Authors' response to the comments of Referee #1 on “In-operation Field of view Retrieval (IFR) for satellite and ground-based DOAS-type instruments applying coincident high-resolution imager data” by H. Sihler *et al.*

We would like to thank Referee #1 for the review of our submission to AMTD and for contributing helpful comments and suggestions to improve the quality and clarity of our manuscript.

For reference, the original Referee comments below are typeset in black, our responses in blue. Modifications of the original manuscript (green) are indicated in red.

The paper by Sihler et al. presents a method to retrieve the field of view of low spatial resolution (LR) instruments by using coincident high resolution (HR) measurements. The method is applied and its results are discussed for three pairs of LR/HR instruments: GOME-2/AVHRR, OMI/MODIS, and a spectrometer used alongside a so2 camera.

Overall, the paper is interesting and well-written, it fits in the scope of AMT, and the method and results will be useful to the community. Therefore I recommend publication, after the authors have taken into account the following remarks.

Major comments

- there is no error analysis for the regularized solution used for OMI and the SO2 camera. Could the the sensitivity studies on lambda (fig 15)could be used to infer some estimation of this error? If this is not the case, the author should stress that the error analysis for the regularized problem is difficult also in the conclusion, not only in the appendix.

We thank the Referee for sharing this idea. However, it is difficult to derive an error estimation for the regularised solution for conjugate gradient methods to which the LSMR method belongs (Yao et al, 1999; Fong and Saunders, 2011). We therefore decided to search for a good regularisation parameter empirically. As pointed out in the manuscript (p.20, l.1), we chose a trade-off between reasonable noise, sharp edges (large shape parameter), and small FWHM.

The following sentence was added to the conclusions (p.29, l.24):

Reasonable results were obtained also for underdetermined problems, for which, however, an error estimation is more difficult (Yao et al., 1999).

- SO2 camera: it s difficult to rule out the effect of the mountain edge in the observed FOV heterogeneity. In principle (not doable with the presented dataset in practice) it seems easy to check that by shifting a bit upward the instrument so that the mountain does not impact the measurements. If the authors agree with that, this could be mentioned in the corresponding section and in the conclusion, as it could be useful for other teams using the method.

It is certainly true that the mountain edge can have a malicious effect on the IFR results. However, it is not straightforward to assess its relative weight using the data presented. If we understand the concerns of the Referee correctly, we may add two qualitative observations here: Firstly, FOV results in Fig. 18 (b) seem to vary around zero over the mountain ridge and at much greater frequency than in the atmosphere above the crest. They probably cancel out in the end. Secondly, the Referee correctly points out that this can be easily checked in future measurements if the algorithm presented here is applied in the field. During the measurements presented here, the viewing direction was adjusted without such information and unfortunately the resulting DOAS FOV was close to the mountain edge.

-the ’artefact’ of the small wings on the swath edges for OMI. The formulation is ambiguous here since ’artefact’ usually refers to an artificial effect introduced by the experiment. In the conclusions, the authors write that this observed pattern (’artefact’) could either originate from stray light (in that case, it would be something physical) or from an effect due to the incomplete FOV model (this would be an artefact of the method not related to something physical). This should be rephrased for clarity.

We agree that the effect called 'artefact' is merely an observed behaviour of the IFR method. The following changes have been applied to the manuscript to improve clarity.

p.21, l.1:

Furthermore, Fig. 16(a) and (b) reveal another artefact: the integrated across-track FOVs (...) increase towards the borders (...).

Figures 16(a) and (b) furthermore show an increase of the integrated across-track FOVs (...) towards the borders (...).

p.27, l.22:

Towards the swath edges, one type of IFR artefact appears: The FOV increases towards the domain edges producing small wings of the along-track integrals (plotted in magenta at the bottom of both Figs. 16(a) and (b)). One possible explanation for this artefact may be atmospheric or instrumental straylight at these viewing angles. Numerical simulations of the method showed that additional random contributions, which are not captured by the applied linear FOV model, can lead to this type of artefact.

Towards the swath edges, a typical behaviour of IFR applying LSMR may be observed: The FOV increases towards the domain edges producing small wings of the along-track integrals (plotted in magenta at the bottom of both Figs. 16(a) and (b)). One possible explanation for this behaviour may be atmospheric or instrumental straylight at these viewing angles. Numerical simulations showed that additional random contributions, which are not captured by the applied linear FOV model, can lead to this type of behaviour.

Minor comments

Introduction

-the authors could add the space borne instruments corresponding to the laboratory FOV characterization (p2 L.15)

Done.

In principle, a-priori information on the IFOV is available from measurements in a controlled environment or raytracing simulations (e. g. te Plate et al., 2001; Xiong et al., 2005; Dobber et al., 2006; EUMETSAT, 2011b; Wolfe et al., 2013).

