



**Infrared and millimetre-wave  
scintillometry in the  
suburban  
environment – Part 1**

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**Infrared and millimetre-wave  
scintillometry in the suburban  
environment – Part 1: Structure  
parameters**

**H. C. Ward<sup>1,2,3</sup>, J. G. Evans<sup>1</sup>, C. S. B. Grimmond<sup>2,3</sup>, and J. Bradford<sup>4</sup>**

<sup>1</sup>Centre for Ecology and Hydrology, Wallingford, Oxfordshire, OX10 8BB, UK

<sup>2</sup>Department of Geography, King's College London, London, WC2R 2LS, UK

<sup>3</sup>Department of Meteorology, University of Reading, Reading, RG6 6BB, UK

<sup>4</sup>Space Science Department, Rutherford Appleton Laboratory, Didcot, Oxfordshire,  
OX11 0QX, UK

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Correspondence to: H. C. Ward (h.c.ward@reading.ac.uk)

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## Abstract

Scintillometry, a form of ground-based remote sensing, provides the capability to estimate surface heat fluxes over scales of a few hundred metres to kilometres. Measurements are spatial averages, making this technique particularly valuable over areas with moderate heterogeneity such as mixed agricultural or urban environments. In this study, we present the structure parameters of temperature and humidity, which can be related to the sensible and latent heat fluxes through similarity theory, for a suburban area in the UK. The fluxes are provided in the second paper of this two-part series. A unique millimetre-wave scintillometer was combined with an infrared scintillometer along a 5.5 km path over northern Swindon. The pairing of these two wavelengths offers sensitivity to both temperature and humidity fluctuations and the so-called “bichromatic-correlation” method is also used to retrieve the path-averaged temperature-humidity correlation. Comparison is made with structure parameters calculated from an eddy covariance station located close to the centre of the scintillometer path. The performance of the techniques under different conditions is discussed. Similar behaviour is seen between the two datasets at sub-daily timescales. For the two summer-to-winter periods presented here, similar evolution is displayed across the seasons. A higher vegetation fraction within the scintillometer source area is consistent with the lower Bowen ratio observed (midday Bowen ratio < 1) compared with more built-up areas around the eddy covariance station. The energy partitioning is further explored in the companion paper.

## Highlights

- First use of two-wavelength scintillometry in an urban area;
- Temperature–humidity correlation coefficient measured by bichromatic-correlation;
- Performance of techniques assessed under a range of conditions;

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et al., 2012). On the whole, these studies have shown that scintillometers installed above or close to the blending height can provide valuable area-averaged fluxes.

With careful selection of a suitable path, the scintillometry technique has been successfully used in urban areas. Kanda et al. (2002), the first to derive the sensible heat flux in an urban setting, used two small aperture scintillometers installed at different heights on a 250 m path over a dense residential area of Tokyo. Other small aperture studies include measurements in Basel (Roth et al., 2006) and London (Pauscher, 2010). Large aperture scintillometers are increasingly being used over longer urban paths (Lagouarde et al., 2006; Gouvea and Grimmond, 2010; Mestayer et al., 2011; Wood et al., 2013; Zieliński et al., 2013). These infrared (or optical) scintillometers must rely on the residual of the energy balance if the latent heat flux is to be estimated. However, the complexity of the energy balance (Oke, 1987) means this is usually not attempted in urban areas. In particular the significant storage heat flux (Oke et al., 1999; Offerle et al., 2005) and contribution from anthropogenic activities (Klysiak, 1996; Allen et al., 2011) are both very difficult to measure.

Sensitivity to both humidity and temperature fluctuations can be achieved with a two-wavelength scintillometer system. In this case, the structure parameter of humidity can be obtained in addition to the structure parameter of temperature, from which both the sensible heat flux ( $Q_H$ ) and latent heat flux ( $Q_E$ ) can be found (Hill et al., 1988; Andreas, 1989). Several studies have reported successful estimates of  $Q_E$  using the two-wavelength method (Meijninger et al., 2002a, 2006; Evans, 2009; Evans et al., 2010). This technique requires that a value of the temperature–humidity correlation coefficient,  $r_{Tq}$ , be assumed. Often  $r_{Tq}$  is taken to be  $\pm 1$ , indicating perfect correlation, as in Green et al. (2001) and Meijninger et al. (2002a), but other values have also been used: Kohsiek and Herben (1983) used  $r_{Tq} = 0.87$ ; Evans (2009) used  $r_{Tq} = 0.8$ ; and Meijninger et al. (2006) used measured  $r_{Tq}$  from a nearby EC station with values between  $-0.5$  and  $0.9$ . Previous studies measuring  $r_{Tq}$  with fast-response sensors suggest daytime values tend to be smaller than 1, typically around 0.8. For example: 0.75 at a flat, homogeneous site (Kohsiek, 1982); 0.76 over sandy soil with patchy vegetation

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(Andreas et al., 1998); 0.70–0.95 for unstable conditions over heterogeneous farmland (Meijninger et al., 2002a). Nocturnal values of  $r_{Tq}$  down to  $-1$  are rarely seen (Andreas et al., 1998; Beyrich et al., 2005; Meijninger et al., 2006).

Some studies have suggested that  $r_{Tq}$  varies with stability (Li et al., 2011; Nordbo et al., 2013), although others have shown no clear relation (De Bruin et al., 1993; Roth, 1993). Explanation of  $|r_{Tq}| \neq 1$  is often related to surface heterogeneity (Roth, 1993; Andreas et al., 1998; Lüdi et al., 2005) but low values have been obtained over homogeneous surfaces too (Kohsiek, 1982; De Bruin et al., 1993). In almost all previous studies, measurements of  $r_{Tq}$  were made using point sensors.

Lüdi et al. (2005) outlined a method to obtain path-averaged values of  $r_{Tq}$  using a two-wavelength scintillometer system. This “bichromatic-correlation” method is an extension of the two-wavelength technique and involves correlating the signals from each scintillometer, thus enabling determination of the combined temperature–humidity fluctuations and  $r_{Tq}$ . The bichromatic-correlation method, applied for the first time during the LITFASS-2003 campaign, gave promising results (Beyrich et al., 2005; Lüdi et al., 2005). An overview of the second study, during LITFASS-2009, is given in Beyrich et al. (2012).

Aside from enabling more accurate structure parameters and fluxes to be obtained from scintillometry, improved knowledge of  $r_{Tq}$  has wider applications. Correlations between scalars are thought to be useful indicators for the violation of Monin–Obukhov Similarity Theory (MOST) (Hill, 1989; Andreas et al., 1998). Correlations are also relevant to the understanding and modelling of turbulent transport processes through physical quantities such as eddy diffusivities.

The objectives of this research are to measure structure parameters and obtain large-area sensible and latent heat fluxes for a suburban area. In this two-part study, a 94 GHz millimetre-wave scintillometer was deployed alongside an infrared scintillometer over the town of Swindon, UK. This is the first use of such a system in the urban environment. In Part 1, structure parameters from the two-wavelength system are compared to structure parameters calculated from an EC system and measured

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values of  $r_{Tq}$  are discussed. In Part 2, the sensible and latent fluxes are determined and analysed. These spatially-integrated observations represent the behaviour of the suburban surface over an area of 5–10 km<sup>2</sup> and constitute by far the longest dataset that uses these techniques. Methodological considerations, the performance of the techniques and the influence of energy and water availability, vegetation cover and seasonality are explored.

## 2 Theory

Structure parameters describe the intensity of fluctuations in the turbulent atmosphere. The structure parameter for a variable,  $y$ , is defined (Tatarski, 1961),

$$C_y^2 = \frac{\overline{[y(x + \delta) - y(x)]^2}}{\delta^{2/3}}, \quad (1)$$

where  $\delta$  is the spatial separation between two points and  $y(x)$  is the value of the variable at location  $x$ . The cross-structure parameter between two variables is defined analogously, for example the cross-structure parameter between temperature,  $T$ , and specific humidity,  $q$ , is written,

$$C_{Tq} = \frac{\overline{[T(x + \delta) - T(x)][q(x + \delta) - q(x)]}}{\delta^{2/3}}. \quad (2)$$

### 2.1 Obtaining structure parameters from scintillometry

The refractive index structure parameter ( $C_n^2$ ) is fundamental to scintillometry. For each wavelength,  $\lambda$ , it can be written,

$$C_n^2 = \frac{A_T^2}{T^2} C_T^2 + 2 \frac{A_T A_q}{T q} C_{Tq} + \frac{A_q^2}{q^2} C_q^2, \quad (3)$$

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where  $C_T^2$  is the structure parameter of temperature,  $C_q^2$  the structure parameter of specific humidity,  $C_{Tq}$  the temperature–humidity cross-structure parameter and  $A_T$  and  $A_q$  are the structure parameter coefficients for temperature and specific humidity respectively, given in Ward et al. (2013b) as  $A_T$  and  $A_q$  (see their Table 2). These coefficients contain the wavelength dependence of  $C_n^2$ , whereas  $C_T^2$ ,  $C_q^2$  and  $C_{Tq}$  are properties of the atmosphere. Each  $C_n^2$  measurement is made up of a combination of the three unknowns:  $C_T^2$ ,  $C_q^2$  and  $C_{Tq}$ .

