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Atmospheric Measurement Techniques
Discussions
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Interactive comment on "Design and characterization of specMACS, a multipurpose hyperspectral cloud and sky imager" *by* F. Ewald et al.

Anonymous Referee #1

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1 General remarks

The manuscript provides a detailed characterization and uncertainty estimation of the hyperspectral line imager specMACS which is build for ground-based and airborne application. The measurement covers the solar spectral range with medium spectral resolution (2.5-12 nm) and therefore is intended to be applied for cloud and aerosol remote sensing. The authors describe several issues which have to be considered for spectral imaging sensors and investigated these by extended laboratory calibration. Theory and results are presented in high detail which proves that the instrument

performance is well understood and sensor deficits (e.g., non-ideal behavior) can be corrected by postprocessing. Finally exemplary measurements highlighting the potential of the instrument for cloud remote sensing are shown.

In future spectral imaging will become more popular to investigate atmospheric processes and different systems will be operated world wide. Comparing measurement of different systems requires knowledge about the sensor performance and common calibration procedure. In this regard, the manuscript provides an important contribution to current and future research and is worth to be published as it substantially helps to access instrument uncertainties of spectral imaging systems.

However, in my opinion the manuscript lacks of two major issues which have to be reassessed in detail before publishing the manuscript. First the manuscript is quite long and difficult to read due to an unfortunate choice of structuring by the authors. Second the investigations are not finalized in a ways, that the uncertainty estimates are not transferred to a real measurement case even though measurement examples are given. Additionally I have some comments on the calibration methods which may change the interpretation of the results.

Below, I compiled a list of comments which have to be considered in a revised version of the paper. There might be some contradictory statements resulting from my misinterpretation of the text when first reading. I am sure the authors will know how to weight in such cases and how to improve the text to avoid misinterpretations by other readers.

2 Major comments

Length of the manuscript

The manuscript is quite long, not well structured and therefore some times hard to read. I found two reasons. First, the objective of the manuscript is merged between 1)

Describing the design (hard- and software) of the instrument and 2) the performance and calibration. I agree, that 2) can not completely be discussed without 1) but, considering the length of the manuscript I would prefer to focus on the performance and calibration and remove all passages which are not essential for the performance of the instrument in terms of measurement uncertainties. Some parts I suggest to remove, at least drastically reduce or move into an appendix are:

- Software description (P9863, 10 - P9864, 19): Data acquisition does not improve the measurement performance in terms of radiometric, spectral or spatial accuracy. Reduce to what is finally connected to the instrument performance (measurement frequency, exposure time, dark current).
- Detailed instrument concept (Sect. 2.1): Are there any aspects given in this section which are related to or needed to explain the calibration results what is the main subject of the manuscript? The section reads like a very detailed description of a common spectrometer concept. Are there any references which can be cited in order to reduce this section to a minimum?
- Auto Exposure (Sec. 3.2.1.): The Auto exposure is again not changing the calibration results and was certainly not applied during calibration. A short note, that in field measurements exposure is adjusted automatically to a set of integration times might be sufficient. All details of how the decision to change integration time is made can be removed or moved into an appendix.
- Scriptable measurements (Sec. 3.2.3.): See comment on software description.

This list might not be complete. I recommend the authors to have a closer look into the manuscript and decide what parts are really necessary and which not.

The second reason increasing the length and reducing the readability of the manuscript is the separation of the calibration studies into two sections. Section 4 explaining the

theory and Section 5 presenting the results. This is very unfortunate and additionally not consequently realized. With this structure it is hard to understand a theory of whatever effect if no measurements are shown. Also some non-ideal sensors behaviors have been anticipated in Section 4 before there is evidence for the reader.

Therefore, I suggest to merge section 4 and 5. First explain the calibration procedure, then the results and finally discuss the results with help of the theory. This structure will make it easier to understand your findings. Readers do not have to move back and forth all the time. Several repetitions in the test can be removed. Also in general, I recommend the authors to go through the manuscript and check if any repetitions not providing any new information can be removed.

Some specific suggestions where to shorten, what to remove, are given in the minor comments below.

Overall uncertainty budget

There is no overall uncertainty budget given. Only radiometric uncertainty in combination with dark signal, which is somehow part of the radiometric calibration, are discussed. In practice also the other effects (signal magnitude, noise, spectral uncertainty, polarization) will contribute to the overall uncertainty. The reader is somehow left alone to judge which of the described effects will be of importance during a real measurement.