In principle, a-priori information on the IFOV is available from measurements in a controlled environment or raytracing simulations, e. g. OMI (te Plate et al., 2001; Dobber et al., 2006), MODIS (Xiong et al., 2005), GOME-2B (EUMETSAT, 2011b), and VIIRS (Wolfe et al., 2013).

-It would be useful to give a few words on how the present study differs from DeGraaf 2016 (p 3, l. 4)

The differences between both studies are already discussed in the OMI results section (p.27, l.31). In order to clarify, we changed (p.3, l.4) in the introduction

Furthermore, de Graaf et al. (2016) presented an approach to infer parameters of a 2D super-Gaussian distribution to characterise the FOV of OMI from MODIS measurements.

to

Furthermore, de Graaf et al. (2016) obtained the parameters of a 2D super-Gaussian FOV by searching for maximum correlation between OMI and MODIS measurements (differences to this study are discussed in Sect. 4.2).

The following two sentences are added to the discussion (p.28, l.1):

Furthermore, the FOV parametrisation applied by de Graaf et al. (2016) did not include any spatial shifts and parameters were obtained by looking for maximum correlation while changing the coefficients rather than by applying a least-squares fit.

See also answers to RC3.

-the structure of the paper should be presented more clearly in the last paragraph of the introduction

Following also the recommendation of RC3 of moving the contents of Sect. 2 to the introduction, the original paragraph

In this paper, we propose a method that retrieves discretised FOVs of low-resolution (LR) spectrometers from correlated high resolution (HR) measurements, where the term resolution refers to *spatial* resolution. The In-operation FOV Retrieval (IFR) relies on a sufficiently large set of inhomogeneous HR measurements, which need to be spatially aligned to the corresponding LR measurements. Three exemplary LR/HR combinations are investigated to demonstrate the applicability to both satellite and ground-based instruments: (1) GOME-2/AVHRR: GOME-2 is a scanning spectrometer, both instruments are borne by the same satellite, (2) OMI/MODIS: OMI is an imaging spectrometer, there is a delay of 8 minutes between both satellite acquisitions, and (3) passive DOAS/SO 2 -camera: both ground-based instruments are usually integrated into one device. The retrieval is in principle independent from the type of correlated information. Hence, we apply radiometric input data to retrieve the FOVs of both satellite instruments (Sect. 3.1 and Sect. 3.2) and optical densities of SO 2 in the case of the SO 2 -camera (Sect. 3.3).

is now replaced by 2 paragraphs merging both structuring paragraphs:

In this paper, we propose a method to retrieve discretised FOVs of *spatially* low-resolving (LR) spectrometers from correlated high-resolution (HR) measurements. The In-operation FOV Retrieval (IFR) method relies on a sufficiently large set of *m* inhomogeneous HR measurements, which need to be spatially aligned to the corresponding LR measurements. Three exemplary LR/HR instrument combinations are investigated to demonstrate the applicability to both satellite and ground-based instruments: (1) GOME-2/AVHRR, (2) OMI/MODIS, and (3) passive DOAS/SO 2 -camera.

The manuscript is organized as follows: Details on the instruments and data sets of these LR/HR combinations are provided in Sect. 2.1. Section 2.2 describes the spatial resampling of the HR measurements, and the formal approach of IFR is explained in Sect. 2.3. Furthermore, Sect. 2.4 proposes a 2-dimensional FOV parametrisation. The resulting FOV are presented in Sect. 3, and discussed in Sect. 4, for the considered LR/HR pairs, followed by the conclusions. Retrieval errors for the GOME-2 results are estimated in Appendix A.

Method

- p 5 l.1 how long is the period after averaging ?

The actual period used after averaging is stated in the manuscript p.6, l.6:
23 February, 24 March, and 22 April 2009 for the narrow-mode MSC pixel

However, we believe that replacing p.5.,l.1
only every 29th day. Without averaging neighbouring pixels, more than one year of GOME-2 would have been required to gather m = 10 5 measurements (see below).
by
only every 29th day (see below).
improves the readability of the manuscript.

- is there not a reference paper for AVHRR?

To the knowledge of the authors, there is no reference paper for AVHRR/3. However, the References are updated to comply with sample AMT papers citing AVHRR products. Two citations are added:

Cracknell, A.: The Advanced Very High Resolution Radiometer, Taylor and Francis, London, ISBN 9780748402090, 1997.

NOAA: NOAA-KLM User's Guide – Section 3.1, Website, http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/klm/html/c3/sec3-1.htm, last updated 3 March 2009, last access 20 Oktober 2016, 2009.

Furthermore, the URL in the (EUMETSAT, 2011a) reference is updated:

EUMETSAT: AVHRR Level 1b Product Guide, Internet, http://www.eumetsat.int/website/wcm/idc/idcplg?IdcService=GET_FILE&dDocName=PDF_AVHRR_L1B_PRODUCT_GUIDE&RevisionSelectionMethod=LatestReleased&Rendition=Web, last access: 20 Oktober 2016, 2011a.

