rangle / \langle T_*^2 \rangle$  plotted against  $-(z-d)/\langle L \rangle$  during unstable conditions. Thick solid line represents the unstable scaling function found by de Bruin et al. (1993); also shown is the free convection relationship found by de Bruin et al. (1993):  $f((z-d)/L) = 1.13(-(z-d)/L)^{-2/3}$  (solid line).

To check whether  $\langle C_{TLAS}^2 \rangle_{agg}$ , calculated from  $\langle C_{nLAS}^2 \rangle_{agg}$  using Eq. (1), behaves according to MOST, we present in Fig. 5 a cross plot of  $\langle C_{TLAS}^2 \rangle_{agg} \langle (z-d)^{2/3} \rangle / \langle T_*^2 \rangle$  and  $\langle (z-d)/\langle L \rangle$ . In order to avoid self-correlation due to MOST already being taken into account during the iterative procedure (Eqs. (1)–(5)), the effective values of  $\langle \beta \rangle$ ,  $\langle T_* \rangle$  and  $\langle L \rangle$  have been constructed using solely eddy-covariance measurements. The result shows that the MOST scaling reported by de Bruin et al. (1993) still holds for heterogeneous surfaces, even though a small overestimation can be observed. Similar results have been found by Meijninger et al. (2002), who used the same scaling. These results confirm that MOST can be used below the blending height. This finding is in agreement with other studies (Shuttleworth, 1988; de Bruin, 1989; Ronda and de Bruin, 1999) which have shown that for surfaces with disorganized heterogeneity there is a layer below the blending height where MOST applies, but where contributions from separate fields can still be “seen”. In the same vein, Kohsiek et al. (2002) reported that when deploying the XLAS (extra large aperture scintillometer, which can be used over pathlengths of up to 10 km) below the blending, the violation of MOST is negligible. This is of interest since the operational deployment of an XLAS over a distance up of 10 km at or above the blending height is just not feasible.

Since both EC systems have been installed at approximately the same height above the canopy, it is safe to assume that each EC system has a similar sized source area, and therefore  $f_{IEC} = 0.5$  in Eq. (6). For the LAS however, since the two scintillometers are not set up with the same orientation, depending on the wind direction, large differences can occur between the dimensions of the source area of each LAS. Therefore, the effect of changing of  $f_c$  on the aggregation model has been investigated by varying  $f_c$  between 0.1 and 0.9. Statistical results for a comparison between  $\langle C_{nLAS}^2 \rangle_{agg}$  and  $\langle C_{nEC}^2 \rangle_{eff}$ , in order to check the sensitivity to the composition of the surface on  $\langle C_{nLAS}^2 \rangle_{agg}$ , are presented in Table 1. It shows that for the experimental site, to a good approximation,  $f_c = 0.5$ . In Fig. 6, a comparison between  $\langle C_{nLAS}^2 \rangle_{agg}$  and  $\langle C_{nEC}^2 \rangle_{eff}$  with  $f_c = 0.5$  for cloud free days is presented. The comparison is good, with  $R^2 = 0.95$  and the RMSD =  $5 \times 10^{-15} \text{ m}^{-2/3}$ . Note that the difference between the statistical results for  $f_c = 0.5$  as shown in Table 1 and in Fig. 6 is caused by the exclusion of cloudy intervals in the data used in Fig. 6.

