Remote Sensing of the Earth's Magnetic Field in the Middle Atmosphere Using a Ground-Based Fully Polarimetric Microwave Radiometer

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Response to reviewer 1

General comments:

- *The Abstract does not clearly present the main research question and significant findings of the study. I suggest reorganizing the Abstract to follow the usual structure, as it clearly explains the problem first, then the methods, main results, and the significance of the work. The study is truly innovative. It employs a unique technique to retrieve magnetic field parameters at altitudes inaccessible to other methods. So, the author needs to focus on the principal findings related to the study objectives, which are not clear shown in abstract at the moment.*

  Thank you for your suggestion. We have revised the abstract accordingly.

- *The text in the Introduction (Lines 38-45) is better suited to the Conclusion section, where the results are described. In this place, it is better to formulate the scientific question that is the core aim of the manuscript.*

  The section in question has been moved to the Conclusions, and the Introduction has been revised accordingly.

- *It would be useful to add a subsection to discuss the limitations of the proposed method and possible errors in determining the magnetic field parameter during the calculation process. It would also discuss ways to mitigate these errors other than using cryogenic cooling of the receiver. One of the weaknesses of the measurements is the relatively low temporal resolution of the obtained magnetic field parameters (about 20 minutes of integration time). It's worth discussing ways to reduce this time.*

  The errors and potential improvements were already discussed in the manuscript. However, these discussions were distributed across several sections, which may have led to confusion. We have therefore moved the relevant content into a new subsection "Error Contributions and Limitations", which presents the error budget, discusses possible approaches to reducing error sources, and outlines potential improvements to further optimize the instrument's performance.

  Regarding the integration time, we would like to clarify that the instrument has already been extensively optimized with respect to both performance and noise level. An integration time of 20 minutes is already relatively short for ground-based microwave remote sensing of middle atmospheric parameters. We also clarify here that the integration time refers to the total time required to acquire a complete spectrum, while the actual scene integration time accounts for only approximately one-third of this period.

At the time of the instrument development, the electronic components, including the orthomode transducer (OMT), noise diodes, low-noise amplifier (LNA), mixer, waveguides, and backend, represented the best available technology. Several components were manufactured in-house to meet the required performance specifications. The calibration target and its material were also recently developed in-house, and the calibration cycle has been optimized. Other technical aspects, such as the pointing accuracy, are already discussed in the manuscript. At this stage, it is difficult to identify further technical improvements, as we believe that all currently known optimization measures have been considered. One remaining possibility for reducing the system noise is active cooling of the front end. Another option with significant potential to improve the observations is environmental rather than technical. Deploying the instrument at a high-altitude site would reduce the tropospheric air mass between the antenna and the middle atmosphere, thereby decreasing tropospheric opacity and its influence on the measurements. A long-term deployment of TEMPERA-C at the Jungfraujoch High Altitude Research Station (3571 m a.s.l.) is planned for future operation. The higher altitude will substantially improve the signal-to-noise ratio. Finally, improvements in the correction of tropospheric effects, particularly those caused by clouds, may further improve the retrieval results, although they would not reduce the required integration time.

- *Figure 9a. The results shown in Figure 9a are very interesting. What causes the jump from positive* $d\boldsymbol{H}_w$ *to negative* $d\boldsymbol{H}_w$ *during the transition from the stratosphere to the mesosphere (approximately 50 km)? Why does the positive* $d\boldsymbol{H}_w$ *disappear between January 18 and January 19? Can such a sharp transition from positive* $d\boldsymbol{H}_w$ *to negative* $d\boldsymbol{H}_w$ *exist with altitude, or is it the result of different calculation procedures at stratospheric and mesospheric altitudes, a technical artifact? However, it should be mentioned that some of these issues are beyond the scope of the manuscript*

  The transition indicates a tilt between the apriori and true state, which presumably results from the convolution of such a tilt with the AVK. During the geomagnetic storm phase, this relatively small tilt appears to be dominated by a negative offset. We agree that the interpretation of specific features in the retrieved time series of $d\boldsymbol{H}_w$ is beyond the scope of this manuscript.

