Author replies are shown in blue
New text is shown in red

Anonymous Referee #2

General Comments

This manuscript evaluates spectroscopic properties of zenith-sky-viewing DOAS instruments by extending the Kurucz fit method using high-resolution solar spectra. The method is applied to 30 years of UV-visible zenith-sky spectra recorded at Kiruna, Sweden, to characterize the dependence of instrument properties (instrument spectral response function, intensity bias, light throughput) on different observing conditions, and to assess the effect of changing from a photodiode array to a CCD detector. The manuscript clearly states the primary findings and gives specific recommendations for applying the Kurucz fit. A major conclusions is that the Ring effect causes a systematic broadening of the width of the instrument spectral response function derived from the Kurucz fit compared to that derived from mercury lamp measurements. The strength of the Ring effect is found to change when optically thick clouds are present and to have a seasonal dependence due to the surface albedo. The manuscript also presents a method for correcting wavelength dependence of the light throughput (such as that caused by the Fabry–Pérot etalon effect) using the results of a modified Kurucz fit.

The work is clearly presented and will be of interest to those involved in UV-visible spectroscopy and DOAS measurements of atmospheric trace gases. I have only a few minor comments to add to those of Reviewer 1, and I recommend publication after both sets of comments are addressed.

Many thanks for the positive assessment and helpful comments, which we all addressed as outlined below.

Specific Comments

Page 7, line 170: Text refers to Figure A3 on page 35 as showing variations of the strength of the Ring effect due to the varying cloud cover, but the figure shows FWHM vs. RSP. It is not clear from the figure or caption how this is related to varying cloud cover – explain.

We added a detailed discussion of the effect of clouds on the Ring effect in section 3.3. In that context, we removed the reference to Fig. A3 on page 7 and changed there the text to:
'This finding is caused by variations of the strength of the Ring effect due to the varying cloud cover (see e.g. Wagner et al., 2004), while noise of the measured spectra hardly contributes to the observed variations. A detailed discussion of the effect of clouds on the Ring effect is provided in Sect. 3.3.'
We also replaced Fig. A3 in the Appendix, by the new Fig. A5, which contains correlations analyses of the data shown in Fig. 5 (as also suggested by this reviewer). The new Fig. A5 also contains O_4 dSCDs as proxy for the cloud effects. The comparison of the O_4 dSCDs and the RSP thus provides a direct link between cloud effects and the variation of the strength of the Ring effect. The new Fig. A5 is shown below:

