Responses to Review of Referee 3 (AMTD-8-1-2015)

We would like to acknowledge the anonymous referee for his/her useful remarks and comments which have helped to improve the manuscript. All comments have been addressed as detailed hereafter in blue.

This is a generally nice paper showing interesting results from some very careful measurements, I do have two major points which should be addressed and several minor suggestions and corrections.

1. First, while the shapes of the measured and modeled spectra appear to be similar, there seems to be a significant difference between the Brightness Temperature shown in Figure 7 (highest peak $\sim$ 64K), which shows the radiation passed through the TEMPERA components as calculated by the model, and that shown in Figure 10 (highest peak $\sim$ 54K), which shows the measurements. Perhaps there is just an offset here which I don't understand, but some explanation is required, even if the answer is just that there is a calibration problem which doesn't affect the results (combined with an explanation as to why it does not). It would be very helpful to the reader to see measured and modeled spectra for a few of azimuth angles plotted on the same figure, with an offset or some other correction added to one or the other if this is appropriate.

As the referee points out there is an offset in the brightness temperature spectra between the measurements and the model. This offset could be due to the fact that the forward model is not detailed enough and it does not consider the contribution from line mixing to the oxygen spectra or an appropriate characterization of the continuum absorption from secondary species (ozone, water vapour, ...). Other reasons that could explain some differences could be related to the uncertainties of the tropospheric correction in the measurements or due to the fact we are comparing different periods of measurements, one day for the simulations (15-Oct-2015) and one month of integrated measurements (October 2013). Anyway, this offset does not affect at all to our results, since all causes do not have any frequency dependence in the very narrow range (4 MHz) in the center of the oxygen emission line, therefore the shape of the spectra is not altered.

As the referee suggests we have pointed out this issue in the manuscript. Moreover a new plot has been added with the modeled and the measured spectra for two different observational azimuth angles. The modified paragraphs in the manuscript read now as (lines 333-354):

"These results are in good agreement with the simulations performed including the Zeeman effect with ARTS (section 4.1). However, we can notice that there is an offset in the brightness temperature spectra from model (highest peak $\sim$ 64 K) and from measurements (highest peak $\sim$ 54 K). The offset could be due to an inappropriate consideration of the continuum absorption from secondary species (water vapour, ozone, ..) in the forward model and the fact that the contribution from line mixing to the oxygen spectra is not modeled. Other reasons that could explain some differences could be related to the uncertainties of the tropospheric correction in the measurements and to the fact we are comparing different periods of measurements, one day for the simulations (15-Oct-2015) and one month of integrated measurements (October 2013). In any case, while the baseline offset affects the absolute difference between model and data, the shape of the center line ($\pm$2 MHz) is not altered. Thus the main conclusions of Zeeman polarization measurements and the ARTS module validation are solid.

"Figure 12 shows a direct comparison of the brightness temperature spectra from SDR measurements (solid lines) and from ARTS model (dashed lines) for two observational azimuth

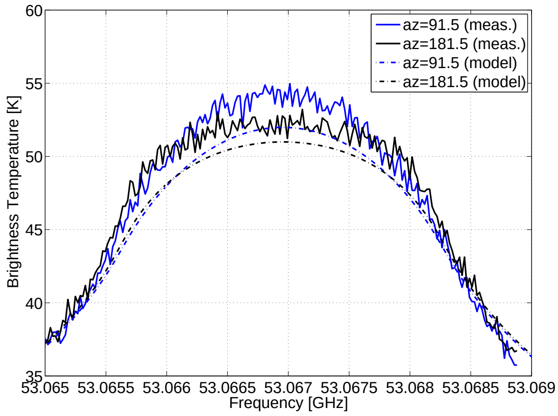

Figure 12. Brightness temperature spectra from the SDR spectrometer (solid lines) and simulated from ARTS (dash lines) for two different observational angles.

angles (91.5º and 181.5º). An offset correction has been applied to the simulated spectra in order to compare with the measurements. Although the absolute values are not exactly the same for the modeled and measured spectra in the center of the oxygen emission line we can clearly observe that the behaviour of the spectra for the two azimuth angles are the same. The spectra show a higher broadening for the highest azimuth angle for both, measurements and simulations. In order to compare in a more quantitative way the measurements with the model ..."

2. The main focus of this manuscript is the comparison presented in Figure 11. The results look reasonable, but given that this is essentially the crux of the paper, a little more relevant information is required. First, please write out explicitly the equation for Teff(max)/Tmean(max), including the precise range over which it is calculated (some of the relevant text related to this on page 15 seems to be wrong). Also, it would be nice to see some error bars on the TEMPERA measurements in this figure. I would assume that these uncertainties would come primarily from uncertainties in the tropospheric optical depth, which could perhaps be estimated.