Specific comments and technical corrections:

- *In my opinion, the title "On the Feasibility of Remotely Sensing the Earth's Magnetic Field Using a Ground-Based Fully Polarimetric Microwave Radiometer" doesn't quite clearly convey the main advantage of the work—measuring the magnetic field at stratospheric-mesospheric altitudes, which are difficult to access by other methods. However, I find it difficult to suggest the necessary changes while keeping the title concise.*

  The title has been revised to: "Remote Sensing of the Earth's Magnetic Field in the Middle Atmosphere Using a Ground-Based Fully Polarimetric Microwave Radiometer"

- *The sentence in line 108: "The term* $\Phi_{M,M'}$ *represents the Mueller matrix describing the polarization of the radiation for the corresponding transition and propagation" is not quite correct. Since the Mueller matrix describes not the radiation but its transformation s So, the following would be more correct: "The term* $\Phi_{M,M'}$ *represents the Mueller matrix that describes how the polarization of the radiation is transformed for the corresponding transition and propagation."*

  The suggested phrasing is indeed more accurate. We thank the reviewer for this suggestion and have replaced the initial phrasing accordingly.

- *The Mueller matrix generally has 16 nonzero elements, which can also be negative. Therefore, it's unclear which of the normalized elements of the Mueller matrix are depicted in Figure 2. Shouldn't* *the circle centers for circular polarizations coincide with the center of the polar coordinate system in Figure 2?*

The Müller matrix elements shown in Fig. 2 refer to Larsson et al. (2014), Eqs. 11-12. Based on these equations, the following elements are illustrated:

$$\Phi^{21}_{A_\pi} = \begin{bmatrix}0\,1\,0\,0\end{bmatrix} \Phi_{A_\pi} \begin{bmatrix}1\\0\\0\\0\end{bmatrix} \tag{1}$$

$$\Phi^{41}_{A_{\sigma\pm}} = \begin{bmatrix}0\,0\,0\,1\end{bmatrix} \Phi_{A_{\sigma\pm}} \begin{bmatrix}1\\0\\0\\0\end{bmatrix} \tag{2}$$

The interpretation of these elements is the fraction of the initial unpolarized radiation detected in the Q-Stokes and V-Stokes channels due to attenuation and a specific $\sigma_\pm$ or π transition, respectively. In the referenced manuscript, these quantities are discussed with reference to Rees et al. (1989) and Jefferies et al. (1989). In the former, these elements appear in Eq. 6 as ϕ_Q and ϕ_V, while in the latter they appear in Eq. 28 as κ_Q and κ_V. For the illustration in Fig. 2, we have chosen the simplest normalization and aligned the polarization axis of the antenna with the magnetic field, corresponding to $\eta = 0$ in the notation of Larsson et al., which corresponds to $\chi = 0$ in the notation of the other two manuscripts. As evident from all three references, the full physics of the polarized Zeeman effect is considerably more complex than illustrated in Fig. 2. However, we consider this simplification appropriate for supporting the interpretation of the main findings presented in Fig. 7. Also, the centers of the circles representing circular polarization, which correspond to the $\sigma_\pm$ components, should not coincide with the center of the polar coordinate system. This can be understood most easily by considering that the intensity of circularly polarized radiation propagating perpendicular to the field lines should be zero (Fig. B1).

- *Maybe, unlike Figure 3, it would be better to clearly indicate the specific Stokes parameters TQ, TU or TV on the vertical axes of the plots in Figure 7; the given general designation Tb here is misleading.*

  The figure axes have been revised according to the suggestion.

- *In Section 3.3 need to mention what parameters are used in the manuscript from GOES-19.*

  A description of the parameters has been added accordingly.

- *The sketch showing the locations of the microwave radiometer, magnetic field line, LOS, and geographical coordinates to visualize the geometry of the experiment will be useful, at least in the attachment, for better explaining the text at L321-325. Where is an area (bulk) of the atmosphere (geographically/geomagnetically) from which the radiometer receives radiation to retrieve magnetic field parameters under different azimuths?*

  A sketch according to the suggestion has been added to the Appendix.

Specific comments and technical corrections:

- *Lines 53-54. In equations (3) and (4) probably it is better to use standard designations for the real and imaginary parts of complex numbers (Re(χ), Im(χ)), for example, as it is done in the paper referred* *to by the authors - Randa et al. (2008).*

The notation has been revised accordingly.

- *L154. Explain abbreviation AVK*

The abbreviation definition has been added. We thank the reviewer for bringing this to our attention.