As  $C_n^2$  from large aperture optical or near-infrared scintillometers is almost entirely made up of temperature fluctuations ( $C_T^2$ ), the (usually small) contributions from  $C_{Tq}$  and  $C_q^2$  can be approximated using the Bowen ratio,  $\beta$  (Wesely, 1976; Moene, 2003):

$$C_n^2 = \frac{A_T^2}{T^2} C_T^2 \left( 1 + \frac{A_q}{q} \frac{T}{A_T} \frac{c_p}{L_v} \beta^{-1} \right)^2 \approx \frac{A_T^2}{T^2} C_T^2 (1 + 0.03\beta^{-1})^2, \quad (4)$$

where  $c_p$  is the specific heat capacity of air at constant pressure,  $L_v$  is the latent heat of vaporisation and the value 0.03 is for typical atmospheric conditions. The required Bowen ratio may be found by using the available energy as an input to the iteration to obtain the sensible heat flux (e.g. Green and Hayashi, 1998; Meijninger et al., 2002b; Solignac et al., 2009). Calculation of the latent heat flux must rely on the energy balance (Ezzahar et al., 2009; Guyot et al., 2009; Samain et al., 2012b; Evans et al., 2012). This is the single-wavelength scintillometry method.

As demonstrated by Hill et al. (1988) and Andreas (1989), a two-wavelength scintillometer system enables retrieval of both  $C_T^2$  and  $C_q^2$  via simultaneous equations (Eq. 3 for each wavelength). The two-wavelength method has the significant advantage of providing both sensible and latent heat fluxes without resorting to the energy balance, but a value for the temperature–humidity correlation coefficient  $r_{Tq}$  must be assumed in the substitution  $C_{Tq} = r_{Tq}(C_T^2 C_q^2)^{1/2}$ .

The bichromatic-correlation method uses the same combination of optical and millimetre wavelength scintillometers as for the two-wavelength method, but additionally exploits the correlation between optical and millimetre-wave signals to obtain a third equation for the cross-structure parameter,  $C_{n_1n_2}$  (Lüdi et al., 2005),

$$C_{n_1n_2} = \frac{A_{T_1}A_{T_2}}{T^2}C_T^2 + \left( \frac{A_{T_1}A_{q_2} + A_{T_2}A_{q_1}}{Tq} \right) C_{Tq} + \frac{A_{q_1}A_{q_2}}{q^2}C_q^2, \quad (5)$$

where the subscripts 1 and 2 refer to the different wavelengths. In this study,  $\lambda_1$  denotes optical (specifically  $880 \times 10^{-9}$  m) and  $\lambda_2$  millimetre ( $3.2 \times 10^{-3}$  m) wavelengths. Thus all three unknown meteorological structure parameters ( $C_T^2$ ,  $C_q^2$  and  $C_{Tq}$ ) can be found from the three measured refractive index structure parameters by inverting the matrix equation (Lüdi et al., 2005),

$$\begin{pmatrix} C_{n_1n_1} & C_{n_2n_2} & C_{n_1n_2} \end{pmatrix} = \mathbf{M} \begin{pmatrix} C_T^2 \\ C_{Tq} \\ C_q^2 \end{pmatrix}, \quad (6)$$

where the inverse matrix  $\mathbf{M}^{-1}$  is given by,

$$\mathbf{M}^{-1} = \frac{T^2q^2}{(A_{T_1}A_{q_2} - A_{T_2}A_{q_1})^2} \begin{pmatrix} \frac{A_{q_2}^2}{q^2} & \frac{A_{q_1}^2}{q^2} & \frac{-2A_{q_1}A_{q_2}}{q^2} \\ \frac{-A_{T_2}A_{q_2}}{Tq} & \frac{-A_{T_1}A_{q_1}}{Tq} & \frac{(A_{T_1}A_{q_2} + A_{T_2}A_{q_1})}{Tq} \\ \frac{A_{T_2}^2}{T^2} & \frac{A_{T_1}^2}{T^2} & \frac{-2A_{T_1}A_{T_2}}{T^2} \end{pmatrix}. \quad (7)$$

As mentioned above, the structure parameter coefficients  $A_T$  and  $A_q$  should be those formulated using specific humidity.

For the bichromatic-correlation method the value of  $C_{Tq}$  obtained can therefore be used to effectively measure the temperature–humidity correlation coefficient:

$$r_{Tq} = \frac{C_{Tq}}{\sqrt{C_T^2 C_q^2}}. \quad (8)$$



If most assumptions (i.e.  $T$ - $q$  similarity) are satisfied, the Bowen ratio can be calculated from the structure parameters (Andreas, 1990; Lüdi et al., 2005),

$$\beta = \text{sgn}[C_{Tq}] \frac{c_p}{L_v} \sqrt{\frac{C_T^2}{C_q^2}}. \quad (9)$$

When the cross-structure parameter has not been measured, the structure parameters  $C_T^2$  and  $C_q^2$  can be calculated from the two-wavelength equations, after Hill et al. (1988):

$$C_T^2 = \frac{A_{q2}^2 C_{n1n1} + A_{q1}^2 C_{n2n2} + 2r_{Tq} A_{q1} A_{q2} S_{2\lambda} \sqrt{C_{n1n1} C_{n2n2}}}{(A_{T1} A_{q2} - A_{T2} A_{q1})^2 T^{-2}}, \quad (10a)$$

$$C_q^2 = \frac{A_{T2}^2 C_{n1n1} + A_{T1}^2 C_{n2n2} + 2r_{Tq} A_{T1} A_{T2} S_{2\lambda} \sqrt{C_{n1n1} C_{n2n2}}}{(A_{T1} A_{q2} - A_{T2} A_{q1})^2 q^{-2}}, \quad (10b)$$

where  $S_{2\lambda}$  is  $\pm 1$ . This choice of sign is an inherent ambiguity of the two-wavelength method and represents two possible solutions to  $C_{n2n2}$  (Hill et al., 1988; Hill, 1997). When expressed as a function of  $\beta$ , a minimum in  $C_{n2n2}$  occurs due to the coefficients  $A_T$  and  $A_q$  having opposite signs at millimetre wavelengths. The contribution of  $C_{Tq}$  to  $C_{n2n2}$  (middle term in Eq. 3) is negative when  $C_{Tq} > 0$ , so for moderate  $\beta$  the terms in Eq. (3) can cancel out leaving  $C_{n2n2}$  close to zero (Hill et al., 1988; Otto et al., 1996). In practice, a finite instrumental noise floor (and  $r_{Tq} \neq 1$ ) means zero  $C_{n2n2}$  will not be observed. Instead a measurement problem of reduced sensitivity is created around the region of minimum  $C_{n2n2}$ , where the scintillation signal may be close to, or below, the detection limit of the instrument. The problematic region is expected to occur for  $\beta \approx 2$ – $3$  (Leijnse et al., 2007; Ward et al., 2013b). For low  $\beta$ , when humidity fluctuations dominate  $C_{n2n2}$  then  $S_{2\lambda} = +1$ , whereas  $S_{2\lambda} = -1$  is required at larger  $\beta$ . The sign of  $S_{2\lambda}$  is not known a priori but must be assumed. Often the two solutions for  $\beta$  indicate which is the most likely solution for the atmospheric conditions and site characteristics (Hill, 1997).

## 2.2 Obtaining structure parameters from eddy covariance

Conversion between spatial and temporal domains enables calculation of structure parameters from point measurements, such as those from EC instrumentation. The spatial structure function,  $D_{yy-x}$ , can be written (e.g. Stull, 1988),

$$D_{yy-x}(\delta) = \overline{[y(x + \delta) - y(x)]^2}. \quad (11)$$

Analogously the temporal structure function,  $D_{yy-t}$ , is given by,

$$D_{yy-t}(\tau) = \overline{[y(t + \tau) - y(t)]^2}, \quad (12)$$

where  $\tau$  is the temporal separation and  $y(t)$  is the value of the variable at time  $t$ . Bosveld (1999) gives the conversion between temporal and spatial structure functions using the horizontal wind vector,  $U$ , and the variances of the three wind components,  $\sigma_{u,v,w}^2$ :

$$D_{yy-x}(\delta) = \frac{D_{yy-t}(\delta/U)}{\left(1 - \frac{1}{9} \frac{\sigma_u^2}{U^2} + \frac{1}{3} \frac{\sigma_v^2}{U^2} + \frac{1}{3} \frac{\sigma_w^2}{U^2}\right)}. \quad (13)$$

Thus temporal structure functions (Eq. 12) can be calculated from EC measurements, converted to spatial structure functions (Eq. 13) and then structure parameters ( $C_y^2 = D_{yy-x}(\delta)\delta^{-2/3}$  defines  $C_y^2$  for  $\delta$  in the inertial subrange). Unlike fluxes, structure parameters are strongly height dependent.

