Reply to:

"Interactive comment on "Footprint issues in scintillometry over heterogeneous landscapes" by W. J. Timmermans et al. By L. Jia (Referee)"

First of all we would like to thank the reviewer for her comments and suggestions, which have been very helpful. The paper has been substantially revised following the suggestions of both reviewers. We have modified the figures and the main text to address both reviewer's questions and concerns, and the text now more clearly conveys the study's objectives and conclusions.

Please find below the numbered interactive comments made by reviewer 2, Li Jia, between quotes followed by our responses in italics.

1. "The paper needs major modifications before it can be accepted for publication. The general comments are given below followed by some specific points both in this document and in the supplement of this review."

Major modifications have been made (see revised manuscript), following most of the comments given. More specifications are provided at the specific points below.

General comments:
2. "The paper discusses the impact of footprint contribution of complex land surfaces with different sensible heat fluxes from each component land patch to the sensible heat flux measured by LAS, both by simulation and by experimental field data. This subject is very interesting and innovative. However, problems are seen in the way that the simulation was setup and the way of evaluating the experimental data, which in turn has an influence on the results and conclusions drawn (see specific comments below)."

These general comments have been assessed under the specific comments below as well as in the revised manuscript.

The paper structure needs some re-arrangement, it is suggested to separate clearly the descriptions of the general approach, the simulation schemes, and the schemes for the tests on the experimental data (see specific comments both below as well as in the supplement file).

The manuscript is re-arranged following the specific comments made below and to our opinion it is now better structured and more clearly reflecting the chosen approach. In addition a more detailed introduction to the simulations is provided, see also below.

English writing needs to be refined, in particular, sentences are often too long and not written in a scientific manner. Precise descriptions on approach and the data collections are expected (see also the specific comments below).

Sentences are made shorter and the English is refined as suggested. Also a more precise description on what is done exactly is provided where applicable; see the comments below.

Specific comments:
1. Section 2.3 Footprint implication
Since the consideration of 'source area' contribution to the LAS measured heat flux by incorporation with a footprint modeling is the innovative point of this paper, it would be useful to describe in more detail how the modeled footprint was combined with the weighting function of the LAS to calculate the new 'weighting factor' rfpj.

A more detailed explanation on how the new weighting factor rfpj was calculated is now added in section 2.3.

To calculate the reference heat flux, the authors have applied the same weighting factors as those for LAS measurements to the component surface fluxes (Eq. 21), this is conceptually not correct. While the simulated as well as the measured LAS heat flux is determined both by the scintillometer response function (as presented by W(u) in Eq. 2) and the footprint of the LAS measurements (by the way, these two terms are different, see below for clarification), the integrated reference heat flux is the inherent nature of the surface and is not relevant to the LAS response function. It could be calculated by weighting the flux of each component by the areal fraction of each component that is fallen in the LAS footprint. The definition of reference flux taken by the authors (Eq. 21) may have led to the self-correlation in the results shown in Section 3 (also see the comments on section 3 and Fig. 1 below). [The weighting function (W(u)) of LAS signal is more related to the inherent properties of scintillation than being the result of the heterogeneity of the surface heat fluxes, though the latter does have impact on the integrated heat flux. It can be interpreted as the response function of the measured structure parameter of air by scintillation along the path length, no matter the surface is heterogeneous or not.]

The reviewer very correctly remarks that the simulated as well as the measured LAS heat flux are determined both by the scintillometer response function (W(u) in Eq. 2) as well as by the footprint of the LAS measurements. We also acknowledge that the weighting function of the LAS, W(u), is related to the inherent properties of scintillation and scintillometer aperture diameters, whereas the footprint depends on the aerodynamic characteristics of the surface, wind characteristics and apparatus position.
The reference flux is defined as the average of the (component) measurements of sensible heat flux weighted by the ratio of their contribution to the pathlength Lagouarde et.al. (2002). Lagouarde et.al. (2002) carried out a simulation experiment using the reference flux as defined above, to verify their assumption that deviations found between average H measured by the scintillometer (using their aggregation scheme) and reference eddy correlation sensible heat fluxes (aggregated using a linear weighing function according to their contribution to the pathlength) originated from the non-linear weighting of C_N^2 *along the pathlength.*
To the idea of the authors, here the reference flux should be derived from the (component) measurement of sensible heat flux weighted by their contribution to the total flux, i.e. taking into account both the footprint as well as the LAS weighting function. The different definition used here for the reference fluxes, as opposed to the

