Response to Referee #1

(Original reviewer comments in italics)

General comments
All-sky polarimetry is in principle a powerful technique to rapidly determine aerosol properties. The paper describes an image analysis technique to analyse polarization images of the sky, using Zernike polynomials.
This is a technically oriented paper on an analysis method of all-sky polarimetry. The physics in the paper is very limited. I therefore propose to change the paper into an AMT Technical Note.
The paper does not describe the polarization imaging itself, but only the analysis technique. Therefore, I propose that the title of the paper is changed to better reflect its
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contents, e.g.: "Analysis method of polarized all-sky images for aerosol characterization using Zernike polynomials."

Response to general comment:

The primary intention of the paper is not of technical nature but rather about the principle of using all-sky images (as opposed to discrete measurement points e.g. in the principal plane) for aerosol characterization. The use of Zernike polynomials, although a novel approach and highly convenient in this case, is not the key issue. The focus is on the evaluation of the feasibility of the method. This is also where the physics lies: The influence of different aerosol optical properties on the Stokes parameter distribution in the sky. The analysis technique is only the basis towards reaching the goal of a retrieval algorithm. So we believe that the title and the placement as a research article in AMT are, in fact, adequate.

Response to specific comments:

Introduction:
- l. 14: "alternative method of measuring the sky radiance": alternative to what? All-sky imaging is not new, see the many references. This paper does not describe a measurement technique but only an analysis technique. In Sect. 1 it should be described what is really new in this paper. E.g. what is new as compared to Kreuter et al. (2009, 2010)?

We write in l.4 that the sky radiance is commonly measured with sky scanning radiometers, so alternative to that, we consider imaging. Indeed, the method is not new at all, the authors of the references all measure radiance distributions with all-sky imagers. Here, we evaluate the method with respect to aerosol property retrieval (which is new compared to Kreuter et al., 2009, 2010) using a novel analysis approach.

- l. 23: Please clearly indicate that the broadband wavelength resolution is a disadvantage of this technique.

A commercial digital camera as sensor (as used in Kreuter et al., 2009 and Kreuter at al., 2010) indeed has a very broadband spectral resolution of typically 100 nm FWHM which is a disadvantage. However, narrow band filtering could always be implemented and spectral capability is not a principal limitation for all-sky imagers. So wavelength resolution is a technical issue in the instrument implementation and not a *disadvantage of the technique* described here. The spectral broadband issue has been eliminated from the introduction and the sentence in the discussion section was clarified:

Also, the broadband wavelength response of typical sensors should be addressed by respective narrowband filtering.

- The introduction should also give the structure of the paper.

This is a possible but not compulsory practice for writing an introduction, i.e. a matter of personal preference. Especially for a short paper like this one, it seems not particularly valuable. Nevertheless, the end of the introduction has been modified a little to improve the lead over to the main part:

Amongst the main disadvantages of all-sky imaging is that the area around the sun, the aureole, cannot be resolved satisfactorily. Furthermore, these sensors are not optimized for absolute radiometric stability. With our proposed analysis method, we aim at circumventing these drawbacks, while extracting maximal information from the data.

Abstract:
- The abstract says: ". . . independent of calibration and robust againt noise": that sounds too good to be true. Please give quantitative information on the errors of this technique.

These advantages are a result of the analysis method that is explained in detail in the paper. Errors are discussed in section 2.3, l.24ff, p8824.

- What is the spectral capability of this technique?
The spectral resolution issue has been discussed above.

p. 8816:
l. 23: limited by ground albedo: please clarify
l. 23/24: 2x remote sensing.
- please mention that groundbased remote sensing of aerosols is important for process studies and for validation of satellite remote sensing.

The end of the paragraph has been rewritten accordingly:

However, satellite retrievals are limited over surfaces with high albedo such as deserts and snow cover. Ground based remote sensing remains a key method to determine aerosol properties with high accuracy and is indispensable for satellite validation.

p. 8817:
first paragraph:
- in different viewing angles > at different viewing angles
- distribution > angular distribution
- wavelength bands > in different wavelength bands
- the vertical plane > which is the vertical plane
- . The so-called almucantar is a scan > , and the almucantar, which is a scan
l. 7: incorrect; the solar zenith angle is 90 deg minus the elevation angle of the sun

The paragraph has been rephrased to accommodate all valuable comments above:

The principal plane (PP), which is the vertical plane containing the sun and the zenith, and the so-called almucantar, which is a scan of the azimuth angle at a constant zenith angle, equal to the solar zenith angle (SZA).

p. 8818:
l. 22: this zero albedo assumption is not realistic. What is the effect on the results?