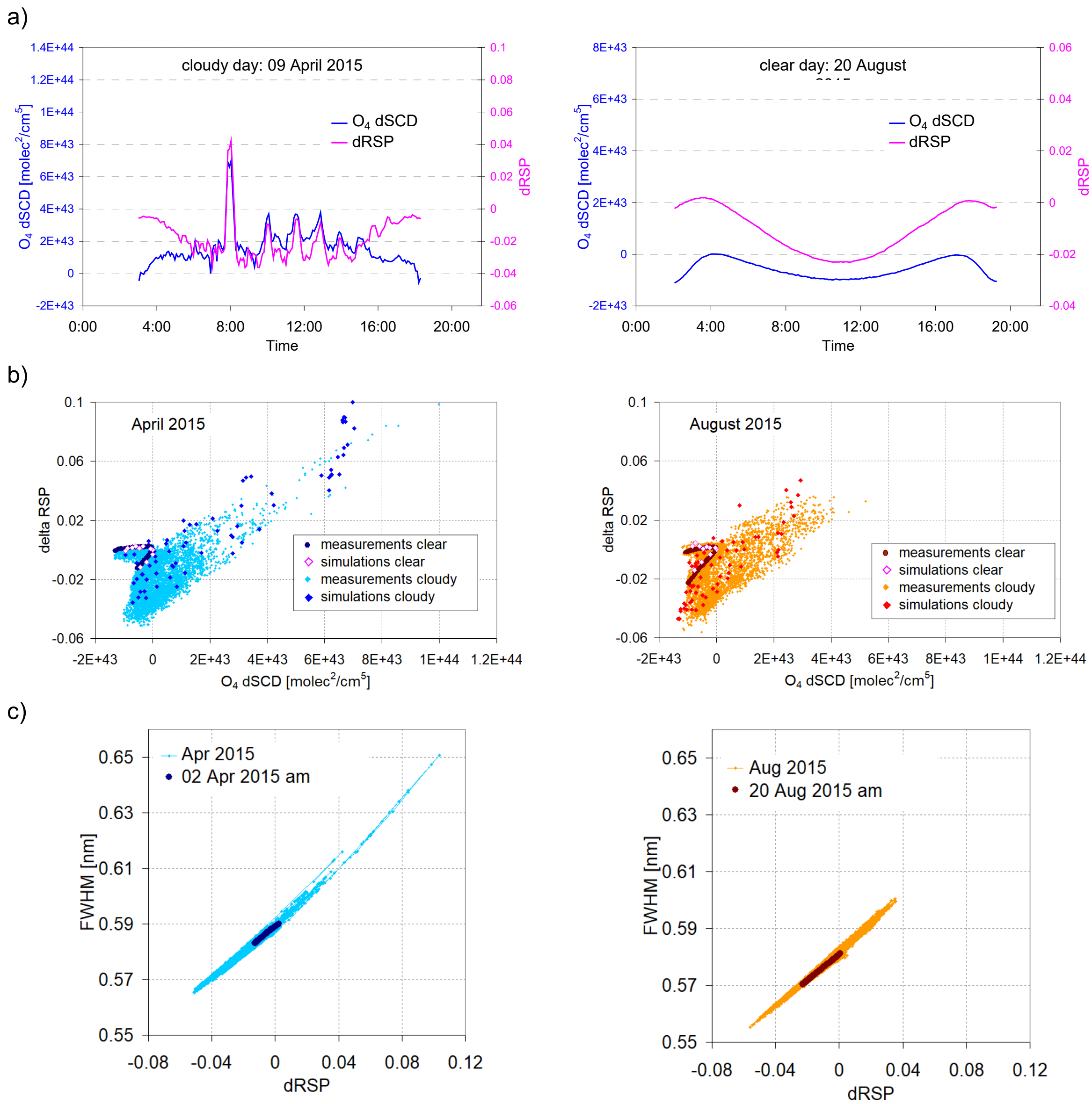
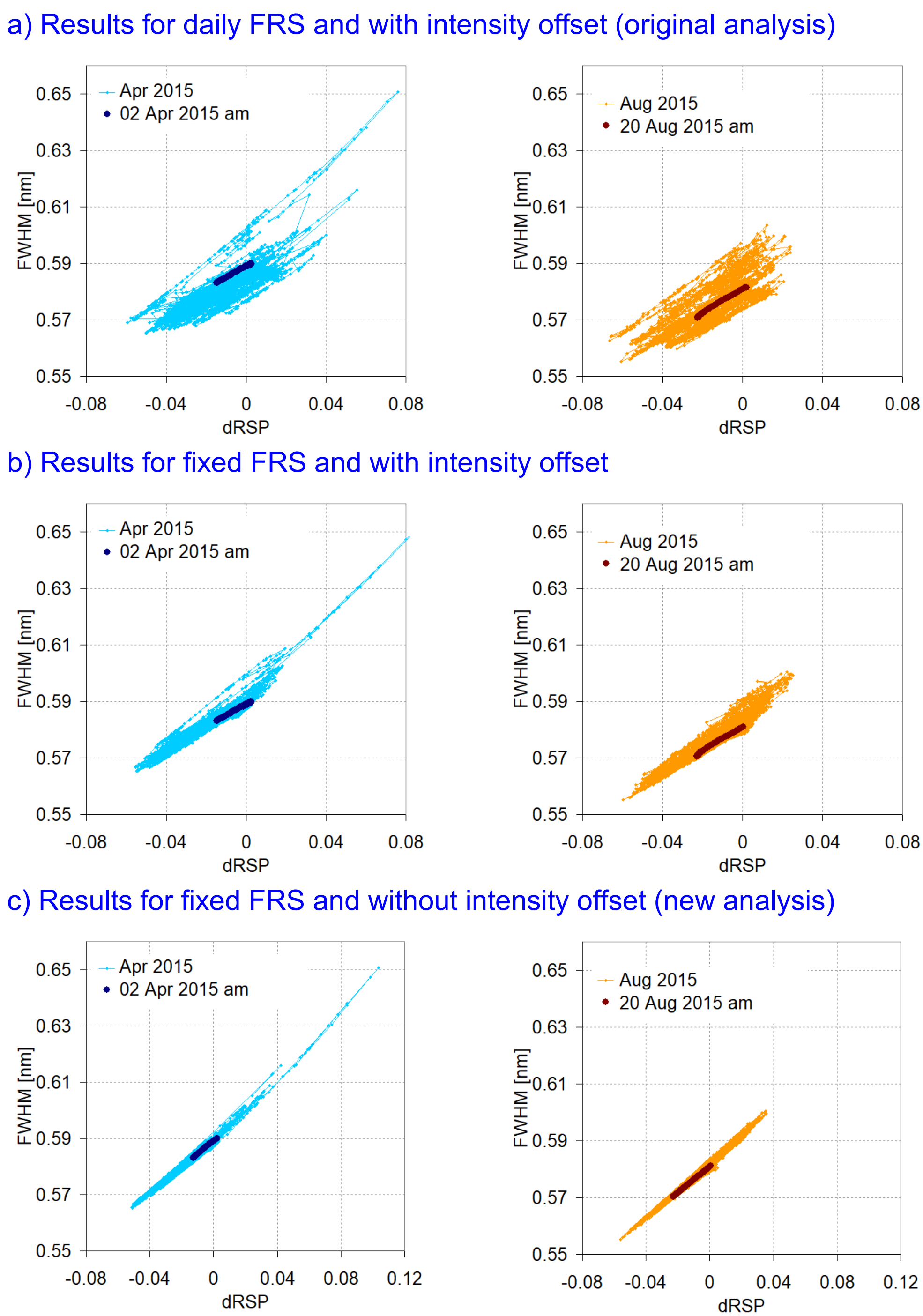