manner described in the reviewers comment and in Lagouarde et.al. (2002), most probably originates from the objectives of the respective studies, which here is, among others, to determine the applicability of the LAS for validating spatially distributed flux estimates (from remote sensing)
When it is known that (the turbulence over) a particular landcover component is contributing to the total flux depending on footprint and LAS weighting function it is incorrect to assume it is only depending on the ratio of the landcover contribution to the pathlength. This is easily noticed from the results of Lagouarde et.al. (2002) who found an underestimation by the LAS, compared to their reference sensible heat flux, when the largest field in the pathlength was the wettest. Due to the LAS weighting function this larger field is contributing more than only based on the ratio of the field contribution to the pathlength. Consequently the fluxes obtained from the LAS are lower than the reference flux which was calculated only based on a linear contribution of the field size to the pathlength.
This effect should not only be taken into account when calculating the aggregated reference flux, but also when aggregating the roughness length and zero plane displacement. Additional lines emphasizing these aspects are provided in sections 2.2 and 2.3.

2. Section 3 Simulation
The simulation setup was not very well described, it was very hard to follow. In section 3, four aggregation approaches were proposed and tested with the simulation data.

An extra paragraph is added in this section, describing the simulation setup in more detail, as also suggested by the reviewer in the supplement. In addition the four aggregation approaches are more clearly and separately described, making the section better understandable.

The authors have commented that the large difference (Fig. 1 a and e) between the average sensible heat flux from the aggregation approach 1 (say by Lagouarde et al 2002a) and the reference sensible heat flux is due to the fact that 'a linear weighing based on the contributing area is assumed' to give the reference sensible heat flux. The authors therefore proposed a correction on the estimate of reference sensible heat flux by applying the weighting factors of the two components derived from the combination of LAS weighting function and the footprint modeling. This does not sound robust (see comments above for 'Section 2.3 Footprint implication').

In sections 2.2 and 2.3 now additional explanation is given on as to why we propose to use the adjusted weighting factors; See also the text above.

Page 2110, line 8 – 20: this paragraph need a careful re-writing, it is confusing as it is now.

This section is rewritten, see also remarks made above. An extra paragraph is added describing the simulation setup and the four different aggregation schemes are more clearly described. In addition the caption of the accompanying figure is adjusted and now more self-explaining.

Fig. 1.: The caption of Fig. 1 is not sufficient, it was very difficult to understand the simulation results shown in the figures. It is suggested to give more explanations in the caption of Fig. 1 and indicate abbreviations of simulation schemes in the figure.

See also remarks above; the caption is adjusted and is now more self-explaining. In addition more clear reference to the four aggregation schemes is made and the suggested abbreviations are added.

Page 2110, Line 13 – 20 and Fig.1 d and h: The authors have stated that: 'When finally taking the weighting function into account for aggregating the aerodynamic properties the errors reduce to zero, see Fig. 1d. and h, meaning that the nature of the scintillometer measurements is properly simulated'.

This sentence is adjusted. It now reads: "When taking the weighing function into account for determining the relative component contribution to the aggregated C_N^2, as well as to the aggregated aerodynamic properties, the errors reduce to zero, see Fig. 1d. and h, meaning that the nature of the scintillometer measurements is properly simulated."

The aggregation approach proposed by the authors is not only applied to the integration of aerodynamic properties, but more importantly for the aggregation of the spatially averaged structure parameter <Cn2>. The improved results could be due to better aggregations of both. As commented above, the results of 'zero errors' need be checked for 'self-correlation' due to the inadequate approach from which the reference heat flux was calculated.

See remarks above as on why we propose to use the adjusted weighting factors. Also in sections 2.2 and 2.3 additional explanation is provided on this issue. The case of a composite surface comprising of two plots is simulated as follows; first the values of the structure parameters, C_{N1}^2 and C_{N2}^2, for the two plots are computed from prescribed values of sensible heat flux, H_1 and H_2, and micro-meteorological conditions. Then C_{N1}^2 and C_{N2}^2 are weighted, following the different weighting schemes, to simulate the measured C_N^2 a scintillometer might provide over such a composite surface. The third step involved computing the resulting H_{sim} from C_N^2. Finally, H_{sim} is compared to a really averaged prescribed flux (H_{ref}) defined as the weighing of prescribed H_1 and H_2 (again following the four different aggregation schemes). To the opinion of the authors such a comparison should result in a perfect fit when proper weighing factors are applied.