## 3 Experimental details

### 3.1 Instrumental setup and site description

A unique millimetre-wave scintillometer (MWS) (Evans, 2009), designed and built by the Centre for Ecology and Hydrology (CEH) and Rutherford Appleton Laboratory

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(RAL), was used in combination with a commercially available large aperture infrared scintillometer, the BLS900 (Scintec, Rottenburg, Germany). Both scintillometers were installed on a 5.5 km path over the town of Swindon, UK. The path is orientated approximately north–south ( $170^\circ$ ) and extends from the edge of the settlement to the town centre (Fig. 1). An EC system was positioned near the centre of the path, consisting of a sonic anemometer (R3, Gill Instruments, Lymington, UK) and open-path infrared gas analyser (IRGA) (LI-7500, LI-COR Biosciences, Lincoln, USA) mounted at 12.5 m above ground level (a.g.l.). The EC site was equipped with an automatic weather station (WXT, Vaisala, Finland) which provides the additional input data required to process the scintillometer data: temperature, relative humidity (RH), pressure ( $p$ ) and wind speed ( $U$ ) are measured at a height of 10.6 m. A four-component radiometer (NR01, Hukseflux, the Netherlands) was installed at 10.1 m on the same mast and a tipping bucket rain gauge (0.2 mm tip, Casella CEL, Bedford, UK) near the base of the mast. These were located in the garden of a residential property approximately 3 km north of the town centre, where the surrounding land use is predominantly residential, consisting of 1–2 storey houses with gardens. Full details are given in Ward et al. (2013a). In addition to the meteorological instrumentation at the EC site ( $MET_{sub}$ ), a second weather station was established on the rooftop of a modern office building close to the town centre ( $MET_{roof}$ ). The setup is summarised in Table 1. To provide a combined dataset of continuous input variables required for scintillometry processing,  $T$ , RH,  $p$  and  $U$  from  $MET_{roof}$  were linearly adjusted to gap-fill  $MET_{sub}$  (required for  $< 1\%$  of  $T$ , RH and  $p$  and  $< 2\%$  of  $U$  data), based on regressions with concurrent data from  $MET_{sub}$  (9 May 2011–31 December 2012).

Northern Swindon is typical of suburban areas in the UK. The area has a relatively large proportion of vegetation and there is a large nature reserve just north of the centre of the study area, which lies directly underneath the scintillometer path. The town centre at the south of the study area has the highest density of buildings and roads (Fig. 1). Industrial areas to the east and southwest with little vegetation contribute to measurement source areas under stable conditions (see Part 2). Despite the variety

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of land cover types, many neighbourhoods appear fairly homogeneous at a scale of a few hundred metres. The area shown in Fig. 1 has land cover that is 14 % buildings, 31 % impervious, 53 % vegetation, 1 % water and 2 % pervious. Land cover, topography and building and tree heights were derived from a spatial database for Swindon (5 m resolution, see Ward et al. (2013a) for more information).

To obtain representative measurements it is important to be high enough above the surface that quantities are sufficiently well-blended, although recent studies have shown successful use of scintillometers even below the blending height (Meijninger et al., 2002b; Ezzahar et al., 2007). Based on the average height of the roughness elements (i.e. buildings and trees) the blending height is estimated at about 15–30 m for the BLS-MWS source area (Pasquill, 1974; Garratt, 1978). The scintillometer transmitters, mounted on custom-built brackets, were installed at 28 m a.g.l. on a television transmitter mast. The receivers of the BLS-MWS system were mounted at 26 m a.g.l. on a rooftop in Swindon town centre. The resulting path is slanted (Fig. 2).

The effective heights of the scintillometers are given in Table 2, calculated according to the stability-independent approximation (Eq. 15 of Hartogensis et al., 2003). These estimates include adjustment to account for the curvature of the earth and displacement height,  $z_d$  (Table 1). Displacement heights were calculated from the mean height of the roughness elements,  $z_H$ , within a distance of  $\pm 1000$  m perpendicular to the scintillometer path (and +500 m in the direction parallel to the path), using the rule-of-thumb  $z_d = 0.7z_H$  (Garratt, 1992). In the case of the EC station,  $z_H$  was calculated within 500 m of the EC mast. The difference in BLS and MWS path-weighting functions (Fig. 3) means that the BLS, MWS and combined BLS-MWS covariance measurements are representative of different heights even though the BLS and MWS beams essentially traverse the same path (Evans and De Bruin, 2011).

For the two-wavelength scintillometer system the BLS and MWS beams must be close together (Lüdi et al., 2005). The separation between beams was minimised ( $< 0.35$  m) and the relative positions of the BLS and MWS were reversed at each end of the path so that the beams crossed near the centre of the path. It was necessary to





values and one  $C_{n1n2}$  value). The resulting data available for analysis constitute 79 % of the total possible 10 min values ( $N = 61\,776$ ).

Kleissl et al. (2010) suggests an empirical threshold for the onset of saturation for infrared large aperture scintillometers of  $C_{n1n1} > 0.074D^{5/3}\lambda^{1/3}L^{-8/3}$ . Approximately 21 % of the BLS data were above this threshold of  $3.2 \times 10^{-15} \text{ m}^{-2/3}$ . BLS data were corrected for saturation using a look up table of numerical values based on the modulation transfer function of Clifford et al. (1974). The correction increased  $C_{n1n1}$  by around 5 % overall ( $\sim 10\%$  during summer daytimes). Where the estimated correction was larger than 25 % data were removed instead (46 values in total). MWS data were well below the saturation threshold of  $5.0 \times 10^{-11} \text{ m}^{-2/3}$  (Clifford et al., 1974) and were not corrected. The BLS-MWS covariance was not corrected as a methodology is yet to be determined (Beyrich et al., 2012). There is therefore increased uncertainty in these measurements due to the extent of currently applicable theory.

To use the refractive index structure parameters in Eq. (6) (or Eq. 10a and b),  $C_{n1n1}$ ,  $C_{n2n2}$  and  $C_{n1n2}$  must be representative of the same height. The  $S$  factors (Evans and De Bruin, 2011) given in Table 2 were applied to  $C_{n2n2}$  from the MWS and  $C_{n1n2}$  from the BLS-MWS to scale them to the same effective height as  $C_{n1n1}$  from the BLS. These factors account for the difference in effective heights between the three  $C_n^2$  measurements resulting from the combination of weighting functions and beam elevation (Sect. 3.1). The  $S$  factors are relatively close to unity as the height differences are reasonably small for this setup. The approximation of using stability-independent  $S$  factors was made here (incorporating stability would give values ranging from 1.0 under very stable conditions to 0.9 for free convection). Calculation of the meteorological structure parameters proceeds as described in Sect. 2.

Data were processed using each of the three techniques in order to investigate their respective merits, although the focus is on the two-wavelength and bichromatic-correlation methods. No Bowen ratio correction was applied for the single-wavelength method (Eq. 4), given the uncertainties in estimating the available energy in urban environments. The impact is estimated to be a 6 % overestimation in  $C_T^2$  (based on  $\beta$  from

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or negative depending on whether the infrared and millimetre-wave signals are correlated or anti-correlated.  $C_{n1n2}$  tends to be negative during the day and positive at night. The sign change occurs at the morning and evening stability transitions. Typically  $C_{n1n1}$  passes through sharp minima at these times, whereas the diurnal course of  $C_{n2n2}$  is flatter and wider, without clearly defined minima. These findings are in broad agreement with data from the LITFASS campaigns (Beyrich et al., 2005; Lüdi et al., 2005; Beyrich et al., 2012).

When averaged by month (Fig. 6), the diurnal patterns are enhanced and seasonal trends are revealed. The amplitudes of the diurnal cycles are largest in summer, except  $C_{n1n1}$  which peaks slightly earlier in the year.  $C_{n1n1}$  is closely related to  $C_T^2$  and, in turn, the sensible heat flux. Hence the peak in  $C_{n1n1}$  in late spring reflects the annual cycle of  $Q_H$ : approaching maximum insolation in mid-summer, the total energy input is large but evapotranspiration rates are limited by phenological development as maximal leaf area is not reached until later in the year. During winter, low radiative input means the midday maximum in  $C_{n1n1}$  is small; larger values are observed at night. For millimetre wavelengths  $C_{n2n2}$  tends to remain low throughout the night. The diurnal cycle in  $C_{n1n2}$  is maintained across all months with changes in the position of the zero-crossings determined mainly by atmospheric stability (usually the sign of  $Q_H$ , related to available energy and day length). In December  $C_{n1n2}$  is negative only for a very short period during the middle of the day. The effect of day length is also seen in the positions of  $C_{n1n1}$  minima, which move closer together as radiative energy input decreases from summer to winter.

