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Interactive comment on "Comparative validation of UAV based sensors for the use in vegetation monitoring" *by* S. von Bueren et al.

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Response from: S. von Bueren, A. Burkart, 16.06.2014

We would like to sincerely thank Dr. Karen Anderson for her valuable comments on our manuscript. We would like to respond to her remarks below:

1) The cross-comparison between instruments mounted on a UAV and a 'reference standard' instrument on the ground (ASD Fieldspec pro) is good, in principle. However in practice there would seem to be a missing link here. I was left wondering about why a UAV was even needed to answer some of these cross-comparability questions. Surely some of the comparisons could have been made by comparing solar reflected radiation measured by these instruments simultaneously measuring the same target in the field?

This would provide a baseline comparison of their radiometric capabilities without the need to launch on a UAV. Perhaps this should have been the first step in the experiment – e.g. a ground-based comparison of instrument radiometric returns from close range, where other factors could be better controlled. Then, putting the instruments into the UAV as a secondary aim as a means of discussing the various extraneous factors and their impact on data quality and reproducibility (e.g. GPS positioning uncertainty, different spatial support, geometric platform wobble, vibration etc).

UAVs were used because we wanted to give the paper a practical focus/approach. E.g. finding that battery lifetime is a major limitation of the application. A number of studies are dealing with laboratory based evaluations of the sensors involved in our experiment (e.g. Kelcey 2012, Burkart 2013) and we wanted to investigate how those sensors are performing under field conditions and what needs to be considered (flight planning, sensor limitations, calibration issues etc.). Oftentimes, it is assumed that if a sensor is working in the lab it is simply a matter of mounting it on an UAV and acquiring the data. Our experiment shows that this as assumption is simplified and it exemplifies problems and limitations that field based UAV remote sensing encounters.

2) The cross-comparison to the ASD measurements itself poses challenges. There is a scale issue – e.g. the sensors are measuring areas of different spatial support, and this would be expected to have some effect on the measured radiant flux. This effect would have been negated at close range (e.g. as suggested above), allowing a more comparable set of measurements to have been obtained, and thus enabling a more complete description and intercomparison of the various instrument capabilities. As it stands, the differences reported could be a combined effect of both spatial support, platform wobble in flight, and radiometric differences in sensor capability. This complexity is currently not discussed in the paper.

That is a valid comment, we have included a discussion of those challenges in the manuscript.

3) The 'overview' images – line 22-25 – captured all of the areas of interest in a single photograph. However, there would have been angular differences across the field of view of these images, and whilst the effect may have been slight, this is not discussed or mentioned. Perhaps a better approach would have been to fly over these as waypoints too, so that the centre of the camera's FOV was aimed at the centre of each of the areas of interest. An 'overview' image could then have been used to test this angular dependency (if it existed).

Despite the potential influence of BRDF, overview images of RGB and canon IR camera were used to compare pseudo NDVI values at different waypoints for reasons of more accurate comparison in the time domain. From earlier measurements it was found that consumer grade digital cameras introduce a lot of variability from picture to picture due to their original purpose of generating visually appealing images. Therefore we tried both approaches: close up pictures of each waypoint as well as overview images. We found more reliability in the overview images compared to the close up ones. In a second approach which is topic of a different manuscript, we performed multiangular measurements over the waypoints 2 and 5 and assessed multiangular dependency of grassland. In the angular range of the used Sony and Canon lenses we found average changes in NDVI due to BRDF of 2%, which is within the noise range of the consumer cameras.

4) The Quadcopter and Falcon8 systems would benefit from a photograph or figure showing the main differences between them. Table 1 is good but if there is scope to add a photograph here it would be a useful addition.

For this suggestion there was a contradiction between the two reviewers. We find that although it is important to briefly introduce the UAVs involved in the study that the actual type and system used is not one of the main points of the study. UAV platform development is continuously advancing and newer systems with better specifications and technical performance become available all the time. Our experiment could have also been performed with other suitable platforms and the systems used (Falcon-8 and

MikroKopter) are state of the art off the shelve products. We have therefore decided to neither shorten nor extend the description of the platforms. Our conclusions are not UAV platform specific as most of the limitations encountered are not limited to the type of platform used in this study.

5) In relation to the two platforms used – it is not really very clear what purpose it served to have two different UAVs. What question was being asked of these two platforms? I could not clearly see why both were used, it would surely have been more comparable to use a single UAV with the different sensors installed on it. Otherwise you just introduce another factor causing variability, which is difficult to untangle in the results. Can the role of these different platforms be clarified please.

This is true, using two platforms can potentially introduce more variability in the data. However, as it is explained in section 2.2, the payload restrictions of the UAV systems justify the use of two different platforms. The Tetracam (790gr) can only be carried by the MikroKopter UAV with a lift capability of 1 kg. The UAV spectrometer however, has a case that has been specifically designed to be attached to the Falcon-8 UAV. That fact and the remarkable stability of the Falcon-8 make this UAV the most suitable platform for that sensor. We added a short explanation in section 2.2 and mentioned the implications in the discussion.