Page 2110, line 21-27: It is not clear what was written in this paragraph. The major difference between the two methods by Lagouarde et al (2002a) and by Ezzahr et al (2007) respectively is that L-method estimated the areally aggregated <Cn2> by weighting values of component Cn2 according to scintiilometer weighting function so that it has to deal with the non-linearity of the Cn2 along the path; while the Ezzahar method <Cn2> was directly calculated from component Cn2 that avoided the above mentioned non-linearity in Cn2. It is suggested to refine this paragraph.

These lines are rewritten; see the revised manuscript. Indeed the L-method estimates areally aggregated $\langle C_N^2 \rangle$ by weighting values of component C_N^2 according to the LAS weighting function whereas the E-method estimates aggregated $\langle C_N^2 \rangle$ from *component C_N^2 using a combination of MOST and an aggregation scheme for the aggregated aerodynamic properties, avoiding the LAS weighting function. The difference in the aggregated $<C_N^2>$ signals is that in the L-method an aggregated $<C_N^2>$ signal is obtained that yields a sensible heat flux that represents a LAS measurement over the two components, whereas the E-method an aggregated $<C_N^2>$ signal is obtained that yields a sensible heat flux that represents a total average over the two components. In the example used in the E-paper the sensible heat flux that is obtained represents the total average H flux over the total part of the oliveyard that is observed; 1070 m of the northern part and 1050 m of the southern part. This however, is different from a sensible heat flux that would be obtained from a (hypothetical) scintillometer which has in its pathlength 1070 m of the northern part and 1050 m of the southern part of the oliveyard, as they also state in their paper. In such a (hypothetical) case still the LAS weighting function (and footprint in a two-dimensional case) will have to be taken into account when determining the relative contribution of the two components. This is what has been proposed in the current manuscript.*

3. Section 4 SPARC2004 Experiment
It would be easy for readers to have an outline of the experiment and the data used in the study if a table can be included to give a summary of relevant measurements and fields.

In addition to the suggested table we have incorporated a new figure showing the relevant sonic measurements over the different fields. We have added descriptions of the used instrumentation, measurements and processing as well as the fields measured in the text. In combination with the overview of the experimental site we believe this now gives a more clear idea about the outline of the experiment.

Page 2113, line 20: A constant available energy flux (450Wm-2) was used to derive LAS sensible heat fluxes for all the 69 intervals of measurements that might not be necessary to be under the similar solar radiation conditions, neither available energy flux. Though the accuracy of available energy flux is not as important as other parameters, taking the sole value of available energy flux for any time of a day does not sound reasonable since it may vary significantly during a day.

We fully agree with the reviewer here. However, not for all sites net radiation and soil heat fluxes were measured. We concentrated on the net radiation and soil heat flux data from the vineyard, that was centrally located in the area. The bulk of the 69 measurements were made between10:00 and 15:00 utc. During these hours the available energy varied from 400 W/m2 (10:00 utc) via 500 W/m2 (12:00 utc) towards 450 W/m2 (15:00 utc). Since the available energy in the current procedure is only used to estimate Bowen ratio, which is in turn only used as a minor correction factor, we feel using a constant value of 450 W/m2 is defendable. Some extra lines are added justifying this assumption.

Page 2115, Section 4.3 Results: The caption of Fig. 3 needs to be refined. More information needs to be included. It would be useful to give a figure showing the sensible heat fluxes measured by the EC systems over the three land surface types to give a general idea what the magnitudes are and how different are the fluxes from different surfaces.

Additional information is provided in the caption of Figure 3 to explain better the 0-,1-, and 2-D approaches. In addition as suggested, a figure is provided showing the magnitude of the component fluxes versus time.

As can be understood in Fig. 2, under the case of 1D and two components, the LAS beam was assumed to overpass vineyard and wheat-stubble fields. The ratio between the two components along the LAS path were not given in the paper. The LAS beam went through three types of surfaces with very different sensible heat fluxes, the authors didn't show the simulated footprint of the LAS under different atmospheric conditions (both the wind directions and the stabilities). Analysis and discussions were less relying on the quantitative footprint modeling results, the latter is important for such a complex land surfaces composite. The way that reference sensible heat flux was estimated is still a problem as indicated above.