### 5.1.2 Meteorological structure parameters

There are clear parallels between the refractive index structure parameters (Fig. 6) and the meteorological structure parameters (Fig. 7).  $C_{n1n1}$  is dominated by  $C_T^2$  with a small contribution from  $C_{Tq}$  (of about 5%, which decreases as  $\beta$  increases, Green et al., 2001). The cross-structure parameter  $C_{n1n2}$  consists mostly of the  $C_{Tq}$  term and





$Q_E$  when water and energy are plentiful have been excluded. The overall results are not substantially changed for the restricted subset:  $C_{T\_BLS-MWS}^2$  and  $C_{T\_EC}^2$  are still similar whilst  $C_{q\_BLS-MWS}^2$  still exceeds  $C_{q\_EC}^2$ , although the difference between  $C_{q\_BLS-MWS}^2$  and  $C_{q\_EC}^2$  is reduced slightly. The spectral correction (Sect. 3.2.2) would increase the EC structure parameters by 5–7%, which would further reduce the discrepancy between EC and BLS-MWS values.

#### 5.1.4 Comparison of two-wavelength and bichromatic-correlation methods

The three estimates of  $C_T^2$  for the BLS-MWS path are similar (on average within 6%) whether the bichromatic-correlation, two-wavelength or single-wavelength approach is used. Larger deviations are seen between  $C_{q\_bc}^2$  and  $C_{q\_2\lambda}^2$  when measured  $r_{Tq\_bc}$  differs from the value assumed ( $\pm 0.8$ ) in the two-wavelength method (e.g. 21 August 2011, Fig. 8). During daytime,  $C_{q\_2\lambda}^2$  is slightly larger than  $C_{q\_bc}^2$  in 2011 but the opposite is true for most of 2012 (Figs. 7b and 9b). This could be due to higher values of  $r_{Tq\_bc}$  in 2012 (see Fig. 10), which result in smaller  $C_T^2$  but larger  $C_q^2$  when  $r_{Tq} > 0$ . The value of  $r_{Tq}$  has a greater impact on  $C_q^2$  than  $C_T^2$  (compare error bars in Fig. 9a and b). Had  $r_{Tq\_2\lambda}$  been assumed to be  $\pm 1.0$  instead of  $\pm 0.8$ ,  $C_{q\_2\lambda}^2$  would have been 7% higher and  $C_{T\_2\lambda}^2$  1% lower.

During winter night-times, large differences are observed between  $C_{q\_bc}^2$  and  $C_{q\_2\lambda}^2$  which cannot be explained by differences in  $r_{Tq}$ . Negative values of  $C_{q\_bc}^2$  are frequently obtained (Fig. 7b). These do not have a physical interpretation but are indicative of measurement limitations and coincide with large negative  $C_{Tq\_bc}$ , which results from large positive  $C_{n1n2}$  (i.e. high correlation between BLS and MWS beams). Particularly during these times, but also in general, the bichromatic-correlation data show much greater variability than the two-wavelength data. To reduce this variability, bichromatic-correlation data are presented as 30 min averages, other than in Fig. 7.

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As for most of the previous two-wavelength campaigns, typical Bowen ratios for this path are expected to lie below the problematic region of minimum  $C_{n2n2}$  (Sect. 2.1). Other urban studies suggest daytime  $\beta$  of around 1.0–1.5 for suburban sites, lower when precipitation is frequent (Grimmond and Oke, 1995) and strongly dependent on the amount of vegetation (Grimmond and Oke, 2002; Christen and Vogt, 2004). However, although average  $\beta$  remains below 1.5 (Fig. 9c), changing surface conditions can drive down the evaporation on the timescale of a few days (e.g. drying of impermeous surfaces (Ward et al., 2013a) or, at agricultural sites, senescing crops, Evans et al., 2012), producing substantial excursions from the average  $\beta$ . Such excursions are seen in this dataset, particularly for  $\beta_{EC}$ , whereas  $\beta_{2\lambda}$  seems to be limited to values  $\leq 1.3$ . There are two potential issues here: (a) the two-wavelength sign ambiguity and (b) the region of reduced sensitivity around the  $C_{n2n2}$  minimum (Sect. 2.1). Selecting  $S_{2\lambda} = +1$  automatically restricts  $\beta_{2\lambda}$  to values below that at which the terms in Eq. (3) cancel out ( $\beta_{2\lambda\_min} = 2.0$ – $2.6$  for this dataset). For a few cases (when  $\beta$  is large), the true structure parameters should be obtained from the alternative solution ( $S_{2\lambda} = -1$ ). Using the bichromatic-correlation results to identify times of high  $\beta$  suggests the impact is small ( $\beta_{bc} > \beta_{2\lambda\_min}$  for a very small proportion of the data ( $< 0.3\%$  of daytime values)). A more significant issue appears to be reduced measurement capability for  $\beta_{2\lambda} > 1.3$ . As the true  $\beta$  increases, if  $C_{n2n2}$  does not decrease as much as expected from theory  $\beta_{2\lambda}$  will likely be underestimated, and the corresponding  $C_q^2$  (and  $Q_E$ ) could be overestimated. It is thought that noise in the setup (instrumental or unwanted intensity fluctuations from absorption, for example) may constrain the measured value of  $\beta_{2\lambda}$  to a greater extent than suggested in the literature.

The region of reduced sensitivity of  $C_{n2n2}$  also compromises the performance of the bichromatic method, as measured  $C_{n2n2}$  will be mostly made up of noise contributions relative to the near-zero true value of  $C_{n2n2}$ . It follows that the correlation between BLS and MWS signals in this region is expected to be dominated by common instrumental or atmospheric effects such as absorption, or any electrical interference, mounting vibrations or obscuration along the path. Although these effects were not found to be

problematic generally, they could become significant when the refraction signal diminishes at moderate  $\beta$ .

## 5.2 Temperature–humidity correlation

Measured  $r_{Tq\_bc}$  follows similar seasonal and diurnal trends to  $r_{Tq\_EC}$  (Fig. 10). During summer, there is a clear plateau of close to +1 during daytime and the transition times when  $r_{Tq}$  changes sign are of short duration compared to the day length. In winter  $r_{Tq}$  remains below zero for most of the day but peaks at positive values around midday, though the average midday  $r_{Tq}$  is less than 1. The EC data rarely exceed the range  $-0.75$  to  $0.85$ , whereas inspection of the time-series reveals that  $r_{Tq\_bc}$  almost always follows a typical diurnal course but individual points may vary about the general trend (e.g. Fig. 8). Some unrealistic values of  $|r_{Tq\_bc}| > 1$  are observed, even when averaged to 30 min (Figs. 8 and 10). Lüdi et al. (2005) also reported frequent occurrences of  $|r_{Tq\_bc}| > 1$ . Since  $r_{Tq}$  is a correlation coefficient these values ( $> 1$ ) do not have a physical interpretation, but result from uncertainties and thus indicate limitations of the measurement. The uncertainty in  $C_{n1n2}$  is around 20% at best (Lüdi et al., 2005). This inherent uncertainty associated with individual measurements means the structure parameters from the bichromatic-correlation method show greater variability than from the two-wavelength method (Sect. 5.1.4), particularly  $C_q^2$  and  $C_{Tq}$  which have a greater dependence on  $C_{n1n2}$  than  $C_T^2$  does. For this reason, bichromatic results are presented at 30 min, rather than 10 min as for the two-wavelength method (Figs. 8–11). In addition, to calculate  $r_{Tq}$ , the structure parameters must be combined (Eq. 8) and so  $r_{Tq}$  amasses the uncertainties in each of the measurements.

Despite the high uncertainty, average  $r_{Tq}$  values provide information on the typical temperature–humidity correlation along the scintillometer path. This is an important quantity in its own right, as well as an indication of MOST violations. The literature suggests  $r_{Tq}$  is typically expected to be slightly less than +1 during the day, but negative and of smaller magnitude at night (Kohsiek, 1982; Andreas et al., 1998; Meijninger

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The bichromatic-correlation data suggest larger daytime  $r_{Tq}$  in 2012 compared to 2011 but this is not seen in the EC data. The contrast between patches of hot, dry impervious areas and cool, wet vegetation may be reduced by altogether wetter surfaces in 2012, which is thought to increase correlation between temperature and humidity (Lamaud and Irvine, 2006; Moene and Schüttemeyer 2008; Ramamurthy and Bou-Zeid, 2014). On the other hand, Lüdi et al. (2005) found lower  $r_{Tq}$  coincides with lower  $\beta$ . Experiments designed to investigate the behaviour of  $r_{Tq}$  (and the performance of the bichromatic-correlation technique) under different conditions would be beneficial.

