

Operational calibration of a ground-based fully polarimetric radiometer for stratospheric temperature retrievals

W. Krochin, A. Murk, A. Luder, and G. Stober

Second Response to Reviewer 2

We thank the reviewer for the comprehensive review. Due to the rearrangement and separation of sections, the section numbering differs between the first and second revised manuscripts. In this document, we will refer to the section numbers from the first revised manuscript unless otherwise stated.

Comments:

- *"To denote the measurements of concern, "operational" was questioned. The authors seem to use this term to mean field observations. This deviates from the general meaning inside the research area (as summarized by Google Gemini): "In the context of atmospheric science and meteorology, operational measurements refer to the routine, systematic, and continuous observation of the atmosphere to support real-time decision-making, such as weather forecasting, aviation safety, and public warnings." In contrast to this, the manuscript describes the measurements performed as being from a "test campaign" with a "breadboard setup".*

The manuscript presents our calibration strategy for the operational TEMPERA-C instrument, which is now deployed at the Zimmerwald observatory and performs continuous soundings. The temperature data is used for validation purposes of meteorological reanalyses such as NAVGEM-HA, MERRA2, MERRA3, JAWARA and SE-WACCM-X(SD). The breadboard setup was used to test the in-field calibration of TEMPERA-C as it is currently implemented in daily operations. The laboratory setup with the wire grid provided certain calibration coefficients that are also used for routine operation. We clarified throughout the manuscript that the instrument is meanwhile deployed and takes routine data (Fig. 1). Therefore, we would retain the term "operational calibration."



Figure 1: The TEMPERA-C is currently set up at the Zimmerwald Observatory, where it is conducting routine measurements.

- *There is a similar consideration regarding whether the radiometer should be termed "fully polarimetric". I now understand that the instrument can be considered fully polarimetric in a lab setting, but for us readers, the phrase still gives the impression that the observations yield all four Stokes components (in a manner related to an atmospheric coordinate system). In fact, text in the Introduction points in the same direction, that it is the outcome of the final observations that matters: "However, passive observations of all four Stokes components simultaneously have not yet been reported in the millimeter-wave range."*

The instrument presented in the manuscript yields all four Stokes parameters, regardless of whether it's under laboratory, on-site, or other conditions. We have carefully considered our terminology and concluded that the terms "fully polarimetric radiometer" and "fully polarimetric calibration" in our manuscript align with standard definitions. We refer to the definitions commonly used in Microwave radiometry as presented in:

- J. Randa, J. Lahtinen, A. Camps, A. Gasiewski, M. Hallikainen, D. Leine, M. Martin-Neira, J. Piepmeier, P. Rosenkranz, C. Ruf, J. Shiue, N. Skou, *Recommended Terminology For Microwave Radiometry*, Technical Note (NIST TN), National Institute of Standards and Technology, Gaithersburg, MD, 2008, https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=33079

The term "fully polarimetric radiometer" is defined as follows:

- **Fully polarimetric radiometer:** *A radiometer capable of directly or indirectly measuring all four Stokes parameters / modified Stokes parameters.*

According to this definition, the instrument described in our manuscript is fully polarimetric by design because for one RF setting (one emission line center), it produces four outputs (Eq. 12 in our manuscript) corresponding to the four modified Stokes parameters. It is important to note that the definition of Stokes parameters and modified Stokes parameters in our manuscript are equivalent to the definitions in Randa et al. (2008). The digital correlation procedure is described in Sec. 4 "Instrument Description":

- *"The integrator on the FPGA accumulates the total power of each linear polarization, as well as the real and imaginary parts of the cross-correlated signals."*

We will provide further clarification on the following points:

1. The "total power of each linear polarization" corresponds to $\langle |E_v|^2 \rangle$ and $\langle |E_h|^2 \rangle$, which, according to Eq. (9) in our manuscript, relates to the first two Stokes parameters.
2. The "real and imaginary parts of the cross-correlated signals" corresponds to $\Re \langle E_v E_h^* \rangle$ and $\Im \langle E_v E_h^* \rangle$, which relate to the third and fourth Stokes parameters.