Following the suggestion from the referee we have explicitly written the equation which gives the ratios showed in Figure 11. The text and the new equation read now in the manuscript as (lines 352-359):

"In order to compare in a more quantitative way the measurements with the model we have compared the ratio between the maximum mean brightness temperature of each spectrum and the mean value for all the spectra at the central frequencies (range of ± 0.25 MHz). Equation 12 explicitly indicates the expression of this calculation:

$$\frac{Teff(max)}{Tmean(max)} = \frac{mean[T_b(\upsilon_1 - \upsilon_2, \psi_i)]}{mean[\frac{\sum_{i=1}^{n_t} T_b(\upsilon_1 - \upsilon_2, \psi_i)}{n_t}]}.$$

where υ_1 and υ_2 indicate the frequency range which corresponds to an interval of 0.5 MHz centered at 53.067 GHz. ψ_i is the observational azimuth angle for a specific position and n_t is the total number of positions scanned by TEMPERA (13 positions)."

Moreover, we have estimated the errors associated with the measurements and the model for the ratios showed in Figure 11 (Figure 13 in the reviewed manuscript). The errors for the TEMPERA measurements were estimated evaluating the uncertainties associated to the different terms of the tropospheric correction (Eq. 11). The error bars showed in the new figure have been calculated

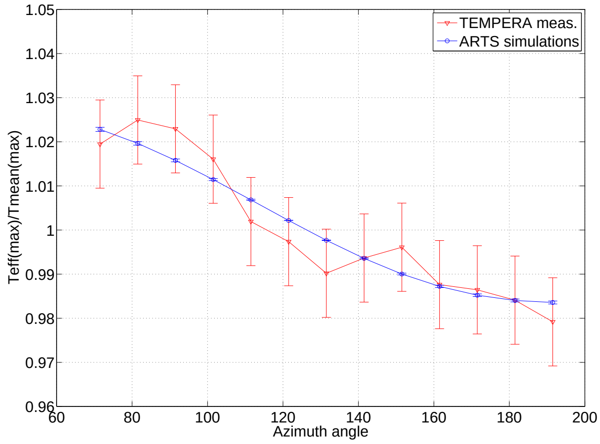

Figure 13. Ratios between maximum brightness temperature of each spectrum and the mean value for all the spectra at the central frequencies for TEMPERA radiometer (red points) and ARTS (blue points).

using error propagation theory and they presented values very similar (~ 0.01) for all the observational angles.

The error associated to the simulations were obtained evaluating the ratio of the simulated spectra plus Gaussian white noise. The calculated uncertainties presented values much smaller than the ones found for the measurements (maximum value of $4.6 * 10^{-4}$).

According to this new estimation we have slightly modified some paragraphs in the section 4.3 and in the conclusions. The text reads now as (lines 360-378):

"Figure 13 shows these ratios calculated with the ARTS model simulating the conditions of 15 October 2013 and the ones obtained from the mean monthly spectra (October 2013) measured by TEMPERA. We can observe, that in general, there is a very good agreement between the measurements and the model. Both simulations and measurements show higher ratio values (>1), which indicate a smaller broadening regarding the averaged spectrum, for the smallest azimuth angles and a larger broadening (ratios <1) for the largest angles. The relative differences between both ratios are lower than 1% for all the azimuth angles. We observe that the ratios for some azimuth angles are almost identical while some discrepancies are observed for other ones. The errors for the TEMPERA measurements have been estimated evaluating the uncertainties associated to the different terms of the tropospheric correction (Eq. 11). The error bars shown in Fig. 13 have been calculated using error propagation theory and they presented values very similar ($\sim$ 0.01) for all the observational angles. The error associated to the simulations were obtained evaluating the ratio of the simulated spectra plus Gaussian white noise. The calculated uncertainties presented values much smaller than the ones found for the measurements (maximum value of $4.6 * 10^{-4}$). It is important to note that the differences found between measurements and simulations are within the measurement uncertainties. From this comparison we can conclude that the agreement between measurements and model is clear. These results show the polarized state of the radiation due to the Zeeman effect, which is revealed for a different broadening in the spectra, when the angle of the Earth magnetic field and the observational path is changed."

and in the conclusions (lines 409-415):

"Similar behaviour to the simulations was observed for the measured spectra from the TEMPERA radiometer. A direct comparison of the ratios between the maximum brightness temperature of each spectrum and the mean value for all the spectra at the central frequencies showed a very good agreement between the model and the measurements. Both simulations and measurements showed a smaller broadening for the smallest azimuth angles, and a larger broadening for the largest angles. The small discrepancies found for some azimuth angles were always within of the measurement uncertainties."