- P.9 L. 2 'ground based stray light DOAS' -> stray light? Should not it be 'scattered light' ?

changed to
a ground-based scattered light DOAS instrument

- p.10 l.1 please add manufacturer of USB2000 (Ocean Optics?)

Done. Yes, it was an OceanOptics USB2000.

- p10, l 7, please add geographical coordinates of the volcano

The geographical coordinates are added to the manuscript (p.10, l.7):
Lastarria volcano (Chile)
Lastarria volcano in Chile (25°10’05" S, 68°30’25" W)

- p11, l.5. The paragraph is not very clear. The second rotation seems to be the one described above in point 2 (?). Could you include it for clarity?

In order to avoid confusion, point 2 now details the three rotations. The entire passage (p.10, l.32):

The HR resampling involves three steps:

1. transformation of latitude/longitude/radius geolocations to earth-centred coordinates x/y/z applying the WGS84 ellipsoid,
2. rotation of HR data into the (0,0,z)-centred x/y-plane using the corresponding LR geolocations (see below), and
3. average HR measurements within each grid cell.

The second step comprises 3 consecutive rotations as already pointed out by Siddans (2016). The LR pixel centre, e. g. point F in Fig. 6 for GOME-2, is rotated to (0,0,z) first. A third rotation along the z-axis aligns the LR pixel edges in the x/y-plane, i. e. for GOME-2, the halfway points between point A and B as well as C and D have the same y-offset (cf. Fig. 6), for OMI the tiled pixel outlines are treated respectively. Hence, one HR radiance image is obtained for each single LR measurement. Figure 6 shows an example of raw and resampled AVHRR data where the pixel centre and edges of GOME-2 were used as input for the projection.

is changed to

The HR resampling involves three steps:

1. transformation of latitude/longitude/radius coordinates to earth-centred x/y/z coordinates applying the WGS84 ellipsoid (x-axis towards 90°E, y-axis towards the north pole, z-axis towards zero meridian)
2. rotation of HR data into the (0,0,z)-centred x/y-plane using the corresponding LR coordinates similar to Siddans (2006):
   (a) (x,y,z) LR pixel centre (point F in Fig. 6), around y-axis to (0,y',z')
   (b) (0,y',z') around x-axis to (0,0,z")
   (c) rotation around z-axis so that the y-offset of both midpoints of the along-track pixel edges (M_1 and M_2 in Fig. 6(b)) are equal
3. averaging of HR measurements within each grid cell.

Hence, one HR radiance image is obtained for each single LR measurement. The definitions of the rotations of step 2 apply for any common quadrangular pixel shape. Figure 6 shows an example of raw and resampled AVHRR data where the pixel centre and edges of GOME-2 were used as input for the projection. It needs to be noted that the choice of the HR grid is somewhat arbitrary - also irregular grid sizes are possible - but the resolution is constrained by original HR resolution and storage capacity. In this study, quadratic grids are mostly chosen for the sake of simplicity.

See also answers to RC2.

-p 12 from eq 2 to eq 3, you add a the constant co but this should be described before eq 3 since it means that the equation 2 is not just ’rearranged’

As also mentioned in our answers to RC2, we applied considerable modifications to this part of the manuscript in order to improve clarity. The changes are detailed in the latexdiff-document.

In particular, the following modification was applied to the manuscript (p.12, l. 17)

c_0 is a constant, which is introduced in order to compensate potential input biases due to instrumental deficiencies and imperfect radiance calibration

constant offset c_0, which adds a further degree of freedom compensating potential input biases due to instrumental deficiencies and imperfect radiance calibration

Results

-p19, l19,20 There is a mix between along and across track between the text and the fig 14. And ’there is a difference between...’ could the author be quantitavie on that?

The subcaptions in Fig. 14 are changed for the sake of clarity.

Changes applied to the manuscript (p.19, l.19):

However, there is a difference between the theoretical along-track FOV and the retrieved shape in Fig. 14(d) due to the simplifications of the parametrised FOV model.

is changed to

However, there is a difference of shape, amplitude, and position between the theoretical and retrieved along-track FOV in Fig. 14(d) due to the simplifications of the parametrised FOV model.

-p.22, l.8 , ’b3 was always positive, ... clearly visible in Fig.16 ’. Is it clearly visible? The integrated values seem to peak at 0 on Fig. 16.

clearly deleted in the manuscript.

Technical comments

p 4, l 4. Comma missing before Calies

Done.

p 4 , l .18 MCSs should be MSCs

Done.

p5, l .12 The -> the

Done.

p.6 l. 10 missing comma before Levelt

Done.

p25 l. 24 8b should be 8a

Done. The passage now reads
FOV for pixel 0 in Fig. 8(a) shows

p.28 l.28, an independent method IFR -> reads weird, should be rephrased eg ’the independent method IFR’

The first sentence of the conclusion now begins with
This paper describes IFR, which is an independent method to characterise