- *L184. What is accuracy of temperature stabilization and how it influences on magnetic field measurements error?*

Both the front end and back end of the instrument are thermally stabilized using temperature-controlled ventilation and a heater. In addition, the receiver itself is stabilized using a Peltier cooler. The daily temperature drift is between 0.3-2 K outside the Peltier-cooled environment and below 30 mK inside the receiver enclosure. The noise level is below 10 mK for measurements at 3-second intervals. This temperature drift is compensated during the calibration and is therefore not expected to affect the measurements. The corresponding change in the calibration uncertainty can be estimated by applying the radiometer equation and Gaussian error propagation. A drift of the calibration target temperature by 2 K results in a change in the brightness temperature uncertainty of approximately 2 mK. (Fig. 1).

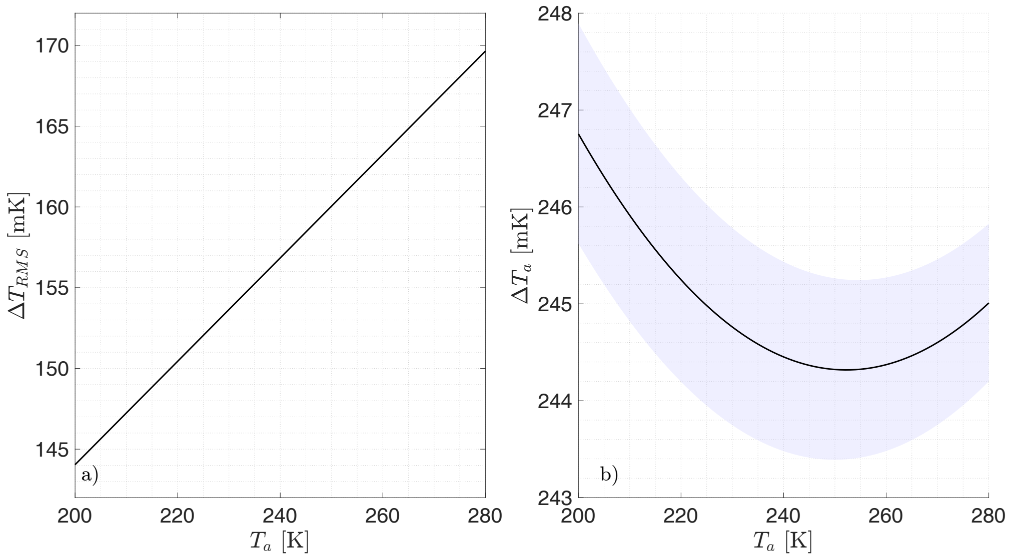

Figure 1: a) Radiometric resolution T_{RMS} calculated according to the radiometer equation. b) Calibration uncertainty ΔT_a derived using Gaussian error propagation. The variation resulting from a drift of the calibration target temperature by 2 K is indicated by the gray area. The parameters used are: calibration target temperature $T_{\text{hot}} = 293$ K, noise diode temperature $T_{\text{nd}} = 800$ K, instrument noise temperature $T_{\text{N}} = 250$ K, bandwidth 24.4 kHz, and scene integration time 400 s.

- *L264. In the text it would be useful to describe the components of the magnetic field here the magnetic field vector H = (Hu, Hv, Hw) which if it corrects is in Cartesian components Hu - zonal or east-west direction, Hv the meridional or north–south direction and Hw - vertical direction, pointing upward or downward (?)*

We have revised the Theory section and added two subsections, "Coordinate System" and "Orientation of the Polarization Plane", which provide a better-structured overview. A detailed definition of the coordinate system used for the magnetic field components has been added in the subsection "Coordinate System".

- *Figure 9e. It's useful to draw a zero-horizontal line on this figure to show where and when the transition dHw from negative to positive values occurs. This is useful for comparison with the data in figure 9a.*

  A zero reference line has been added to the figure.

Comments to Editor:

- *It would be useful if, as is now common practice in scientific publications, the authors made the Python code (on GitHub?) for the magnetic field calculations they perform in the manuscript for the proposed method available. Especially since the calculation procedure itself is very complex and cumbersome, and providing the code would allow the community not only to verify the accuracy of the calculations but also to improve them.*

  We will provide a Python script implementing the synthetic retrievals described in this manuscript. The optimization of the retrieval parameters, however, depends on the specific instrument configuration and measurement environment and must therefore be adapted to the individual application.

References

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