My first suggestion is to differentiate and note in the text, which effects contribute to the overall uncertainty and which effects could be corrected on basis of the calibration performed. This should be made clear to the reader in order to make sure which uncertainty finally remains.

Additionally an estimate of how the overall uncertainty differs when single calibrations are not considered would be helpful. How large is the improvement of performance for each calibration? Some might not be worth the effort if to be repeated for specMACs or a similar system.

In this regards, the uncertainty presented in Fig. 13b does not consider one point. In Fig. 13 the uncertainties are only discussed for a distinct measurement (laboratory measurements). However, when atmospheric signals are week, then the contribution of dark signal and noise uncertainties will increase. Especially over dark surfaces and in absorption bands (H_2O). I suggest to show how uncertainties depend on the radiance or for real atmospheric measurement (see next comment). The uncertainties will certainly differ from the laboratory measurements using an integrating sphere.

Application to measurement data

Section 6 shows some nice measurements indicating the potential of the instrument. However, no measurement uncertainties are given. Without error bars the value of the measurements for the intended applications is not clear. Uncertainties have to be added, especially when all the sections before were mend to estimate the instrument uncertainties. So why not demonstrating in Section 6 what is learned from the extensive characterization.

Suggestion 1: Error bars in Fig. 19 for all wavelength and spectra. Maybe also relative uncertainties below. Discuss which wavelength ranges has which uncertainty. As I discussed above, the different radiance values will cause a different contribution of dark signal and noise to the overall error. This should be shown here.

Suggestion 2: The same holds for the image presented in Fig. 20. Different spatial pixel in a scene of different illumination will have different uncertainties due to dark signal and noise. Fig. 20 presents an excellent example of an inhomogeneous cloud with radiance differing over magnitudes. Thus I expect uncertainties (relative and absolute) in the image to be different at different areas of the image. Showing this for two representative wavelengths of VNIR and SWIR will help to understand how the

uncertainties will potentially migrate into cloud retrieval.

Approach to vary sensor signal for nonlinearity calibration

The authors investigated the non-linearity of the radiometric calibration and the signal noise by changing the integration time while using a constant illumination. This is one approach but in my view not the right choice to investigate nonlinearity of the calibration. With constant illumination the number of photons arriving at the sensor does not change. Varying only the integration time does only increase the time of photon collection. This has one implication. As the authors wrote, the temporal mean of noise is zero. Increasing integration time therefore should reduce noise (N_{phot} at the same time.

A more appropriate approach which is closer to reality is changing the illumination (radiance of integrating sphere) despite integration time. The measurements usually are done at certain integration time while the radiance changes due to clouds, etc.. Therefore the radiometric calibration mostly accounts for the radiance changes and not changes of integration time. The question is now, how linear is the response of the sensor to changes in radiance. This was not investigated here but is a known issue of other sensors.

3 Minor comments

P9855, 4: Why two infrared sensors are given here? SpecMACS is measuring solar radiation. There exist also solar spectral satellite sensors.

P9855, 24: There is some literature which investigates the adding value of spectral measurements which might also helpful to motivate the use of hyperspectral imaging.

Coddington, O., P. Pilewskie, and T. Vukicevic (2012), The Shannon information content of hyperspectral shortwave cloud albedo: Quantification and Practical Applications, J. Geophys. Res., 117, D04025, doi:10.1029/2011JD016771.

P9856, 11: There is a break in the text when reading. After giving an outlook of the paper you jump back to describe existing instrumentation. A new subsection with title may help.

P9856, 27: Typo: "become"

Introduction in general: I'm missing a review on existing hyperspectral imaging systems and their application in atmospheric sciences. How they compare to specMACS? To name only a selection:

Mayer, B., Schröder, M., Preusker, R., and Schüller, L.: Remote sensing of water cloud droplet size distributions using the backscatter glory: a case study, Atmos. Chem. Phys., 4, 1255-1263, doi:10.5194/acp-4-1255-2004, 2004.

Bierwirth, E., Ehrlich, A., Wendisch, M., Gayet, J.-F., Gourbeyre, C., Dupuy, R., Herber, A., Neuber, R., and Lampert, A.: Optical thickness and effective radius of Arctic boundary-layer clouds retrieved from airborne nadir and imaging spectrometry, Atmos. Meas. Tech., 6, 1189-1200, doi:10.5194/amt-6-1189-2013, 2013.

Schäfer, M., Bierwirth, E., Ehrlich, A., Heyner, F., and Wendisch, M.: Retrieval of cirrus optical thickness and assessment of ice crystal shape from ground-based imaging spectrometry, Atmos. Meas. Tech., 6, 1855-1868, doi:10.5194/amt-6-1855-2013, 2013.