Fig. A5 a) Diurnal variation of the O_4 dSCD and strength of the Ring effect (dRSP) for a clear day (right) and a cloudy day (left). The O_4 dSCDs are analysed in the spectral range 353 – 387 nm. b) Correlation plots of the dRSP and O_4 dSCD for the two selected months shown in Fig. 5. In addition, also results from radiative transfer simulations are shown. The clear sky data cover only a small part of the overall variability, which is dominated by the cloudy cases. For the radiative simulations, clouds with altitudes between 1 and 10 km and optical depths between 1 and 50 were assumed. c) Correlation plots of the FWHM derived from the KF and the dRSP derived from the DOAS analysis for the two selected months shown in Fig. 5.

The following text is added (directly before Fig. 5):

'The influence of clouds was further investigated as illustrated in Fig. A5 in the Appendix. In Fig. A5a the diurnal variation of the strength of the Ring effect and the O_4 dSCD for two selected days is shown. For the clear day, both quantities show a smooth and similar variation. In contrast, for the cloudy day both quantities show strong simultaneous short-term variations caused by light path changes (mainly affecting O_4) and changes of the number and type of atmospheric scattering events (mainly affecting the Ring effect). The different sensitivities to cloud effect also explain why the variation of the two quantities is not aways consistent. Fig. A5b presents correlation analyses of both quantities for all measurements shown in Fig. 5. Also, results of radiative transfer simulations are shown. The comparison of the measurements and simulation results further confirms that the large variations of both quantities are caused by clouds, while the results for a clear day show only rather small variations. Fig. A5c displays the correlation between the FWHM and the strength of the Ring effect for the measurements shown in Fig. 5. The strong correlation between both quantities confirms that the large variability of the FWHM derived for the KF is caused by the effects of clouds.'

