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Interactive comment on "In-Flight Calibration of SCIAMACHY's Polarization Sensitivity" *by* Patricia Liebing et al.

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We thank Ruediger Lang very much for the thorough and thoughtful review. We will consider the comments in the revised version of the paper. The issue of general applicability of the new calibration approach will be discussed in the Conclusion section of the paper. See detailed answers below.

"The paper is generally very well written, although some introductions to equations and models could be clearer at various points (see detailed comments). The two empirical models established for the limb and the nadir scanner- and OBM system provide a very important extension to the existing tools for polarisation data quality monitoring (like e.g. the well-established special geometry method used for near-real time Stokes fraction correction for GOME-2). They will be especially useful for any future mission data reprocessing from the GOME, GOME-2 and SCIAMACHY instrument types. The paper also demonstrates that the scan mirror model by Krijger et al can be successfully applied to test and compare the end-to-end MMEs and may even be adousted to account for on-ground to in-flight OBM MME changes (like the to be expected pre-disperser prism stress during launch). I am generally missing a discussion of the applicability of the empirical approach to other wavelength providing the appropriate measurements would exist. One can see that empirical representations of mu_P *can*

be derived for e.g. a GOME-2 instrument with many more accurate PMD measurements at different wavelength and for both 90 degree polarization directions. But the 350 nm feature is an unwanted case for SCIAMACHY and the polarization sensitivity of the rest of the large spectral range is therefore completely unobserved. The users for other instrument cases would there- fore need to rely on the validity of the model. "

The general applicability to other instruments has not been discussed in much detail because it indeed depends on the specific instrument, its measurement modes and available data. In each case the method would have to be adapted to the available measurements and the information to be inferred. Note that the calibration approach presented here consists of two rather independent parts: The first is the determination of more or less “effective” polarization sensitivities for a limited set of detectors and a rather small wavelength range. The second is the derivation of instrument parameters which reproduce those polarization sensitivities and predict the instrument behavior for an extended wavelength range and other detectors. In the case of SCIAMACHY the combined model for the scan mirrors and the retarder serves such a purpose very well. A similar model could in principle be applied for all GOME-like instruments, though the lack of limb data may decrease the sensitivity to retarder parameters. This could be compensated to some degree by the larger scan angle range.

The overarching requirements for the polarization sensitivity measurement to work are a sufficiently accurate model (or data) applicable to the particular measurement conditions or sufficient statistics and leverage to extrapolate to a limiting model to determine polarization signals, and sufficient coverage in the (q,u)-plane for the determination of polarization sensitivities. Limiting models can be in principle improved by including information on known wind speeds or surface reflectance over particular sites. An approach of calibration over natural targets, as performed for instruments such as MODIS, MERIS, PARASOL etc. may also be considered. This approach has been tested for SCIAMACHY as well, though it turned out that using a few selected oceanic sites gives too small leverage in (q,u) to retrieve meaningful information.

Another option would be to cross calibrate with other instruments such as PARASOL. This had been attempted for SCIAMACHY nadir data using a statistical distribution of polarization vs. reflectance derived from PARASOL data for the same viewing geometries as SCIAMACHY's. The resulting polarization sensitivities for the PMDs were consistent with those from the model approach. Due to the wide range of viewing geometries available from POLDER/PARASOL data, this should also be viable for GOME instruments. The combination of polarization data from PARASOL and the co-located reflectance measurements from MERIS allowed for the determination of science channel sensitivities at the MERIS wavelengths up to 900 nm, using the SCIAMACHY to MERIS reflectance ratio vs. (q,u) as a polarization signal. The reason why this approach was not followed up on was that there seemed to be indeed a calibration error in the PARASOL data at that time, as shown in the attached figure. This figure shows a two-dimensional histogram of u at 850 nm as measured by PARASOL vs. its single Rayleigh scattering value u_{SS}, for viewing geometries corresponding to SCIAMACHY's Easternmost scan position in August 2007, and selected to likely contain sun glint scenes over ocean. The dots are the SCIATRAN model results for the same geometries and varying wind speeds. The distribution is evidently shifted sidewards w.r.t. the model. Such a shift can arise from a “contamination” of about 10% q in the u measurement. At lower wavelengths it is less prominent. Given an accurate calibration of the POLDER/PARASOL data, they would prove to be extremely useful in addition, or complementary to, the use of (limiting) models. GOME-2 for instance might be able to use AVHRR data for reference reflectances.