6a) In response to "The green band (551nm) achieves lowest correlations with ASD convolved reflectance values (R2=0.68) with MCA6 reflectance factors overestimated over all waypoints" and the fact that for NIR data, the R2 values are around 0.7 – this would seem to be the two areas where if one wanted to discover something about biochemical processes in vegetation, one would need the most accurate information – how do the author's respond to this. i.e. the lowest accuracies seem to be in the most important parts of the spectrum for assessing vegetation state? 6b)The same issue as the above is true for the UAV spectrometer which reported largest differences in the NIR when compared to the ASD on the ground. I suspect this discrepancy is entirely down to the different spatial support (and possibly even the different portion of the land surface being sampled) by both instruments. A field-based campaign before putting the instruments onto a UAV would have answered this question quite easily.

This is an important finding of the study that is discussed in the manuscript more extensively now. We put the differences down to mainly sensor calibration differences and potential mismatches in actual footprint.

7) The issue of footprint matching is quite important – presumably the GPS on the UAVs was a standard type with nominal accuracy of +/-10 m. If that's the case, then the fine spatial resolution offered by the sensors is somewhat negated by this spatial positioning precision issue. Without improvement on this, the issue of image matching is a very difficult thing to address. Perhaps a differential GPS correction of the images to a more precise location prior to use of the spectral data would have been a good method to use.

We are aware that footprint matching is a major issue not only due to the sensors' different field of views but also because of uncertainties in UAV positioning over the target introduced by the onboard GPS. As described in section 2.4 white tarpaulin maker squares were used to mark the area of interest over which we positioned the sensor. In subsequent image analysis, the marker helped to identify the image area to process. Moreover, waypoints were selected in homogeneous areas and can be regarded as being representative for that area of the paddock. Because the GPS on board the MikroKopter UAV was found to be too inaccurate for our purpose during previous test flights, that UAV was manually hovered over the target to ensure the images acquired cover the footprint area. While differential GPS correction would certainly ensure highly accurate UAV positioning, this was not practically possible due to non-availability of equipment at the time of our experiment. The limitations of the GPS and its implications for footprint matching are now stated in the discussion along with a more detailed explanation of how the waypoints were selected in the methods section of the paper.

8) For me, one major element is missing and this is the link to the "vegetation monitoring" part. Sure, there are some field spectra in the paper that show the classic vegetation spectrum but I think an end user of the technology would want to know how these data actually relate to something about the vegetation properties of the landscape you were monitoring. Of course, we all accept that from a vegetation spectrum, one can derive various other parameters but for your site, what information do these data carry, specifically? E.g. Ryegrass pastures – what is useful to know about the productivity of these areas and can this be derived from the systems you used (and to what extent in the multispectral vs optical vs hyperspectral systems). I think this connection needs to be made in relation to some kind of field data (e.g. Leaf Area Index, chlorophyll content, carbon content or some other biophysical parameter).

We agree, that the link to vegetation monitoring needed to be stronger. Link to ryegrass pastures has now been made in the introduction and we also specified what pasture biophysical parameters are useful to know about. How this information can be derived from our systems will be discussed in the discussion part of the paper. However, as the focus of the paper is on sensor comparability and not primarily on relating the data to actual pasture parameters such as chlorophyll content and LAI, we have not actually included any correlations to field data. This is however, an interesting basis for further experiments where the focus lies on the derivation of pasture parameters from UAV based sensors.

9) Discussion – "Four optical sensors were flown over ryegrass pastures and validated; including the first available UAV based micro spectrometer" – This is not strictly true in my view – the validation can only be claimed if one had a good match in space, and time between the data collected from the UAV and the data on the ground. I can't agree that spatial and temporal matching was possible to within a good enough level of accuracy to accept that this constitutes a robust validation. At best, it is more a cross-comparison of data points with different spatial support, where there is some certainty that the different instruments were viewing a similar point on the ground (but not the

exact same point). The temporal offset in the timing of the ASD measurements and the UAV survey would also mean that some BRDF effects in the data are likely, and these are not considered in the discussion.

We have changed that statement. In terms of comparability under field conditions, we have aimed to maximise the field of view overlay between the different sensors. As for the imaging sensors we ensured this by placing a clearly visible marker in the field above the region of interest. The UAV spectrometer due to its non-imaging state, can be expected to have the largest potential deviation from the area investigated. However, with the live video feed footprint matching can be considered high too. The temporal offset between the ASD and UAV measurements was attempted to be minimised but we agree, the measurements were not taken at precisely the same time. As for BRDF implications, please refer to our response to point 3.

10) “ground reflectance data calculated from the four UAV based sensors correlated signif- icantly” – again this is slightly misleading because this was true when all the data were aggregated but on a band-by-band basis the correlations were slightly compromised.

We have changed this statement to ensure it is not misleading the reader.