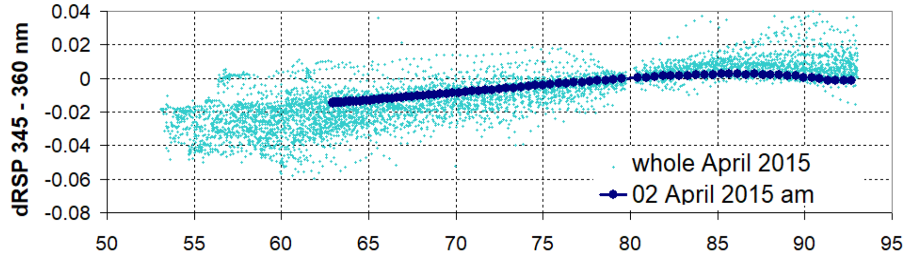
Note that the original Fig. 5 was replaced by a new figure with dRSP results obtained using fixed Fraunhofer reference spectra (instead of daily Fraunhofer reference spectra) and excluding the intensity offset in the fit. Fixed Fraunhofer reference spectra were chosen to avoid varying offsets of the retrieved dRSP caused by the changing strength of the Ring effect in the daily Fraunhofer reference spectra. The intensity offset was excluded to minimise the 'cross-talk' between the fitted Ring spectrum and intensity offset. The effect of both changes is illustrated in the figure below. The correlation between the FWHM and dRSP is already present in the correlation analyses of the original data (a), but the results for the individual (half) days show systematic biases along the x axis. If fixed Fraunhofer reference spectra are used, these biases mostly disappear (b), but still some minor variations remain. If also the intensity offset is excluded from the fit, the correlation becomes very tight (c).



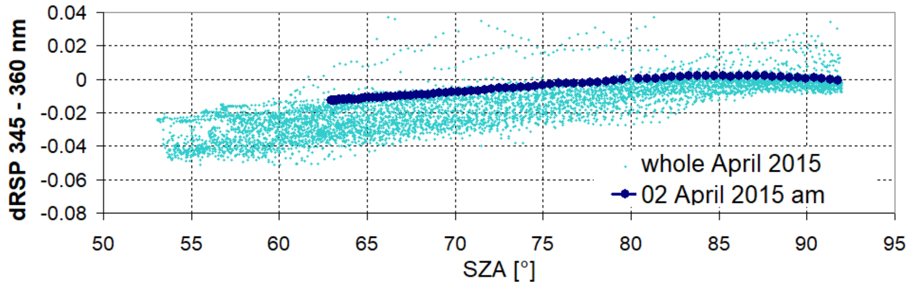
Correlation analyses between the FWHM and dRSP (data from Fig. 5) for different analysis settings.

The comparison of the old and new dRSP results of Fig. 5 is shown below. The main conclusions (SZA-dependence, cloud induced variability) remain unchanged.

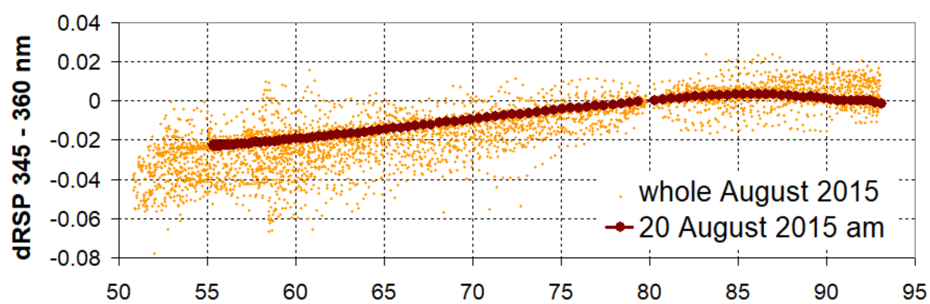
old Fig. 5b



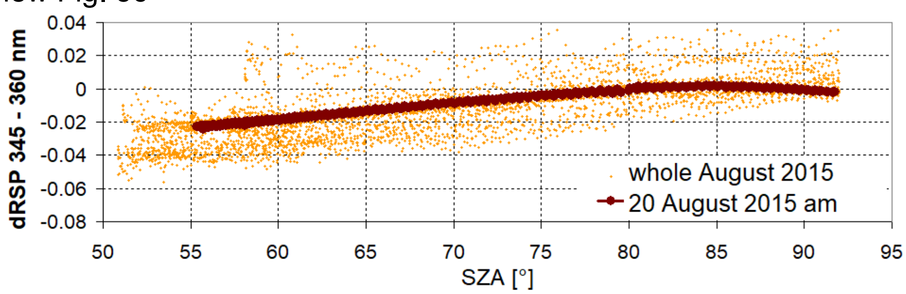
new Fig. 5b



old Fig. 5c



new Fig. 5c



Page 9, lines 205-211 and Page 10, Table 1: Clarify why different fitting parameters are used for each of the BrO bands.