In the UV, below 300 nm, both nadir and limb (science channel) data can be calibrated using directly the ratio of the measured reflectances to those obtained from model which includes an accurate assumption about the O_3-concentration. This has been done for SCIAMACHY as well, resulting in a clear polarization signal and derived sensitivities not too far from expectations given the observed behavior at higher wavelength. The lack of accurate O_3 data for the relevant altitudes > 40 km, however, inhibited an interpretation in terms of instrumental parameters.

In order to address this question in the paper, we propose to add a corresponding paragraph to the Conclusions section, such that the first 2 paragraphs should now read:

A novel statistical approach for the in-flight polarization calibration of the SCIAMACHY PMDs and a part of its science channels is presented. It exploits the relationship between polarization and measured reflectance. This approach can in principle be further refined and adapted for the polarization calibration of other instruments which measure polarization, such as GOME, GOME-2 or even POLDER/PARASOL. The overarching requirements for the polarization sensitivity measurement are a sufficiently accurate model or data applicable to the particular measurement conditions, or sufficient statistics and leverage to extrapolate to a limiting model to determine polarization signals. The resulting polarization signals should cover a significant portion of the (q,u)-plane to provide enough leverage for the determination of polarization sensitivities.

The general applicability to other instruments has not been discussed in much detail here because it depends on the specific instrument, its measurement modes and available data. Limiting models can be in principle improved by including information on known wind speeds or surface reflectance. An extension of well established calibration methods employing natural targets (see Frouin (2013) for an overview) with the *Extrapolation Method* to include polarization may also be worth considering. For SCIAMACHY, though, using a few selected oceanic sites resulted in too small leverage in (q, u) to retrieve meaningful information, for other instruments such as PARASOL or MODIS with many observations of the same scene from different angles this may not pose a problem. For MODIS, for instance, cross calibration with SeaWIFS data and modeled polarization values has been successfully applied (Meister et al., 2009). The modeled relationship between reflectance and polarization may be replaced by suitable data, such as accurately calibrated data from the POLDER or PARASOL instruments. Co-located reflectance measurements may provide a reference reflectance to determine polarization signals when dedicated polarization measurements are not available.

For instance, the combination of MERIS reflectance data co-located with SCIAMACHY measurements, together with a statistical distribution of (q, u) vs. reflectance derived from PARASOL data matched with SCIAMACHY viewing geometries, resulted in an independent measurement of science channel polarization signals at MERIS wavelengths, e.g., 510, 665 and 885 nm. The derived polarization sensitivities for nadir were roughly consistent with expectation (Liebing et al., 2014). The investigated time span was only one month, August 2007, such that any further interpretation of the results was inhibited by too large uncertainties.

Detailed comments:

p.3, l.1: The transformation . . .. The transformation of what... the OBM model? Or the scanner on-ground model?

Yes, that's indeed not clear. I suggest the following change: “The application of the model to limb and nadir measurement configurations ...”

p.4, l.18: The Mueller matrix needs. . . The sentence is not very clear... better: "... and if necessary, the reference frames defined...".

I propose the following: “The Mueller matrix needs to be given in the same reference frame as the Stokes vector, and if necessary, reference frames for individual components have to be transformed to this particular reference frame.”

p.5, l.15: Realistically, . . . Sentence and comma needs to be checked. though? ... -of the?

I've changed the sentence to: “Realistically, the limited information contained in the combination of calibration measurements used only allows for the determination of a single, wavelength dependent refractive index which is constant in time, and the time dependent thicknesses on each of the scan mirrors.”

Section 2.3 2nd paragraph. The orientation of the slit for the ESM configuration should be mentioned. Along flight direction and also parallel to q=-1?

We propose to add the following at the end of section 2.3:
“In Fig. **??**, the scan mirror configurations and viewing geometries for the nadir and limb observation modes are depicted on the left and right, respectively. In the nadir configuration, the instrument slit is oriented along the flight direction and therefore perpendicular to the meridional plane, which lies in the scan direction. In limb, the projection of the slit is along the horizon and thus again perpendicular to the plane connecting the line-of-sight and local zenith or tangent point. Therefore, in both cases, $q = -1$ if the polarization direction (in the atmospheric Stokes frame) is along the instrument slit projection. ”

p.8/9, l5ff, Eq 6 to 8: The derivation of Equation 8 is confusing since you want to determine the ratio but you start with the absolute signal. Suggestion In the following we determine the polarization from the ratio.... by first determining the signal measured by the PMD S_P as.... Then in line 12 you need to add that you now calculate a ratio P of the polarized signal to the unpolarized signal, which you define as the virtual sum S_D. By additionally (!) assuming that the ...