In winter, and also during night-time, turbulence tends to be less well-developed. This presents challenges to measurement theory. Measurements are also more likely to be outside the surface layer when stable stratification occurs and the boundary layer height is smaller. Due to the rough surface, near neutral conditions were far more common than stable and, for the most part, there remains a close match between the diurnal behaviour of EC and scintillometer measurements. On the few occasions when strongly stable conditions were observed at the EC station, comparison of time-series indicated periods when the BLS-MWS was likely higher in the atmospheric boundary layer than is ideal, and thus potentially affected by other processes not related to surface fluxes. However, these were relatively rare occurrences.

In this study, the performance of the bichromatic-correlation method was generally observed to be poor under conditions of low crosswind speeds (the wind speed component perpendicular to the BLS-MWS path). At times of low or near-zero crosswinds ( $< 2 \text{ m s}^{-1}$ ), the retrieved values are less robust,  $|r_{Tq\_bc}| > 1$  is commonly observed and  $r_{Tq\_bc}$  is highly variable frequently changing sign (even during the day when both turbulent fluxes are reasonably expected to be positive and EC data do not suggest otherwise). The reason for this is unknown, but two possible explanations are considered here. Firstly, Taylor's frozen turbulence hypothesis is assumed in order to relate intensity fluctuations to  $C_n^2$  (Clifford, 1971; Wang et al., 1981). When crosswind speeds are low, this assumption is less justified and eddies decay as they are slowly blown through the beam. Correlation between the received scintillation pattern from one sample to the

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next is reduced compared to higher crosswind cases (Poggio et al., 2000). Correlation between the scintillation signals of the BLS and MWS will likely show greater variation too, depending on how the decay of eddies affects each beam, which would result in variability in  $C_{n1n2}$  that propagates through to  $r_{Tq\_bc}$ . Secondly, when wind speeds are low, turbulence may be sporadic and not well-developed over the whole path length. Perhaps sudden gusts or turbulence events cause spuriously high correlation between BLS and MWS signals which outweighs the correlated scintillation signal the technique aims to measure. Given the complexity of this suburban site it is difficult to draw firm conclusions on this apparent effect of crosswind on bichromatic scintillometry at this stage.

## 6 Conclusions

This study reports the first use of a two-wavelength scintillometer system in an urban area. The behaviour of structure parameters and temperature–humidity correlation is investigated at various timescales. By examining the structure parameters themselves, more direct insight into the performance of the measurement techniques is gained; assessment of fluxes introduces additional uncertainties (e.g. similarity functions). Furthermore, structure parameters are important quantities in their own right. The spatial and temporal resolution of scintillometry observations offers advantages for assimilation into or evaluation of hydro-meteorological models. One approach for achieving this would be to work with structure parameters directly, rather than fluxes (e.g. Wood et al., 2013).

The structure parameters presented here extend previous observations to a different climatic region, different land cover type and, most importantly, across a much longer time period. Summertime behaviour is broadly in agreement with other published trials (Beyrich et al., 2005; Lüdi et al., 2005) but the long time-series presented here offers insight into seasonal variations. Day length, or more specifically, atmospheric stability, has a distinctive impact on the diurnal cycle of structure parameters and  $r_{Tq}$ .

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Overall, the structure parameters obtained from the BLS-MWS and EC systems exhibit remarkably similar tendencies. The Bowen ratio calculated from the measured structure parameters decreases across the two summer-to-winter periods studied here and  $\beta_{\text{BLS-MWS}}$  is smaller than  $\beta_{\text{EC}}$ , attributed partly to different source area characteristics.

Part 2 explores energy partitioning further via turbulent fluxes.

As well as extending the two-wavelength technique to a new environment, several recently developed improvements have been implemented in the processing. To obtain the structure parameter of refractive index from the millimetre-wave scintillometer, the validity of the small aperture approximation is considered (Appendix A) and the more accurate full formula used instead (Eq. 14b, for this setup). To adjust for the difference in effective heights between the BLS and MWS, the  $S$  factor approach of Evans and De Bruin (2011) was used. The structure parameters use the specific humidity formulation outlined in Ward et al. (2013b). The cross-correlation between BLS and MWS signals enabled estimation of the temperature–humidity correlation coefficient, thus extending the application of the bichromatic-correlation method to the suburban surface.

The bichromatic-correlation method sometimes returns values outside the physically meaningful range  $|r_{Tq}| \leq 1$ . The inherent variability of the cross-structure parameter  $C_{n1n2}$  limits the accuracy of any particular measurement, whereas the two-wavelength results are more robust over shorter periods. On average, results closely follow the expected diurnal cycle of correlated temperature and humidity during the day and anti-correlated at night. Measured  $r_{Tq}$  is approximately 0.6–0.9 in unstable conditions; stable values are more variable but tend to be smaller in magnitude, averaging around  $-0.3$  to  $-0.5$ . Observed  $r_{Tq}$  was furthest from  $\pm 1$  during winter and in near neutral conditions. Similar behaviour is seen in  $r_{Tq\_bc}$  and  $r_{Tq\_EC}$ , including times when the assumed two-wavelength value will be wrong.

Two-wavelength scintillometer systems have considerable potential to deliver large-area measurements representative of complex environments. Limitations of the two-wavelength method include the ambiguity due to two possible solutions for  $\beta$  and the region of reduced sensitivity around the  $C_{n2n2}$  minimum. Research is needed; firstly,

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to better understand the behaviour in this region and secondly, to investigate improvements to the instrumentation, setup or post-processing to minimise the impact. Advantages of the bichromatic-correlation method include additional information about the atmospheric conditions from  $r_{Tq_{bc}}$ , e.g. the relative sign of the heat fluxes and to what extent MOST conditions are satisfied. For the minimal extra hardware requirements the recommendation is therefore to measure the bichromatic correlation even if the additional information is not used directly in data processing.

The large proportion of vegetation and cool, wet summers helped to maintain a low Bowen ratio in this study. In drier periods or at more built-up sites the results may have been less useable. Future work should focus on the performance of two-wavelength scintillometry under different conditions (notably low crosswind, high Bowen ratio, near neutral stability). Theoretical development (e.g. modelling studies exploring the impact of differences in footprint and effective height between instruments) combined with careful experimental testing is needed. Comparison data (structure parameters and fluxes) from different methods will be required for thorough evaluation of these techniques.

## Appendix A: Validity of the small aperture approximation for millimetre-wave scintillometers

The log amplitude of a scintillometer system can be written in a generalised form (e.g. Lüdi et al., 2005),

$$\begin{aligned} \sigma_{\chi_1\chi_2} = & 4\pi^2 k_1 k_2 0.033 C_n^2 \int_0^\infty dK \int_0^L dx K K^{-11/3} \sin\left(\frac{K^2 x(L-x)}{2k_1 L}\right) \sin\left(\frac{K^2 x(L-x)}{2k_2 L}\right) \\ & \times \left[ \frac{2J_1(0.5K D_{r1} x/L)}{0.5K D_{r1} x/L} \right] \left[ \frac{2J_1(0.5K D_{t1}(1-x/L))}{0.5K D_{t1}(1-x/L)} \right] \\ & \times \left[ \frac{2J_1(0.5K D_{r2} x/L)}{0.5K D_{r2} x/L} \right] \left[ \frac{2J_1(0.5K D_{t2}(1-x/L))}{0.5K D_{t2}(1-x/L)} \right] J_0(K|d|), \end{aligned} \quad (A1)$$

where  $\sigma_{\chi_1\chi_2}$  is the covariance of log amplitude,  $C_n^2$  the refractive index structure parameter,  $K$  the eddy wavenumber and  $x$  the position along the path of length  $L$ ;  $k$  is the optical wavenumber and  $D$  the aperture diameter of the receiver (subscript r) or transmitter (subscript t) for each instrument (subscript 1 or 2) separated by a distance  $d$ .  $J_0$  and  $J_1$  are Bessel functions. The three-dimensional Kolmogorov spectrum  $\Phi_n(K) = 0.033 C_n^2 K^{-11/3}$  is assumed.