This paper focusses on the feasibility and one albedo was chosen and used throughout. The same question could be valid, had we used albedo 0.3. In general, the effect of albedo on the *relative differences* of radiances under different aerosol scenarios is of second order.

p. 8819:
- why do you use a Monte Carlo method if you only want to model radiative transfer in a plane parallel atmosphere? The error characteristics of MC are quite poor.

Within the highly respected and freely available package LibRadtran, the MC code is better suited for the vector radiative modeling than the discrete ordinate (DO) codes DISORT when sharply peaked phase functions (as applicable to aerosols) are considered. The MC code is well validated (A. A. Kokhanovsky, V. P. Budak, C. Cornet, M. Duan, C. Emde, I. L. Katsev, D. A. Klyukov, S. V. Korkin, L. C-Labonnote, B. Mayer, Q. Min, T. Nakajima, Y. Ota, A. S. Prikhach, V. V. Rozanov, T. Yokota, and E. P. Zege. Benchmark results in vector atmospheric radiative transfer. *J. Quant. Spectrosc. Rad. Tr.*, 111(12-13):1931 - 1946, 2010.) This reference has also been included now.

For reasonable computation times, the MC noise in the Stokes *I* component is low, around 1%, so the model is well suited for our purposes here. Compared to DISORT, the computation times of MYSTIC are even slightly faster for vector RT.

Finally, errors are also inherent in DO models, however they are of systematic nature and more difficult to quantify.

- l. 5: what is the numerical MC noise in Q and U?

We have only quoted the standard deviation of *I* (1% relative error) because it a concise and meaningful figure of merit for the numerical MC noise in general. The relative errors for *Q* and *U* are ill-defined at points in the maps where they vanish, but otherwise, the relative errors are of the same order of 1%.

- l. 9: what is the AOT in this map?
The aerosol optical depth (AOD) is 0.12 at 650 nm. The value has been included in the text and also the abbreviation AOD is now explained.

- l. 9: so that > such that
Corrected.

- l. 13-20: please clarify this definition of polarization reference with a figure, since this is an essential point

The paragraph has been carefully rephrased to clarify the difference between the two polarization reference frames. This should elude the need for an extra figure.

For a sky-scanning instrument, the reference angle for the Stokes vector is defined with respect to the viewing direction, i.e. the instrument reference frame rotates along with the viewing azimuth angle. In the imaging method (using a rotating polarizer in the image plane), the Stokes reference angle is constant across the image plane, independent of the viewing azimuth angle.

- l. 22-23: this description is the other way round than what is given by Eq. 2: there you rotate from the fixed to the corotating reference plane.

Eqn. 2 has been checked and is correct. The inverse of the transformation matrix would just have a reverse sign in front of the sines. So depending on the definition of the azimuth angle, it could also be negative.

p. 8820:
- l. 1 – 8: the description of the Figs. 1-3 is generally unclear. What is contained in them ? Q and U, or Qr and Ur ? Please also indicate in the figure legends themselves what is shown: Q and U or Qr and Ur.

The descriptions have been rephrased to clearly indicate what is shown in the figure:

An example of three Stokes maps of *I, Q* and *U* are shown in Fig. 1 a-c.

In Fig. 2, the maps from the above example are shown in the rotated basis, Q_r and U_r

The first three captions have been slightly modified so they clearly and unambiguously describe the figures, see Figure captions:

Fig.1 Stokes maps *I* (a), *Q* (b) and *U* (c) from model calculations for 650 nm, SZA=60° and OPAC continental average aerosol with AOD=0.12. Azimuth angles are shown, while the zenith angles are indicated as concentric circles of 30°, 60° and 85°, respectively. The radiance values are normalized to the extraterrestrial irradiance.

Fig.2 Rotated Stokes maps Q_r (a) and U_r (b) from model calculations for 650 nm, SZA=60° and OPAC continental average aerosol with AOD=0.12.

Fig.3 Rotated relative Stokes maps Q_r/I (a) and U_r/I (b) from model calculations for 650 nm, SZA=60° and OPAC continental average aerosol with AOD=0.12.

- l. 11: say that normalization largely removes this problem

In accordance with Referee 2, we have merged the two paragraphs and have added the sentence:

So our processing eludes the requirement of absolute calibration and reduces the impact of undesired aureole artifacts.

- l. 11: because > because of

Corrected.