I hope this reshuffling of the entire paragraph makes it a bit clearer:

“The polarization is determined by equating the synchronized and integrated (over the exposure time of the science channel) PMD signal with the calibrated science channel signal, scaled with the PMD response and integrated over the PMD spectral band:

$$S^{\mathrm{P}} = \mu_1^{PD} \cdot \sum_i S_i^{\mathrm{D}} M_{1,i}^{\mathrm{PD}} \frac{1+\mu_{2,i}^{\mathrm{P}} q+\mu_{3,i}^{\mathrm{P}} u}{1+\mu_{2,i}^{\mathrm{D}} q+\mu_{3,i}^{\mathrm{D}} u}\,, \quad \text{with} \tag{1}$$

$$M_{1,i}^{\mathrm{PD}} = \frac{M_{11,i}^{\mathrm{P}}}{M_{11,i}^{\mathrm{D}}}\,. \tag{2}$$

The sum goes over all pixels in the relevant spectral range, the superscripts P and D indicate PMD and science detectors, respectively. The $\mu_{n,i}^{P,D}$ are end-to-end Mueller

vector elements and vary with observation mode and scan angle. The factor μ_1^{PD} is an additional in-flight calibration factor that accounts for calibration offsets in the relative PMD to science channel response to unpolarized light. Assuming that the polarization and the polarization sensitivity varies sufficiently slowly with wavelength, this equation can be further simplified:

$$S^{\mathrm{P}} = \mu_1^{PD} \cdot \sum_i S_i^{\mathrm{D}} M_{1,i}^{\mathrm{PD}} \frac{1+\langle\mu_2^{\mathrm{P}}\rangle q+\langle\mu_3^{\mathrm{P}}\rangle u}{1+\langle\mu_2^{\mathrm{D}}\rangle q+\langle\mu_3^{\mathrm{D}}\rangle u}. \tag{3}$$

The quantities in the angular brackets are now wavelength independent and refer to the intensity weighted spectral average of the polarization sensitivities:

$$\langle\mu_n^{\mathrm{P,D}}\rangle = \frac{1}{S^D}\sum_i S_i^{\mathrm{D}} M_{1,i}^{\mathrm{PD}} \mu_{ni}^{\mathrm{P,D}}\,, \quad n=2,3 \tag{4}$$

with

$$S^D = \sum_i S_i^{\mathrm{D}} M_{1,i}^{\mathrm{PD}}\,. \tag{5}$$

The term S^D is also called *virtual sum* and describes the expected PMD signal for zero polarization, given the science channel signal and the relative detector responses. With Eq. 5 a *polarization signal*, P, can be defined as the ratio of the PMD signal to the virtual sum,

$$P \equiv \mu_1^{PD}\frac{S^P}{S^D} \approx \frac{1+\langle\mu_2^{\mathrm{P}}\rangle q+\langle\mu_3^{\mathrm{P}}\rangle u}{1+\langle\mu_2^{\mathrm{D}}\rangle q+\langle\mu_3^{\mathrm{D}}\rangle u} \tag{6}$$

which depends on polarization only.”

Eq 6.: Why is mu2 and mu3 for P also detector pixel dependent? Isnt the sum over i not only referring to science channel detector pixels covering one PMD measurement?

Eq. 6 would allow for wavelength dependent PMD sensitivities (which is in principle possible), though in the current version of calibration data they are not. The wavelength dependence of the PMD mu2,3 is retained here for historical reasons, and because technically the calibration data are given as a function of wavelength. Some of the previous versions of calibration data on mu2,3 indeed showed a wavelength dependence.

p.8, l.11: Better $mu_n i$ *instead of* m_i *p.8, l.7: The* $->$ *the*

This has been corrected in the manuscript.

p.8, l15. C1B is not explained where and how it is applied in the previous equations so far.

C1B has been replaced with the previously defined μ_1^{PD}.

p.11, Eq 15 and previous paragraph: What you are trying to say here is not very clear. I guess what meant is that every measurement R with $R <= R_R TM$ is corrected with cPRTM derived at the limit $R = R_R TM$, for which $cpRTM = Eq 15$.

Yes, that’s correct. To clarify this, the preceding sentence has been slightly changed:

“Since in this step of the analysis the actual polarization values for each data point data are not yet available, the polarization values used in the correction are the RTM values themselves, i.e., each data point is corrected for the *maximum* polarization (q_{RTM}, u_{RTM}) at $R = R_{RTM}$:”

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figure-1.pdf

Fig. 1. Parasol data on u vs. its single scattering value for August 2007 over ocean, with viewing geometries selected to match SCIAMACHY's Easternmost scan position and high likelihood for sun glint. The small dots are the result of SCIATRAN simulation with different wind speeds.