For a single instrument, this reduces to the standard formula for a large aperture scintillometer (Hill and Ochs, 1978):

$$\begin{aligned} \sigma_\chi^2 = & 4\pi^2 k^2 0.033 C_n^2 \int_0^\infty dK \int_0^L dx K K^{-11/3} \sin^2\left(\frac{K^2 x(L-x)}{2kL}\right) \\ & \times \left[ \frac{2J_1(0.5K D_r x/L)}{0.5K D_r x/L} \right]^2 \left[ \frac{2J_1(0.5K D_t(1-x/L))}{0.5K D_t(1-x/L)} \right]^2. \end{aligned} \quad (A2)$$

For cases when aperture averaging is unimportant, the standard formula for small aperture scintillometers,

$$\sigma_x^2 = 4\pi^2 k^2 0.033 C_n^2 \int_0^\infty dK \int_0^L dx K K^{-11/3} \sin^2 \left( \frac{K^2 x(L-x)}{2kL} \right), \quad (\text{A3})$$

which gives

$$\sigma_x^2 = ck^{7/6} L^{11/6} C_n^2 \quad (\text{A4})$$

on integration with  $c = 0.124$ , is often applied (Meijninger et al., 2002a, 2006; Lüdi et al., 2005).

Here we consider the validity of applying the small aperture approximation to millimetre-wave, microwave and radiowave systems. For the effects of aperture averaging to be insignificant, the aperture diameter must be sufficiently small compared to the size of the Fresnel zone. With  $F$  around 10 times  $D$ , the small aperture approximation causes an appreciable (7%) underestimation of  $C_n^2$  compared to evaluating the full formula (Fig. A1). The relatively long path over Swindon means the difference between formulations is quite small here (3%), but will be more important for shorter paths, shorter wavelengths or larger aperture diameters. Use of the full equation also modifies the path-weighting function slightly; for Swindon the difference in effective heights between using the approximation and full form is 0.15 m.

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**Table 1.** The instrumental setup. For the scintillometers the mean height of the beam above the land surface ( $z_m$ ) is given (for the effective measurement height ( $z_{ef}$ ) see Table 2); for MET<sub>roof</sub> the heights above the roof surface are given. Roughness length,  $z_0$ , and displacement height,  $z_d$ , were not calculated for the rooftop site. Tx denotes transmitter, Rx receiver.

Instrumentation	Height [m]	Location	Path length [m]	$z_0$ [m]	$z_d$ [m]
Two-wavelength scintillometer system	44.3	51°36′33.9″ N 1°47′38.6″ W (Tx) 51°33′38.1″ N 1°46′55.3″ W (Rx)	5492	0.7	4.9
EC station	12.5	51°35′4.6″ N 1°47′53.2″ W	–	0.5	3.5
MET <sub>sub</sub>	10.6 (WXT) 10.1 (NR01)	51°35′4.6″ N 1°47′53.2″ W	–	0.5	3.5
MET <sub>roof</sub>	2.0 (WXT) 1.1 (NR01)	51°34′0.3″ N 1°47′5.3″ W	–	–	–

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**Table 2.** Instrument and site-dependent characteristics of the scintillometers and paired scintillometer system.

Scintillometer	Instrument characteristics		Site-dependent characteristics		
	Wavelength [m]	Aperture diameter [m]	Fresnel zone [m]	Effective height [m]	Scaling (S) factor
BLS ( $C_{n1n1}$ )	$880 \times 10^{-9}$	0.145	–	45.0	–
MWS ( $C_{n2n2}$ )	$3.2 \times 10^{-3}$	0.25	4	42.8	0.952
BLS-MWS ( $C_{n1n2}$ )	–	–	–	43.1	0.958

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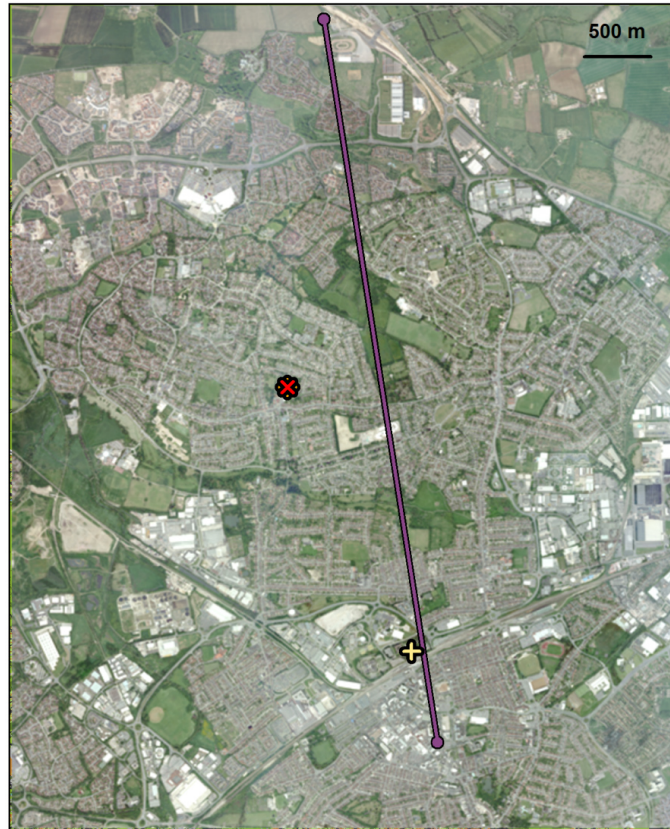
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- BLS-MWS
- ✕ EC
- ⊕ MET<sub>sub</sub>
- ⊕ MET<sub>roof</sub>

**Figure 1.** Aerial photograph (2009, GeoPerspectives<sup>®</sup>) of the study area showing the locations of the two-wavelength scintillometer path (BLS-MWS), eddy covariance station (EC) and two meteorological stations (MET<sub>sub</sub>, MET<sub>roof</sub>). The location of Swindon within the British Isles is shown (top right).

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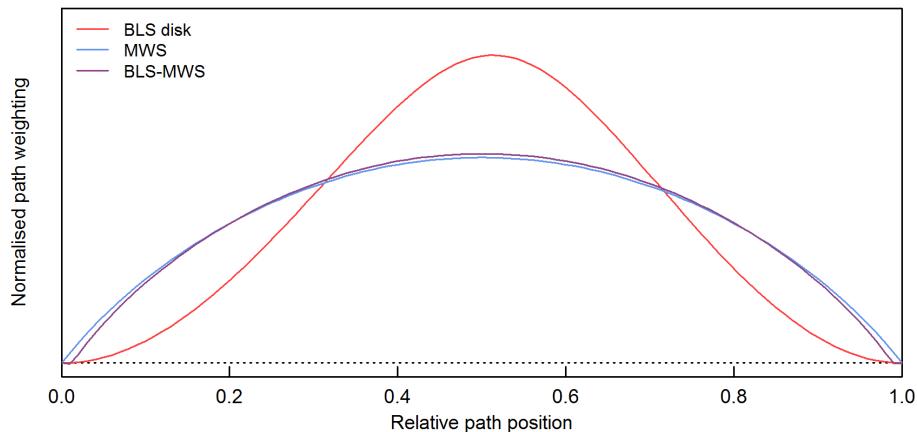
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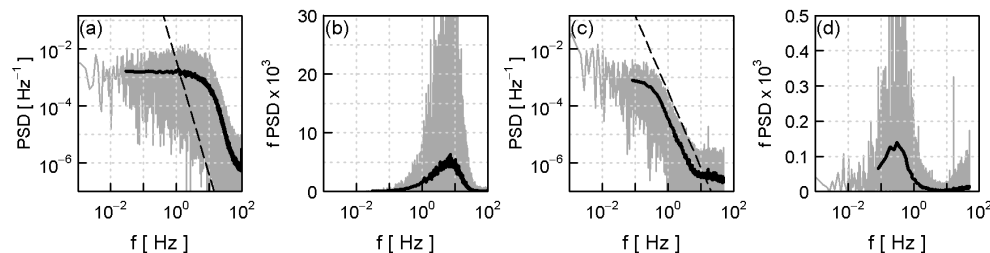


**Figure 3.** Path-weighting functions for the infrared scintillometer (BLS disk), the MWS and the BLS-MWS combination, normalised so that the total area under each curve equals one.

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**Figure 4.** Example power spectral density (PSD) and frequency ( $f$ ) spectra for **(a, b)** the BLS and **(c, d)** unfiltered MWS for 14:30–15:00 UTC on 2 July 2011. The dashed lines represent theoretically predicted slopes of  $-12/3$  and  $-8/3$  for the BLS and MWS respectively.