- l. 26: please explain more and give an equation for the Zernike polynomials. This is an essential part of this paper.

The definition of the Zernike polynomials includes an angular term (sines and cosines) and a radial term with a lengthy expression. The definition can be found in many textbooks on applied optics and much quicker on Wikipedia. Furthermore, the expression is implemented in many technical programming languages (e.g. Matlab) and will unlikely have to be implemented manually. In our view, the mathematical expression does not enhance the reading of the paper.

For an enhanced readability and independence of the manuscript, we have now included the polar plots of the first Zernike polynomials in Fig. 4.

p. 8821:
- l. 12: using the degree of polarization sqrt (Qrˆ2 + Urˆ2)/I is more logical than (Qr + Ur)/I since it is a physical parameter not depending on the reference plane.

We did not introduce a new parameter (Q+U)/I, we are saying that because of opposite symmetry, Q/I and U/I are orthogonal (in the sense described in the manuscript) and as a result, they can be added. The degree of linear polarization (DOLP) involves squared quantities and therefore its map is a symmetric function (in the sense described in the manuscript) and its feature vector has the structure of Q/I.

Interestingly, its turns out that the feature spaces with respect to the aerosol scenarios are very similar and DOLP and could also be used as an alternative way of defining the FV. It is true, of course that in such a case, the FV would be independent of the reference frame. However, yet other ways of defining the FV exist, e.g. normalizing to the zenith radiance or not normalizing at all, in which cases Q/I_{zen} and Q, respectively, do depend on the reference frame. So the description of the transformation between reference frames is important for generally processing polarized all-sky images.

p. 8822: explain AOD acronym

Aerosol optical depth (AOD) is now defined on first appearance in section 2.1.

p. 8823:

- l. 10: this low SSA is not realistic for absorbing soot aerosols. Did you only use OPAC results, or did you also do Mie calculations yourself?

We used OPAC aerosol optical properties throughout this study. Indeed, the OPAC soot aerosol type has an unrealistically low SSA. The reason probably is that this type refers to pure black carbon particles, not actually encountered as isolated particles. In reality, it is mixed with other types (e.g. INSO and WASO). The urban mixture which represents aerosols of a heavily polluted atmosphere containing the highest ratio of SOOT, has SSA=0.82 (at 550nm).

SSAs measured by AERONET in urban environments actually vary considerably between 0.97 (for 670nm) Greenbelt and 0.88 (for 670 nm) in Mexico City (Dubovik et al., 2002). So in the OPAC mixtures such as urban, SOOT may result in a little low, but not unrealistic value for the SSA.

p. 8825:
- last line: airmass
Corrected.

p. 8826:
- l. 10-12: this model simplification raises quite some questions. Firstly, you should mention this important limitation much earlier, in sect. 1 or sect. 2. Secondly, what would be the effect on the FV-space? Is the method still useable? Did you verify this?

We mention this model simplification only in the discussion section because it is not a serious limitation with respect to the actual conclusion of our work. What we are saying is, that a scaling of the SSA may also be accompanied by a change in the phase-function (or asymmetry parameter), which will slightly affect the Stokes parameter angular distribution, but not the amplitude of the distribution. So it a second order effect, which, for now, we have neglected here in favor of a more elegant modeling strategy.

However, we agree that for a rigorous, real-world retrieval this issue will have to be considered and in future steps we will look at alternative aerosol models on the basis of micro-physical properties and also considering non-spherical particles.

The corresponding paragraph in the discussion has been rewritten:

These issues will result in a modified shape of our FV space but will not significantly change its size (i.e. the information content in each map), so it does not weaken our conclusion. This article is mainly aimed at showing the proof-of-principle for the method, and a proper retrieval scheme will be implemented in the future.

p. 8829:
- l. 14: Spectrosc. Ra. > Spectrosc. Rad. Tr.
Corrected.

Figures:
- Figs. 2 – 3: give the degree tick marks and values on all the axes.

Cartesian plot axes are actually not well suited, so Figures 1 -3 are now plotted in proper polar plots, including azimuth and zenith angles.

Figure captions:
Fig. 1:
- add = sign: SZA=60, AOD=0.2

- Please specify the AOD at 650 nm, which is the relevant wavelength
Corrected.

Fig. 5: use capitals for aerosol types. Which three scalings are meant?

Aerosol types are capitalized. The scalings are now explained in a separate sentence in section 2.3 on page 8822 :

The scaling factors are chosen such that the maximum AOD is around 0.5

Fig. 6: trajectories > curves
Corrected.