Below are some more minor points that should be addressed:

3. The inserts on Figure 5 are really quite small and impossible to read unless expanded to ∼ 400 % on my monitor. Perhaps it would be better to put these on figures. The one on Figure 7 is perhaps large enough.

Following the suggestion from the referee we have put these two plots in two different figures (Fig. 5 and 6). After this change, all the figures have been properly enumerated and cited in the manuscript.

4. Page 3 - It would be appropriate to point out that Hoppel et al. (Monthly Weather Review, 2013) used the work of Han et al. was used to assimilate SSMIS Upper Atmosphere Sounding channels, together with MLS data, into a NWP model.

We agree with the referee that it is an appropriated reference to include in the introduction. We have added it and the correspond paragraph reads now as (lines 45-55):

"Comparison of satellite measurements and radiative transfer models including the Zeeman effect have also been addressed (Han et al., 2007, 2010; Schwartz et al., 2006). Han et al. (2007) used spectral passband measurements from the Special Sensor Microwave Imager/Sounder (SSMIS) on board the Defense Meteorology Satellite Program F-16 satellite to measure the oxygen magnetic dipole transitions (7+, 9+, 15+ and 17+, Rosenkranz, 1993). These measurements were used to validate a fast model developed from the radiative transfer model of Rosenkranz and Staelin (1988). Moreover, the measurements were also used together with data from Microwave Limb Sounder (MLS) on board of Aura spacecraft for assimilation in a NWP model (Hoppel et al., 2013). Schwartz et al. (2006) also reported a comparison of another radiative transfer model with measurements of the 118 GHz oxygen line from MLS."

5. Page 6 line 5. I'm curious as to why the calibration discusses only a hot load and noise diode. Figure 1 shows a cold load. How is the noise diode calibrated without a cold load? Is there perhaps an initial calibration with a cold load?

Yes, a cold load is used for the calibration of the noise diode. As the referee suggests we have clarified this point in the discussion about the calibration in the manuscript, the text reads now as (lines 88-92):

"A noise diode in combination with an ambient hot load are used for calibration in each measurement cycle. The noise diode is calibrated regularly (about once a month) using a cold load (liquid nitrogen) and a hot load (ambient). The receiver noise temperature T_N is in the range from 475-665 K. More details about the calibration with TEMPERA can be found in Stähli et al. (2013)"

6. Figure 8 - Should the x-axis be MHz and not GHz?

Yes, it was a mistake. It has been corrected in the manuscript.

7. Page 13 - "In order to correct our measurements for tropospheric effects". Strictly speaking, there is no need to "correct for tropospheric effects". Equation (7) is clearly valid everywhere along the pathlength. The reason (9) is of use here is, I assume (but the author should explicitly

state this), because the tropospheric portion of the pathlength provides a relatively spectrally flat signal.

We agree with the referee's specification. In order to clarify this point we have rewritten this sentence. It reads now as (lines 284-286):

"Since the tropospheric portion of the pathlength provides a relatively spectrally flat signal the microwave radiative transfer equation can be rewritten as"

$$T_b(z_0) = T_b(z_{trop})e^{-\tau} + T_{trop}(1 - e^{-\tau})$$

8. Page 13 - "Since the atmospheric opacity is dominated by the contribution from the troposphere, the cosmic background radiation, Tbg, is in practice used instead of Tb(ztrop) in Eq. (10)." I think that this statement is somewhat misleading. Tb(ztrop) depends upon the optical depth of the stratosphere. It's probably true, that this happens to be small, and perhaps so small that it is dominated by Tbg. But that is not what this sentence states.

In order to clarify this point we have restated the sentence. It reads now as (lines 291-293):

"Since the atmospheric opacity is dominated by the contribution from the troposphere, the stratospheric contribution is considered negligible and the cosmic background radiation, T_{bg}, is in practice used instead of $T_b(z_{trop})$ in Eq. 10."

9. Page 15 - "However, differences in the intensity and in the shape are observed in the very narrow range centered on 53.07 GHz." Actually, 53.07 GHz is at the edge of the plot where there is no data shown. Presumably you the authors mean 53.067 GHz. The exact number here is quite crucial, since it is the basis for the results in Figure 11. I assume that the numbers in Figure 11 come from 53.0665 to 53.0675 GHz, but please state this explicitly.

Yes, indeed, as the referee point out the center of the line is 53.067 GHz. We have corrected this number in the manuscript (line xx). The frequencies range used for the calculus shown in Figure 11 is 0.5 MHz which is centered at 53.067 GHz, it is indicated in lines 357-358.