An additional figure is provided showing the magnitude of the component fluxes versus time as well as the ratios between the component fluxes as suggested by the reviewer. We ackowledge the reviewer's comments on the quantitative footprint modeling results, which could be different when using other footprint approaches, but this is not the objective of the current manuscript. We have added some remarks with respect to this issue in the discussion section.

4. Section 5 Discussion
The authors have stated that the unrealistic results were partly caused by the fact that stable conditions were included in the calculation. Such conclusion would have been more confident if the stable conditions could have been excluded in the analysis.

Unfortunately from the signal of a scintillometer it is not possible to discriminate whether stable or unstable conditions occurred. The observations that showed both stable and unstable conditions within the footprint of the scintillometer are encircled in Figure 4; basically indicating stable conditions over the corn. For those observations clearly the difference between simulated and reference sensible heat fluxes were largest. Some additional explanation is provided in the Discussion section.
(The RMSD was as large as 140.4 W/m2, whereas for those observations that showed unstable conditions over the corn the RMSD was 86.4 W/m2).

However, this might have not been the only reason if one looks at Fig. 4 in which the significant overestimate of the simulated H over the reference values is still quite obvious for many cases that were under unstable conditions.
It was stated by the authors that the large discrepancies between the simulated LAS sensible heat fluxes and the reference fluxes were probably partly attributed to incorrect flux measurements by the three eddy correlation systems, however there was no evident for such a argument. Such argument would lead one to think about the reliability of measured heat fluxes by the ECs that were used for the whole analysis. A more appropriate explanation is expected here.

The reviewer very correctly remarks that this might not have been the only reason. Therefore we examined the "purity" or quality of the EC measurements used. We have to state at this point that the 69 observations used were those where all three

ECs as well as the scintillometer were producing observations. The instrumentation was located such that during prevailing wind directions they would produce the most "pure", or highest quality observations. These occurred during the first two days of the experiment as may also be noted from figure 3 (i.e. the newly added figure). Unfortunately wind directions changed during the experiment, resulting in lesser quality EC observations (mainly for vineyard and corn). This is shown in Figure 4.b. where for western and northern wind directions less than 30% (50% for the corn) of the vineyard is contributing to the footprint of the sonic in the vineyard. However, with the change of wind direction to the west, the corn was almost entirely excluded from the scintillometer footprint, rendering this EC observation less crucial.

The caption in Fig.5 needs to be refined.

This has been done. It has been added that the newly proposed aggregation scheme is used and it is mentioned which components ratio is used for Figure 5.b.

It is not indicated which aggregation scheme was used in producing the results in Fig. 5a and b, and what were the surfaces considered in calculating the ratio?

See the response provided above. (In the Supplement it was mentioned that it was unclear how the ratios were determined and how they were implemented. A remark is added that they were obtained from the measured fluxes by the sonics. They were implemented by decomposing the first estimate of the aggregated sensible heat flux into the component fluxes by the respective ratios in combination with the respective footprint contributions. These component fluxes were then used in the aggregation approach.)

5. Section 6 Conclusions
The authors have stated that 'The soundness of the method is demonstrated by reproducing simulated component fluxes by model inversion'. This was not discussed in the paper.

The reviewer is very correct; we have changed the text to "The soundness of the method is demonstrated by reproducing reference fluxes from component fluxes."

According to the authors the disagreements (mainly overestimates) between the simulated and reference sensible heat fluxes were attributed to the 'nature of the available data' that is the observations under stable conditions were also included in the analyses. However, there was no discussion on the energy balance closure associated with turbulent heat fluxes measurements by the three EC systems which often was documented to yield severe underestimates of both sensible and latent heat fluxes.

We have added several lines on the energy balance closure problem, which might also very well be a potential reason for the disagreements, as very rightly remarked by the reviewer. This effect might even be pronounced due to the fact that 10 minute integrations had to be used (also remarked by the other reviewer), although no major consequences from the integration method were noted for those observations that multiple temporal integrations were available (EC vineyard), Su et.al., 2008. Text on this aspect is added as well.

Please also note the Supplement to this comment.

The majority of the remarks in the supplement have been incorporated in the answers provided here and in the revised manuscript as well.