11) “The novel high resolution STS spectrometer can now be regarded as a fully charac- terised stand-alone UAV spectrometer system, capable of reaching data quality in the range of an ASD.” – again, this is still not quite fully evaluated in the results. Earlier in the text, you said, “depending on the status of the vegetation target the ASD derived reflectance factors can be up to 1.5 times (Fig. 4) higher than the UAV spectrometer measurements”. So, I think the claim is over-stated in the discussion.

We have changed this statement.

12) Specific comments – In the abstract, line 10, data were (data = plural)

Corrected.

13) Abstract – line 12, multispectral camera is not really the same as an imaging spectrometer. The two things are completely different. So I think it is best to just say this was a multispectral camera.

We now use the term ’multispectral camera’ throughout the paper.

14) Last line of abstract – I think that the claim “The high resolution spectrometer was val- idated and found to deliver spectral data that can match the quality of ground spectral measurements.” Is overstated (see more detailed comments). I think you could possibly argue that it matches the ‘information content’ but the quality does not appear to be the same if you look at statements made in the results section. I think this is also a ‘fine spectral resolution’ spectrometer.

We changed the statement. A general revision of the abstract has been made too.

15) Line 35 - Camera settings, such as exposure time and white balance settings were op- timized and fixed to the illumination conditions. Please specify these settings otherwise others will find this difficult to interpret and repeat.

As lined out in the response to the other reviewer, we agree that not fixing the settings of the two consumer digital cameras are a major point of criticism in this study. The RGB and Canon IR camera were used in a rather simple way for the acquisition of overview images. Experience from earlier use of the cameras showed that even with fixed settings, single close scale images are hard to compare to each other due to various effects, such as camera specific internal conversion of pixel values and blurriness introduces by platform instabilities caused by winds. Due to the stable illumination conditions ISO values, shutter speed and aperture did only adjust minimally. Furthermore, because images were taken over the course of a few hours some variability is introduced by the changing solar angle too. We used the overview images from higher altitudes which are of high visual quality and processed multiple waypoints inside of one single image for comparison. Our retrieval showed overall good agreement between values derived from automatic settings of consumer cameras and the other scientific grade instruments (eg.Table 4 IR vs. UAV STS). We however do agree that for future studies under less favorable illumination conditions fixed camera settings would improve the results.

16) Section 2.2 – what autopilot software was used. Did you use some kind of algorithm in that software to get a good overlap? Were the cameras gimballed or levelled so that they were always viewing the ground from a fixed position / geometry?

The Falcon-8 UAV used the AscTec Autopilot Control V1.68 autopilot software and an active nick and roll stabilised gimbal as stated before. Earlier assessments of accuracy show about 1°-3° of accuracy, depending on weather conditions. For conditions prevalent during the NZ experiment we expect a stabilisation of about 1-2° deviation from nadir. Two identical exchangeable gimbals were used on the Falcon-8, one for the Sony camera and the other one for the UAV spectrometer and the Canon camera. A different gimbal was mounted on the QuadKopter. The gimbals are dampened and active stabilized in nick and roll. To ensure the UAV spectrometer on board the Falcon-8 viewed the correct area of interest, a live feed from a video camera that simulated the spectrometer's field of view (section 2.3) was used. We have added the information in the manuscript.

17) Section 2.4 – GPS survey. I assume this is just a standard GPS survey or was it a differential system? Not clear from the description of the method.

The additional GPS referencing done during this study was performed with a consumer smartphone GPS with an accuracy of < 3 m. As no better equipment was available, we decided to use markers inside the images for the accurate positioning of all the sensors. As the Falcon-8 was equipped with a little video camera that produced a live stream during flight, positioning accuracy of the UAV spectrometer and the digital cameras could be assessed during the flight.

18) Table 2: canon powershot – 'zoom lens' is not a helpful description. What's the focal length? What setting was used (Aperture priority? Etc...).

Term 'zoom lense' is replaced and a field of view calculated. The Canon camera was operated on a 33mm focal length (in a 35mm film equivalent).

19) Table 2 – STS spectrometer spatial resolution – single point is too vague. Surely for the hovering height of the UAV one could calculate for a fixed FOV a nominal 'spot size' on the ground?

We put down the view angle of the UAV spectrometer in the table. Given this information, an actual ground footprint can be calculated for any fliying height.

20) Figure 4 – label UAV OO confused me. I think this should be STS?

That is correct, we have changed it.

21) In figure 3c the alignment of the 6 cameras is mentioned as being an issue but I cannot see where the method for aligning the camera views is discussed or explained in the text. How is this achieved?

Tetracam supplies a camera specific alignment file (.mca) that can be used to align the six cameras dependent on the flying height. In this study we did not need to generate an aligned image because we worked with the six individual bands. We believe it is a bit misleading to show that image and decided to show the green band instead as we did not work with multiband images anyway. All six bands were processed separately for image calibration and spectra extraction.

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