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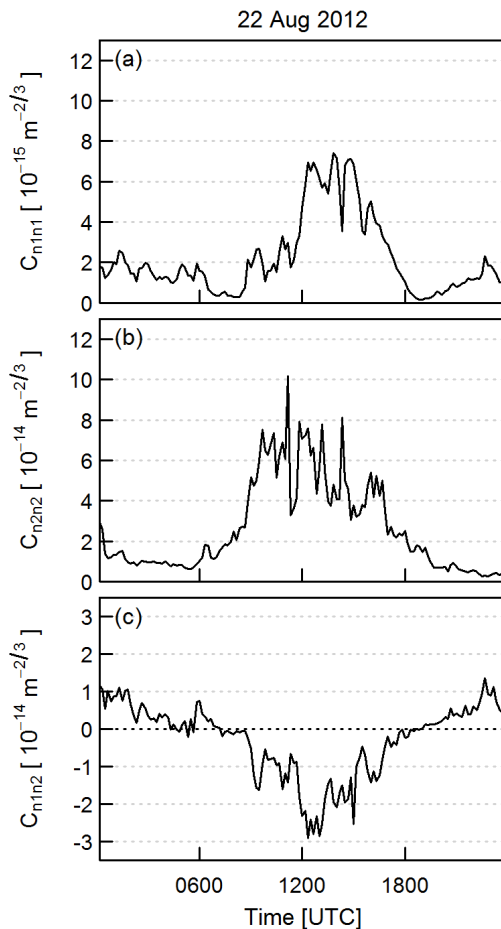
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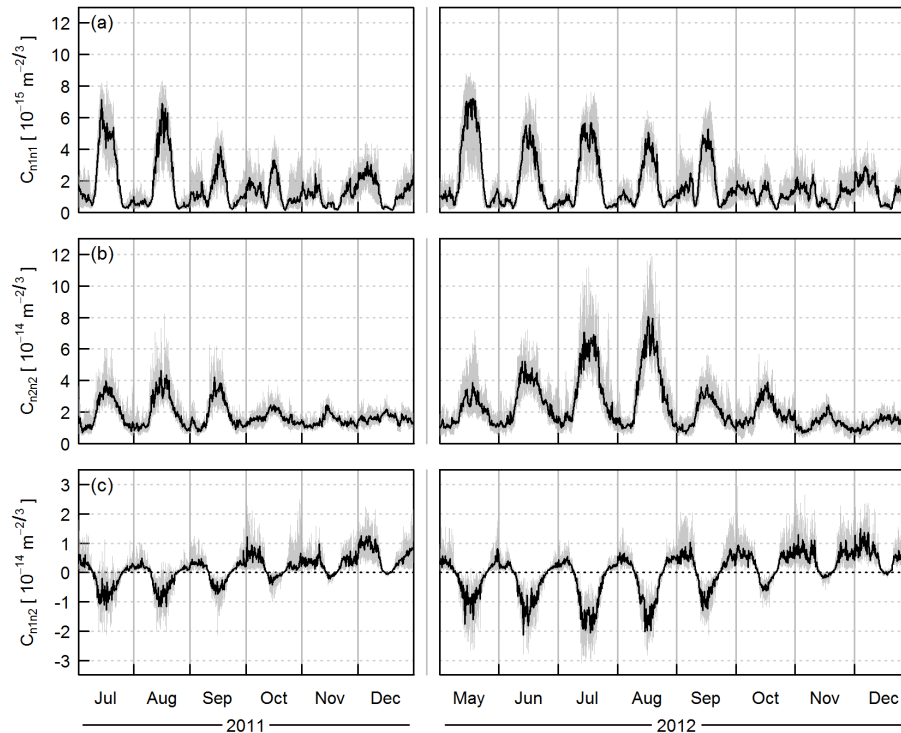
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**Figure 5.** Structure parameters of the refractive index as measured by (a) the BLS and (b) the MWS, and (c) the cross-structure parameter as measured by the BLS-MWS combination for an example day (22 August 2012).

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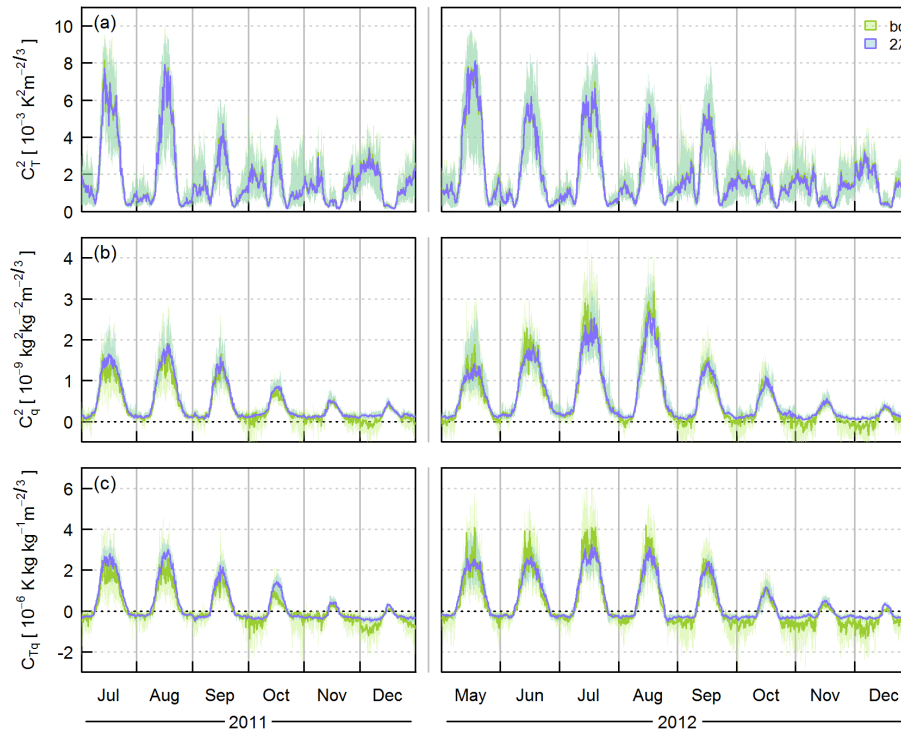
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**Figure 6.** Median diurnal cycles and inter-quartile ranges (shading) of the structure parameters of the refractive index as measured by (a) the BLS and (b) the MWS, and (c) the cross-structure parameter as measured by the BLS-MWS combination, separated by month.

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**Figure 7.** Median diurnal cycles and inter-quartile ranges (shading) of the meteorological structure parameters **(a)**  $C_T^2$ , **(b)**  $C_q^2$  and **(c)**  $C_{Tq}$  calculated using the bichromatic (bc) and two-wavelength ( $2\lambda$ ) techniques. In **(c)**  $C_{Tq}$  for the two-wavelength technique is given by  $\pm 0.8(C_T^2 C_q^2)^{1/2}$ .

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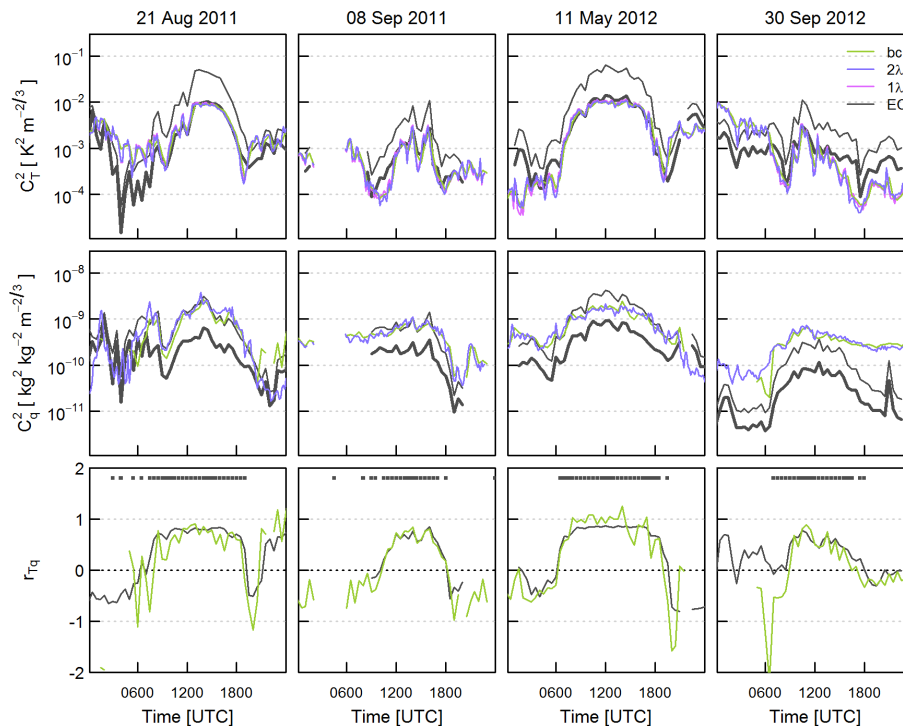
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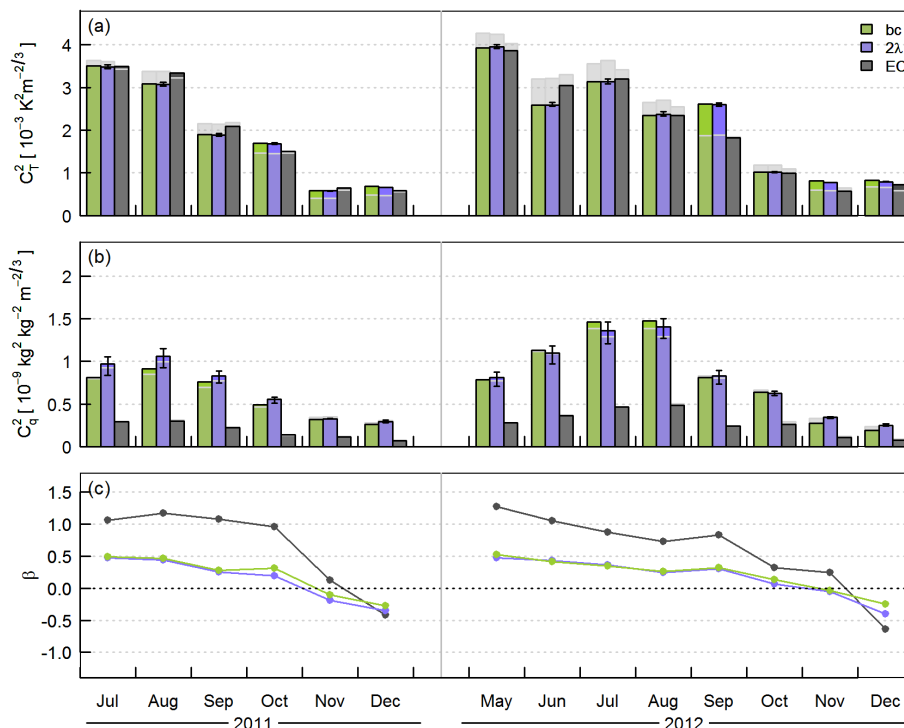