The following information was added to the caption of Table 1: 'For the different fit ranges, different fit settings are used, mainly to account for the effects of the increasing ozone absorption towards shorter wavelengths. For the smallest fit range, a lower polynomial degree and only one Ring spectrum was used, because of the weak effect of the wavelength dependence of the atmospheric scattering processes.'

Page 12, paragraphs 1 and 2: Could correlation plots be added to strengthen the conclusions regarding the various hypotheses?
Correlation plots for the data of Fig. 5 were added as new Fig. A5 as outlined above.

Also, for the data shown in Fig. 4, correlation analyses were added as new Fig. A4 (see below). The following information was added to the text:
'Correlation analyses of the quantities shown in Fig. 4b-f versus the snow depth (Fig. 4a) are presented in Fig. A4 in the Appendix. The variability caused by clouds dominates the variability of all quantities, but still for all quantities (except for the KF results including an intensity offset) a positive dependence versus the snow depth is found.'

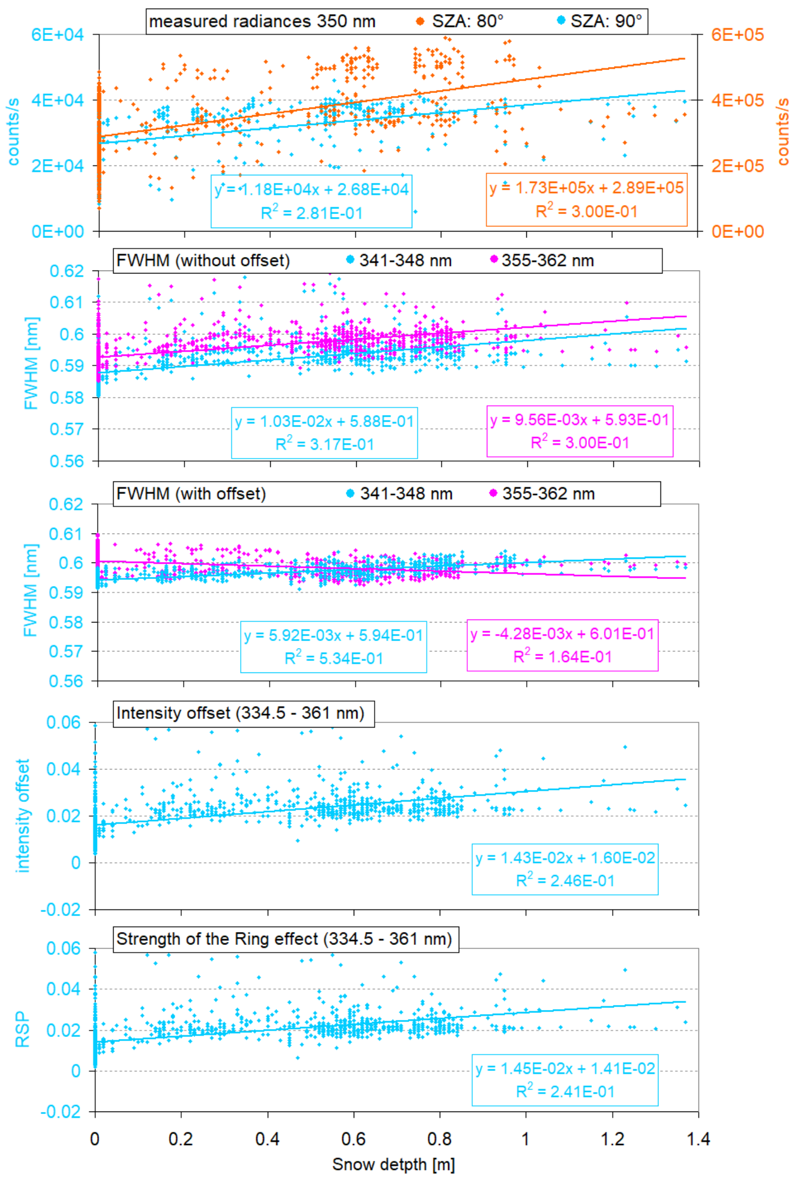


Fig. A4 Correlation plots of the quantities shown in Fig. 4 (b to f) versus the snow depth (Fig. 4a)