Itten, K.I.; Dell'Endice, F.; Hueni, A.; Kneubühler, M.; Schläpfer, D.; Odermatt, D.; Seidel, F.; Huber, S.; Schopfer, J.; Kellenberger, T.; Bühler, Y.; D'Odorico, P.; Nieke, J.; Alberti, E.; Meuleman, K. APEX - the Hyperspectral ESA Airborne Prism Experiment. Sensors 2008, 8, 6235-6259.

P9857, 27: Can you give a reference confirming the accuracy range.

P9858, 1: You may add here, that the high spectral accuracy is mostly needed for VNIR.

P9858, 5: In this discussion I'm missing how the uncertainties will migrate into the final retrieval results.

P9859, 11: That's irritating. The instrument is build for ground-based operation but samples of airborne observations are shown. Why? Also later in section 6 no example of ground-based measurements is shown. When no ground-based measurements are presented I also see no need to describe the scanning mount.

P9859, 12-18: This section is not well placed. Until here the instrument and especially its spectrometer cameras with its specifications are not introduced. Without this information the exemplary data cube does not help because the reader may not understand where it comes from. I suggest to move or even remove Fig. 2.

P9859, 26: Is the entrance slit similar for both camera systems?

P9860, 1-26: I'm not sure if this entire section is needed. Are there any aspects related to or needed to explain the calibration results which is the main subject of the manuscript? The section reads like a very detailed description of a common spectrometer concept. Are there any references which can be cited in order to reduce this section to a minimum?

P9861, 2: What "PFD" stands for? Introduce abberations.

P9861, 16: What "SWIR" stands for? VNIR was introduced.

P9861, 22: What is the dynamic range of both spectrometers? Can you provide numbers.

P9861, 26: Wording: "Just like in the case of" change to "Similar to"

P9862, 3: Why these important parameter are not discussed here in the text? In section 2.2 and 2.3 a lengthly explanation of all single components (inculing type names etc.) is given but the most important parameter describing the main characteristics of the system are not discussed. E.g. pixel number, nominal spectral resolution, FOV, dynamic range, sampling frequency, etc.

P9862, 6-10: The nature of stray light is somehow obvious. I suggest to remove this introduction of the section.

P9862, 14: Does the stray light affect both camera systems in same magnitude?

P9862, 17: "FOV" number was not given in the text jet. And the abberation was not explained.

P9862, 19: Is there any example image comparing the same scene with and without baffles illustration the efficiency of the baffles?

P9863, 3: What is the IFOV of both cameras?

P9863, 3-8: I do not see the need to explain all this details especially the handling of the system. Restrict to the most important parameters such as the accuracy of the rotation stage. All other things which improve the convenience of the instrument operation are add-on which do not improve the scientific output of the system.

P9864, Sec. 3.2: Structure. There was no discussion about the dark signal of the system jet. The reader still does not know how good or bad dark signal of the system is and if there is a need to consider it at all. I would suggest to move this part to the end after all the components and problems of the system are described. The section

is more connected to the application in field measurements based on the finding of the instrument characterization. Similarly this holds for the automatic exposure (non-linearity of radiometric calibration) and dark frames (drift of dark signal).

P9865, 13: "All CMOS pixel": That means spatial and spectral?

P9865, 26 and 29: Translate frames also into a time.

P9866, 12: Variation of dark signal has to be shown first.

P9867, 10: "auxiliary data" is misleading. Dark current for example is essentially for the radiometric calibration. I would suggest to include dark current into the radiometric calibration. That's basically where it is applied.

P9867, 9-12: Discrimination between characteristics and auxiliary data is misleading. What do you mean here? Above it was stated that three characteristics are required. Now auxiliary data is needed as well.

P9867, 21: "IMF" abveration had already been introduced.

P9867, 22: "DLR" abveration had already been introduced.

P9868, 6: "Bad pixel" are not part of sec. 4.1.

P9868, Sec. 4.1.1: Why starting with noise? The reader still does not know about the characteristics of the dark signal. I would suggest to start with dark signal, then radiometric calibration and finally noise.

P9869, 4: N_{dc} should depend on temperature, right?

P9869, 7: I would suggest to discuss the theory after showing the results of your calibration. Just add a theoretical curve into your plot. Then it is easier to understand for the reader.

P9869, 20: How stable is you integrating sphere? Due to noise in the current the radiance output may already have some noise level.

P9869, 26-27: Explain how these parameter (which?) are applied for the correction? This again suggests to change the order of your structure. First calibration, then noise.