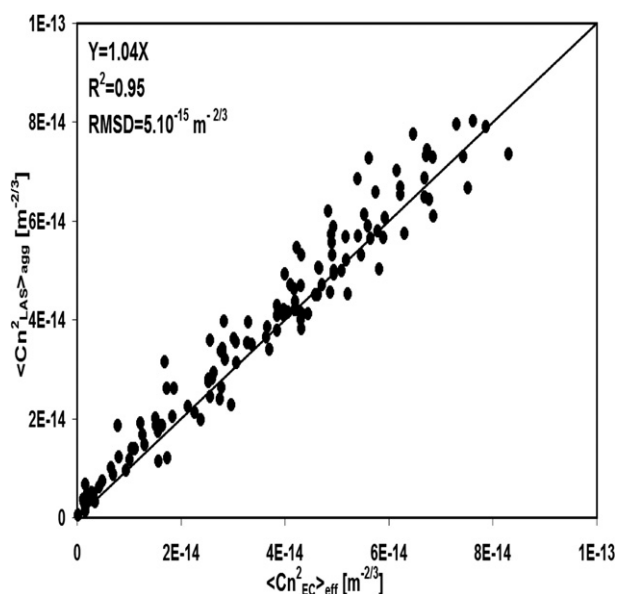
Finally, in Fig. 7 the grid scale sensible heat flux ( $\langle H_{LAS} \rangle_{agg}$ ) simulated from  $\langle C_{nLAS}^2 \rangle_{agg}$  (using Eqs. (1)–(5)) is compared with the area-average sensible heat fluxes  $\langle H_{EC} \rangle_w$  defined as the linear weighing of sensible heat fluxes observed by the EC-systems of both fields with  $f_c = f_{IEC} = 0.5$ . The linear regression (forced through the origin) yields  $\langle H_{LAS} \rangle_{agg} = \langle H_{EC} \rangle_w$ ,  $R^2 = 0.89$  and RMSD =  $20.3 \text{ W m}^{-2}$ . This result shows less scatter than the comparison at patch scale, and correlation is good.

In the present experimental setup, no third scintillometer has been installed over the two patches (and above the blending height) for validation. Besides practical constraints, it should be noted that it is practically impossible to have a source area that matches the ensemble of the source areas of the two LAS installed at the individual patches. This scintillometer would have a varying contribution of the southern and northern sites, depending on wind



**Table 1** Statistical results of the linear regression (forced through the origin) between simulated effective grid average  $\langle C_{nLAS}^2 \rangle_{agg}$  with  $f_c$  (the fraction of the source area of LAS<sub>s</sub> in the entire grid surface) varying between 0.1 and 0.9, and  $\langle C_{nEC}^2 \rangle_{eff}$  with  $f_{IEC} = 0.5$

Portion of south surface ( $f_c$ )	Slope	Correlation coefficient	RMSD $\times 10^{15}$ ( $m^{-2/3}$ )
0.1	0.77	0.8	12.8
0.2	0.83	0.83	10.8
0.3	0.89	0.85	9.1
0.4	0.95	0.87	8.2
0.5	1	0.88	7.8
0.6	1.07	0.88	8.78
0.7	1.14	0.87	10.6
0.8	1.2	0.87	13
0.9	1.27	0.86	16



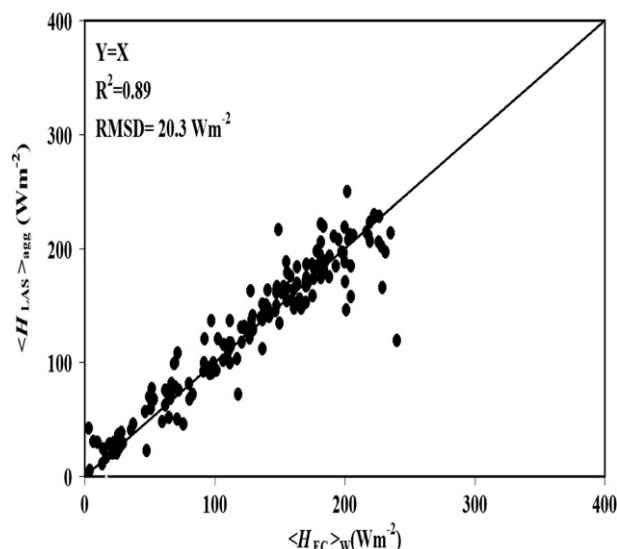
**Figure 6** Comparison of  $\langle C_{nLAS}^2 \rangle_{agg}$  obtained from the aggregation model and  $\langle C_{nEC}^2 \rangle_{eff}$  obtained from  $\langle H_{EC} \rangle_w$ ,  $\langle LvE_{EC} \rangle_w$  and  $\langle L_{EC} \rangle$ ; intervals without cloud passes.