To avoid future confusion, we have revised this phrasing to:

- *The integrator on the FPGA accumulates the total power of each linear polarization ($\langle |E_v|^2 \rangle, \langle |E_h|^2 \rangle$), as well as the real and imaginary parts of the cross-correlated signals ($\Re \langle E_v E_h^* \rangle, \Im \langle E_v E_h^* \rangle$).*

Another term defined in Randa et al. (2008) is:

- **Fully polarimetric calibration:** *the determination of the offset and gain matrix elements of a fully polarimetric radiometer. See also: response of a fully polarimetric radiometer, tri-polarimetric calibration.*

The definitions of the "offset" and "gain matrix elements," as well as the "response of a fully polarimetric radiometer" in our manuscript, are also consistent with the recommended terminology (Eq. 12 in our manuscript). The calibration method we present estimates all gain matrix elements (Eq. 25,

34-37, 40-41, 51-52) and the offset vector (Eq. 41); therefore, it can accurately be called "fully polarimetric calibration." All four Stokes parameters were measured continuously on the campaign site and are illustrated twice. Once in the representation of the modified Stokes Vector (T_v, T_h, T_3, T_4) in Fig. 12, and once in the classic representation of the Stokes vector (T_I, T_Q, T_U, T_V) in Fig. B1. Regarding potential issues that could have led to confusion, we can only speculate on the following:

– **The definition of the polarization plane is not relative to an atmospheric coordinate system:**

In the context of instrument calibration, it is standard to define horizontal and vertical polarization relative to the antenna plane (i.e., relative to the OMT) and then rotate the polarization plane after the calibration to any reference coordinate system of choice. Additionally, the definitions of Stokes parameters and the term "fully polarimetric" do not depend on a specific coordinate system. What matters is that the polarization axes are perpendicular, which they are by the design of the OMT. It is also important to note that this is not a technical incapability, as the rotation by the optics is a known quantity. We mentioned in Sec. 6.1 that, in our analysis, rotating the polarization plane is unnecessary since we focus on circular polarization, which is independent of the orientation of the polarization plane.

– **Some elements of the gain matrix g were measured in the laboratory:**

We estimated the crosstalk and phase offset parameters in a laboratory setup, which is a standard procedure in the context of polarimetric calibration, as these parameters are typically not measurable during operation. For example, in the publication by Lahtinen et al. (2003), fully polarimetric calibration was also performed through a combination of laboratory and field measurements. Typically, the radiometer is calibrated before and after a flight, with the calibration cycle lasting between 2 to 3 hours. In our case, we estimated the crosstalk parameters c_a, c_b , which are relatively constant characteristics of the OMT, before the campaign in the laboratory and use these measurements during the campaign. Gain parameters, which are highly variable, are measured frequently on-site. It was noted in the discussion that no significant drift of the crosstalk parameters was observed.

– **The measurement spectrum is used to estimate the phase offset $\Delta\phi$:**

In our calibration method, characteristics of the measurement are used to calibrate the instrument's phase offset. This approach has strong justifications for its validity. Firstly, the phase offset $\Delta\phi$ was measured additionally in the laboratory (Eq. 47,48). A comparison between the laboratory and on-site measurement of $\Delta\phi$ demonstrated the equivalence of the results within the uncertainty limits (Sec. 6.6). Secondly, we use a given physical property (symmetry), which is a constant characteristic of the emitted line being observed. It is correct that this method applies only to emission spectra that display similar symmetry properties in the third and fourth Stokes parameters. However, since the phase offset can still be accurately estimated in the laboratory and every component of the instrument has been specifically designed for the relevant frequency band, this presents no additional limitations to performance.

– **A constant bias was found between T_v and T_h :**

The reported bias falls within the measurement uncertainty

- *That is, by using the terms "operational" and "fully polarimetric" as done, an incorrect impression of the extent and use of the measurements is created. It is an unnecessary exaggeration; the actual achievements are sufficient to merit a publication. It is better to save these wordings for later publications. Accordingly, there is a strong suggestion to change the title and revise wordings in the text. For further clarity in the title, it is also suggested to change "radiometer" to "ground-based radiometer".*

The term "radiometer" has been replaced with "ground-based radiometer".

- *The abstract was not raised in the initial review, but it is now noted that the abstract is not very specific. At least some conclusions and/or quantitative results should be added to, e.g., clarify the "the advantages of the fully polarimetric approach".*

We have added quantitative results in the abstract.

- *The introduction is still far from arranged in a logical order. For example, it starts by listing some applications, switches to define fully polarimetric, makes some special notes about circular polarization (which are not relevant at this point), and then goes back to an application (ocean wind vector). The same paragraph also reviews polarimetric measurements of microwave oxygen transitions. That is, the first paragraph covers three-four subjects. This information needs to be organized more clearly.*

We appreciate your attention to this matter. We have completely reorganized the introduction and integrated Section 2 into it. The new structure of the introduction now includes:

1. Temperature retrievals in the oxygen band
 2. Overview of the Zeeman effect in atmospheric oxygen
 3. Role of polarimetric measurements
 4. Overview of polarimetric measurements in microwave radiometry
 5. Summary of the content in this manuscript
 6. Section outline
- *In addition, the scope of the text must be clear. For example, the extent of the review of polarized measurements is not clearly stated, but it can be taken as a complete review of older fully polarimetric measurements. This should be far from the case. Two examples from a very quick (incomplete) search:*
 1. Lahtinen, J., Pihlflyckt, J., Mononen, I., Tauriainen, S. J., Kemppinen, M., and Hallikainen, M. T. (2003). Fully polarimetric microwave radiometer for remote sensing. *IEEE Transactions on Geoscience and Remote Sensing*, 41(8), 1869-1878.
 2. Xie, X., Löhnert, U., Kneifel, S., and Crewell, S. (2012). Snow particle orientation observed by ground-based microwave radiometry. *Journal of Geophysical Research: Atmospheres*, 117(D2).

We followed standard citation practices by referencing prior work that is relevant or influential to our manuscript. We cited an example of wind vector measurements, as this was the closest application to ours. It was not our intention to provide a comprehensive review of polarized measurements, which would be outside the scope of this manuscript. We agree to include additional examples of wind vector measurements as suggested, specifically the work by Lahtinen et al. (2003). However, we chose not to reference the work by Xie et al. (2012), which reports measurements of snow particles with a dual-polarized radiometer (two channels at 150 GHz and one at 90 GHz), as we found no relevance to polarimetric observations, calibration, the Zeeman effect, high spectral resolution observations, the oxygen band at 60 GHz, atmospheric temperature retrievals, or stratospheric signals.

- *Section 2, first, it is just a review (it does not present any theory; it merely refers to other articles) and could be incorporated into the Introduction (see also the next comment). The title of the section is "Zeeman effect in atmospheric oxygen". This title hints at a focus on theoretical work, but it is rather about observations.*

Section 2 has been included in the introduction.

- *Anyhow, the text should use a broader choice of references. The work around both MLSs is lacking, as is the one by Juan Ramon Pardo. To be clear, single-polarization measurements are relevant because they must account for the Zeeman effect and its associated polarization effects.*

The suggested references have been added to the introduction, although we initially had concerns about including them. The Microwave Limb Sounder (MLS) on the Upper Atmosphere Research Satellite

(UARS) operated around 63 GHz and also considered the Zeeman effect for temperature retrievals. However, with 15 channels that have a spectral bandwidth of 500 MHz, the Zeeman splitting could not be resolved. In addition, the Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura satellite has already been cited in our revised manuscript. The work from Pardo et al. (1995) reported measurements from the isotopologue $^{18}\text{O}^{16}\text{O}$ at 233.95 GHz with a single polarized instrument. We considered this work of relatively low relevance to our application since it involves a different isotopologue at a different frequency. Therefore, we have decided not to cite this reference in our manuscript. However, the discussion regarding the capability of fine structure lines for stratospheric retrievals (Pardo et al. 1998), has been included in the introduction.

- *As indicated in the comments above on Sec. 2, there is a tendency to create full sections on relatively narrow issues. As a result, there are eleven sections. The material should be organized in a more standard fashion, which would help the reader know whether a section presents, for example, theory, methodology, or results.*

We have reorganized the section structure to provide a more standard fashion organization, reducing the total number of sections to 8. The new sections are as follows:

1. Introduction
 2. Stokes Formalism
 3. Instrumentation
 4. Calibration
 5. Simulations
 6. Results
 7. Discussion
 8. Conclusion
- *Figure 2/4: An incorrect order of figures was pointed out, and the response says that it would be corrected. Changes have been made, but in the wrong way. The figure cited at the start of Sec 4 is called Fig. 2. This is the correct numbering, but the figure of concern is in fact Fig. 4. It is also noted that the figure caption is incorrect. The figure covers both the front- and back-end, not just the front- end as stated. (To clarify a comment in the introductory paragraph: It is fully reasonable to expect that both these problems should have been identified by any of the co-authors.)*

Thank you for bringing this to our attention. The figure label and caption have been corrected.

Changes made during revision

Major Changes:

- The title has been revised from: "*Operational calibration of a fully polarimetric radiometer for stratospheric temperature retrievals*", to: "*Operational calibration of a ground-based fully polarimetric radiometer for stratospheric temperature retrievals*"
- The introduction has been restructured, and Sec.2 has been integrated into it.
- The section separation has been rearranged, reducing the number of sections from 11 to 8.

Minor Changes:

- The order of the figures has been changed to correctly cite Fig. 2 in the second position. In the figure caption, the term "*front-end*" has been changed to "*front- and back-end*"
- Additional references have been added.
- The term "altitude resolution" has been replaced with "vertical resolution".