Page 28, end of paragraph 2: Comment on relevance of these findings to MAX-DOAS scattered-light measurements.

The last sentence of this paragraph was modified, and MAX-DOAS are now explicitly mentioned: 'In contrast, for measurements of trace gases located close to the surface, and in particular for MAX-DOAS observations and satellite observations in nadir geometry, a spectrum without a contribution from Raman scattering, e.g. a direct sun spectrum (or an earth shine spectrum after the subtraction of the Raman scattering contribution), might be a better choice.'
(see also the answer to general comment (4) from reviewer 1)

Page 29, lines 588-591: The reasoning in this last paragraph seems circular ("it is recommended to monitor the instrument characteristics of a DOAS instrument … In this way … the instrument properties can be continuously monitored during routine operations"). Suggest rewriting this paragraph for a clearer final message.
We deleted the last sentence.

Technical Corrections

I noted many of the same typographical corrections as Reviewer 1 (ist, Mio, prepared, teh, charateristics, spectromter, etc.) so will not repeat them here.
corrected, see also replies to Reviewer 1

Check the manuscript for correct use of hyphens in compound adjectives before nouns, e.g., for zenith-sky, clear-sky long-term, high-resolution, wavelength-dependent etc.
The use of hyphens was corrected in many places. Further corrections will be applied through the copy-editing process

Many sentences could benefit from the use of commas to separate clauses.
As non-native english speakers, we trust that the use of commas will be optimised through the copy-editing process

Wikipedia is cited twice as a reference (for the length of polar day and night, and for snow cover, at Kiruna). Both should be replaced by references to primary sources.
The reference to wikipedia was removed

Check capitalization of sect./section --> Sect./Section, eq./equation --> Eq./Equation, appendix --> Appendix. Also follow AMT guidelines on when to abbreviate section, equation, and figure.
Numbers could be written as words when not referring to specific values.
corrected according to the AMT guidelines

Add punctuation after equations.
corrected

Page 2, line 32: define DOAS
The definition was added.

Page 2, line 54: Here and throughout - why use “sub window” (sub-window)? No windows have been defined, so why not “fitting window”?
We prefer to use the term ‘sub-window’ because usually the KF is performed in separate sub-windows within the entire wavelength range chosen for the KF.
We added the following information to the text: ‘(in the following referred to as sub-windows, for details see Sect. 3)’

Page 4, lines 92-93, 102, and in legend of Figure 1a: capitalize Swedish Institute for Space Physics
corrected

Page 5, Equation 1: define all terms in this equation
definitions were added

Page 9, line 195: Fig. A4 (not 4A)
corrected

Page 9, line 208: define FRS on first use (it’s defined on page 12, line 237)
The definition was added to page 9 and removed from page 12.

Page 10, caption and first row: change Alliwell to Aliwell
corrected

Page 12, line 252: there are no “black dots” in Figure 5 – fix
changed to ‘filled markers’

Page 20, line 399: change migh to might
corrected

Page 27, line 519: change monotonous to monotonic
corrected

Page 33, line 698: change self-built to custom-built
corrected

Page 33, line 702: change photo diode to photodiode
corrected

Page 33, line 707: Is the integration 6 minutes at all SZA? Wouldn’t noon spectra be saturated for such a long integration time?
Depending on the brightness of the sky, a varying number of scans are taken which are then added to yield the measured spectrum. We changed the text to ‘The total integration time (including several scans) for individual spectra (for both detectors) is 6 minutes.’

Page 41, line 800, 805, 806, 811, 825: broad band --> broadband
corrected