539 direction, which will differ considerably from  $f_c$ . Therefore,  
540 a third LAS does not provide a measurement that can be  
541 used to validate the aggregation method developed in this  
542 study.

### 543 Summary and conclusions

544 The general objective of the present study is to investigate  
545 the applicability of MOST at grid scale (i.e., the combination  
546 of the several individual fields, or patches). This is done by  
547 combining the LAS measurements over two individual  
548 patches with an aggregation scheme to infer the grid averaged  
549 refractive index structure parameter  $\langle C_n^2 \rangle$ .

550 The comparisons between the half-hourly sensible heat  
551 fluxes obtained from eddy-covariance and LAS at patch



**Figure 7** Comparison of grid scale sensible heat flux  $\langle H_{LAS} \rangle_{agg}$  simulated from  $\langle C_{nLAS}^2 \rangle_{agg}$  and  $\langle H_{EC} \rangle_w$  derived by weighing the sensible heat fluxes observed from the EC-systems of both fields ( $f_c = f_{IEC} = 0.5$ ).

scale yield a good result. The RMSD is 24.5 and 28.3  $W m^{-2}$  for the southern and northern sites, respectively. The difference in flux between the two fields is mainly caused by an irrigation event which took place in the northern site during the experiment. This also explains part of the scatter and lower correlation between  $H_{EC}$  and  $H_{LAS}$  for the northern site, since during irrigation, the impact of the differences in the source areas of the two instruments increased significantly. However, despite some scatter, it can be assumed that MOST is applicable over relatively tall and sparse trees. Furthermore, the two comparisons show the difference between the two sites at the time of the experiment. Consequently, the grid, comprised of the two patches, can be considered as heterogeneous.

A combination of patch scale LAS measurements, meteorological data and an aggregation model have been used to derive a grid averaged  $\langle C_{nLAS}^2 \rangle_{agg}$ , from which the grid averaged structure parameter of temperature is calculated. This  $\langle C_{TLAS}^2 \rangle_{agg}$  is shown to behave according to MOST, although some scatter is observed. However, this scatter can be considered acceptable (see for example Beljaars et al., 1983; Weaver, 1990; de Bruin et al., 1993), and therefore MOST is considered to be applicable at grid scale, even when the measurements have been taken below the blending height.

There are practical constraints for the installation of a third scintillometer to measure over the entire grid; to overcome saturation and to be above the blending height (see for example Meijninger et al., 2002), one would have to install this third scintillometer much higher than the two LAS in used in this study. Therefore, in order to verify the accuracy of the values of  $\langle C_{nLAS}^2 \rangle_{agg}$ , an effective parameter has been used. This effective approach uses averages of friction velocity and sensible and latent heat fluxes from the EC system in combination with MOST to calculate  $\langle C_n^2 \rangle$  values. In the case where MOST is applicable, this would be the grid-scale value of  $C_n^2$ , and this  $\langle C_n^2 \rangle_{eff}$  can therefore be used to

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589 validate  $\langle C_{nLAS}^2 \rangle_{agg}$ . Despite some scatter, the comparison is  
590 good which confirms the consistency of the aggregation  
591 method.

592 The results of this study demonstrate the applicability of  
593 the LAS and thus the XLAS, over large and heterogeneous  
594 grids when deployed below the blending height. Conse-  
595 quently, the minimum height at which a scintillometer can  
596 be operated is not the blending height, but the height below  
597 which saturation of the signal occurs (see for example  
598 Moene et al., 2005). Furthermore, since available energy  
599 is easily obtained from spaceborne sensors, e.g. Meteosat  
600 Second Generation or MODIS (<http://postel.obs-mip.fr/postel/>),  
601 this allows the determination of evapotranspiration  
602 at the aforementioned scales, which can be used for  
603 e.g. irrigation monitoring, or the validation of mesoscale  
604 atmospheric models or hydrological models.

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