P9870, 20: The dependence of the dark signal on temperature should be discussed.

P9870, 22: Shouldn't both cameras act different? The SWIR is temperature stabilized, the VNIR not.

P9871, 3: For the proposed ground-based measurements higher temperature changes are expected. How to deal with it?

P9871, 4: What is DN?

P9871, 13: Why in the equation a * is used and in Eq. 8 and 9 not. I'm not sure if here one redundant quantity is introduced. How Eq. 7 and 10 can be connected? I don't see it at the first view. You may add R here somehow in Eq. 7 instead of the $\propto$. And when it is correct write $S_0^* \neq S_0$.

P9871, 14: You may add $s_{\mathrm{n}} = s_{\mathrm{n}}(L)$.

P9871, 15 and 21: You draw conclusions from measurements which are not shown. Merging Sec. 4 and 5 may help to avoid this.

P9875, 1: Are bad pixels randomly distributed or e.g., for one wavelength 265 spatial pixel are bad.

P9875, 13: Can you first show measurements. Otherwise the reader does not know how the LSF and SRF looks.

P9875, Eq. 14: How Δx is practically derived? Is the fit systematically changed to force the ratio to be 0.7610?

P9876, 1: How the data was measured?

P9876, 1: Always try first to introduce figures and then explain, discuss the plot.

P9876, 4-7: One of many repetitions. Try to shorten. "already defined" signals that it's

already done. No need to repeat.

P9877, 15-16: Again repetition.

P9877, 25: A sketch or image may help to understand the setup.

P9878, 13-18: Wasn't that already stated in Section 4.2.3?

P9870, Figure 9: Aren't top and bottom panel the same? Just once logarithmic and once linear scale? Why you have to show both? The parameters main parameters and characteristics can be read from both.

P9880, Eq. 15 and 16: The equations are identical to Eq 3. I would suggest to just give the values of parameters of Eq. 3. A table might help.

P9880, 17: You refer to results of an upcoming section. This is not a good way and makes the reader to think about jump to Sec. 5. Shifting the noise analysis might help to avoid that.

P9880, 20: A short comment why the maximum dynamic range is not reached would help. Dark current signal for sure?

P9881, Sec. 5.1.2: I was missing a discussion on the importance of the dark signal compared to dynamic range and the radiometric calibration. Is it possible to translate dark noise into radiance. The question is not how the dark signal behaves in general. As you do sequently measure it in field. the question is how good the dark signal is measured. Uncertainties in dark current migrate into the radiances. And this depends also on the ratio between signal and dark-signal-uncertainty. This will for example change for different spectral regions.

P9881, 8: I'm surprised that it is not the other way around: SWIR is cooled to have a stable sensor temperature. Why dark-current should react on temperature? That can only happen when the cooling system does not cool sufficiently. VNIR is not cooled. So the sensor should somehow react to temperature changes. That's what was written in 4.1.2 "originates from thermally generated electrons and holes within the semiconductor". Can you explain this behavior of the VNIR sensor?

P9881, 23: How do you explain the independence of the dark signal to t_{int}? Is there an internal dark current correction already applied in the camera?

P9881, Figure 10: What about the temperature range expected for ground-based operation? This is not covered here.

P9882, 5: First introduce the figure, then discuss.

P9882, 6-8: That's obvious. I suggest to remove the sentence.

P9882, 15: There is no figure showing the radiometric response and the fit? Would be helpful for the reader to see the non-linearity.

P9884, 27: Discuss what polarized radiation can be expected in atmospheric applications and how large the error will be in different cases. E.g. remote sensing of clouds? Aerosol from ground-base measurements where Rayleigh scattering of the sky may contribute polarized radiation?

P9886, 5-7: Repetition.

P9888, 5-6: That's an obvious procedure. Has not to be mentioned.

P9888, 7-11: This information is not needed.

P9888, 24: Give the value of refractive index.

P9889, 4: Why not calculating absorption? You have the refractive index and can use Lambert-Beers law.

P9891, point 3.: I would conclude different. Wasn't stated, that radiometric uncertainty is about 3% in the best wavelength? If the radiometric calibration changed about 10% indicated by the difference in manufacturer and own calibration this suggest that the calibration has to be repeated over time. Otherwise you can not claim to have an

accuracy of 3%. It would be rather 10% due to temporal changes.

P9892, 5: The overall accuracy is not but should be given in the conclusions.

P9892, 16-19: Repetition.

P9909, Figure 4: Give a scale or dimensions.

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