**Figure 8.** Structure parameters of temperature and humidity and the temperature–humidity correlation coefficient for selected days, derived from eddy covariance measurements (EC) and from the BLS-MWS system using the single-wavelength ( $1\lambda$ ), two-wavelength ( $2\lambda$ ) and bichromatic-correlation (bc) methods. EC structure parameters are shown for the EC measurement height (thin line) and scaled to the effective height of the scintillometry results (thick line). Unstable times according to the EC data ( $L_{Ob} < 0$ ) are indicated by grey dots. Single-wavelength and two-wavelength data are for 10 min intervals; EC and bichromatic-correlation data are for 30 min intervals.



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**Figure 9.** Mean daytime (incoming shortwave radiation  $K_{\downarrow} > 5 \text{ W m}^{-2}$ ) structure parameters **(a, b)** and Bowen ratio **(c)** for each month calculated for the BLS-MWS system (bichromatic-correlation and two-wavelength approaches) and eddy covariance data scaled to match the BLS-MWS height. For the two-wavelength results  $r_{Tq-2\lambda} = \pm 0.8$ ; error bars in **(a)** and **(b)** indicate the effect of assuming  $r_{Tq}$  values of  $\pm 0.5$  and  $\pm 1.0$ . Light grey bars **(a, b)** indicate means calculated when both  $C_T^2$  and  $C_q^2$  from all three methods (bc,  $2\lambda$  and EC) are available.

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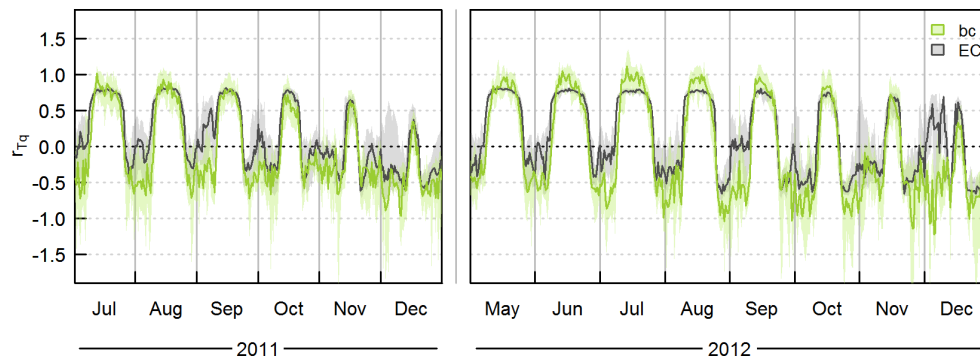
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**Figure 10.** Monthly median diurnal cycles and inter-quartile ranges (shading) of the temperature–humidity correlation coefficient calculated from the BLS-MWS system via the bichromatic-correlation method and from EC.

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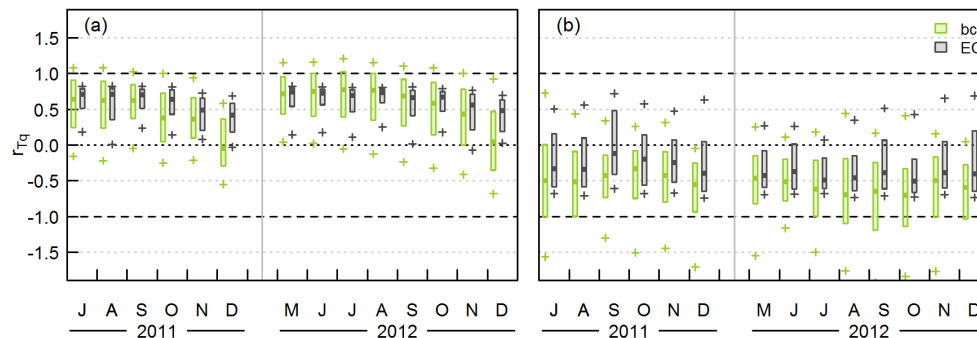
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**Figure 11.** Boxplots of  $r_{Tq}$  from eddy covariance (EC) and the BLS-MWS bichromatic-correlation method for **(a)** unstable and **(b)** stable conditions. Crosses indicate the 10th and 90th percentiles, boxes enclose the interquartile range (25th to 75th percentiles) and heavy lines indicate the medians.

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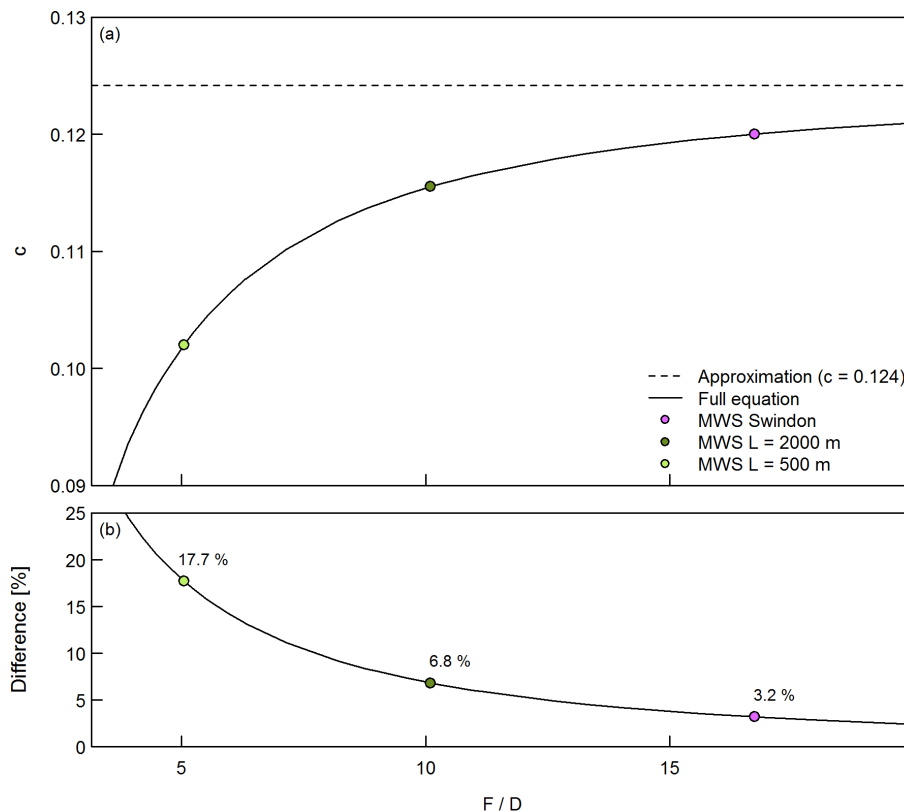
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**Figure A1.** (a) Value of the multiplier,  $c$ , in Eq. (A4) when calculated using the full equation (Eq. A2) as a function of the ratio of Fresnel zone  $F$  to aperture diameter  $D$  and (b) percentage difference from the small aperture approximation (Eq. A3). Some example experimental setups are selected for the CEH-RAL MWS.