

This manuscript introduces a new microwave forward model implemented in Python, PyRTlib. The tool has a relatively narrow scope compared to some existing radiative transfer programs and is brought forward as an educational tool. On the other hand, it has some unique features that are of scientific interest.

As a start, I would suggest putting less emphasis on “educational” (is an educational tool even inside the scope of GMD?). If having education as the main aim, it should be shown that the tool has pedagogical advantages, i.e. how it facilitates learning compared to what can be achieved with other software. As far as I can see, educational is here more or less equal to the second aim of being user-friendly (page 7).

There are two possible target audiences: the students and younger scientists, the “newbies” expected to be the users of PyRTlib, or the teachers and advisers of those users (and there could even be old scientists that master Python and would use PyRTlib in their work!). The manuscript in its present form seems to have both audiences in mind but is not meeting the full expectations of any of them. It could be possible to handle both audiences in parallel, but it is probably best to target one of them. The most reasonable choice seems to prioritise teachers, advisers and scientific use. Targeting newbies would likely result in a too low scientific level for a journal article, and they will primarily look for information in the user guide. However, I fully understand that it is not possible, or even preferred, to have a strict separation between “science” and documentation. Here, a pragmatic approach must be allowed. To be useful, the journal article must contain aspects of documentation, but it should be on a relatively high level, such as the general principles of the software’s design.

We thank the reviewer for raising these thoughts. We agree that with “educational” we meant to highlight PyRTlib is "user-friendly" and thus it can be used by students and teacher/advisers with a relatively modest learning curve. We use “educational” also to indicate that several examples are provided with documentation to get the user quickly started. This is not unique of PyRTlib, as it is also true for some of the other available RT codes, though not all. In any case, the purpose of PyRTlib is not to compete with other available RT codes, but to provide a user-friendly alternative with somewhat different, although much narrower, features, i.e.: Python native, quick get started, online absorption model comparison, and spectroscopic uncertainty enabled. The intent is to reach and guide new users (either students or teacher/advisers) to engage with RT modeling, not excluding the scientific community that is active in developing atmospheric microwave absorption models.

The choice of units is an example of general principles. The only way to determine the chosen units is if the example codes clarify them. Please add a table or explain if they are found in the user guide. If the units are selected according to some guidelines (using the ones typically found in atmospheric models?), that would be helpful to know. Further, is there a strategy when importing data? Are the units kept from the original data source or converted to standard units? Taking the function IGRAUpperAir as an example, where do I find out what variables it returns and their unit? The example codes show that the user must employ unit conversions. This is error-prone, and I question whether this aligns with a user-friendly tool.

We thank the reviewer for pointing this out. Indeed, units are a very important aspect for the example codes. Although we had defined the units within the source code, we missed to report into the documentation of the module that retrieves public datasets. Units are kept the same as in the original datasets, although conversion is applied to use the dataset as input and to perform the model in the main function. The units needed of input parameters are shown in the function documentation (https://satclap.github.io/pyrtlib/en/main/generated/pyrtlib.tb_spectrum.TbCloudRTE.__init__.html).

For the public datasets available within PyRTlib (IGRA2, Wyoming, ERA5), the units have been added to the documentation, e.g:

Wyoming:

https://satclon.github.io/pyrtlib/en/main/generated/pyrtlib.apiwebservices.WyomingUpperAir.request_data.html

IGRA2:

https://satclon.github.io/pyrtlib/en/main/generated/pyrtlib.apiwebservices.IGRAUpperAir.request_data.html

ERA5:

https://satclon.github.io/pyrtlib/en/main/generated/pyrtlib.apiwebservices.ERA5Reanalysis.read_data.html

It would be helpful to explain the organisation of the documentation. Where do I look for different types of documentation? The existence of a user guide should be mentioned in the introduction and referred to in the text.

Section 6 “Code and data availability” introduces source code and available documentation. Links to the documentation and to the versioning of source code from GitHub repository are indicated. Currently, documentation is available only for the latest PyRTlib version, but a developer and a version tag documentation are planned for the next release of PyRTlib.

Another missing piece of information is how altitude and observation angle are specified. Please note that it needed to specify an altitude for satellite observations if Eq. 7 is applied. It is the radius of the instrument that sets the constant.

Agreed. We modified the text in Section 2.3 as follows:

“This approximation only requires the elevation angle θ and the profile of the atmospheric thermodynamical status (pressure, temperature, relative humidity, cloud water content) as function of altitude over the Earth surface (h), and it is the default option in PyRTlib. A one-dimension spherical atmosphere can also be considered, which assumes the atmosphere as uniform concentric layers around a smooth spherical Earth. Following Schroeder and Westwater (1991), the ray path for a spherically stratified atmosphere is modelled through the Snell's law for polar coordinates:

$$n r \cos\theta = \text{constant} \quad (9)$$

where n is the atmospheric refractive index and r is the radial distance from the center of the Earth to a point on the ray path. All these qualities depend only on height above the surface. The radiance distance r is assumed as the Earth geoid radius (R_E) plus the altitude over the Earth surface. Note that the constant in Eq. (9) must be set in one point of the ray path. This is currently set at the lowest available atmospheric level, which imposes the limitation that PyRTlib version 1.0 cannot simulate limb sounding observations.”

I suggest using some tables for better clarity. It is mentioned that “intermediate RT variables” can be accessed, but the exact set is unclear. This information would be suitable for a table, then including units of these variables. A table would also help get a quick overview of the absorption models. Here, I recommend including the reference matching the implementation to avoid confusion.

We thank the reviewer for this suggestion. We added tables in Section 4 to summarize output and all the intermediate variables as follows:

Table 4.1: Output variables from PyRTlib.

Variable	Description	Units
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tbtotal	brightness temperature includes cosmic background	K
tbatm	atmospheric brightness temperature, no cosmic	K
tmr	mean radiating temperature of the atmosphere	K
tmrcld	mean radiating temperature of the lowest cloud layer	K
taudry	dry air absorption integrated over each ray path	Np
tauwet	water vapor absorption integrated over each ray path	Np
tauliq	cloud liquid absorption integrated over each ray path	Np
tauce	cloud ice absorption integrated over each ray path	Np

Table 4.2: List of all the intermediate variables accessible from PyRTlib.

Variable	Description	Units
taulaydry	dry air absorption integrated over each ray path	Np
taulaywet	water vapor absorption integrated over each ray path	Np
taulayliq	cloud liquid absorption integrated over each ray path	Np
taulayice	cloud ice absorption integrated over each ray path	Np
srho	water vapor density integrated along each ray path	cm
swet	wet refractivity integrated along each ray path	cm
sdry	dry refractivity integrated along each ray path	cm
sliq	cloud ice density integrated along each ray	cm
sice	cloud liquid density integrated along each ray	cm

Also, the PyRTlib documentation, introduced in Section 6, provides info on all the intermediate output variables at the following link:

https://satclp.github.io/pyrtlib/en/main/generated/pyrtlib.tb_spectrum.TbCloudRTE.execute.html

The results in Figure 7 give confidence in PyRTlib, at least for the two absorption models used. Has there been any comparison between PyRTlib and other forward models? Or internally, comparing the different absorption models? This provides no validation against reality but is the fastest way to detect possible bugs.

It's true that Figure 7 gives confidence in PyRTlib, although the purpose was to show that PyRTlib can be used to monitor MWR observations and to evaluate different absorption models. Several tests have been performed before releasing the software using the available absorption models in PyRTlib. Most of the tests were performed against the original code from NOAA (in Fortran) and later translations (in Matlab). One test was also performed against the results from ARTS using the same absorption model (Rosenkranz, 2021), as shown in the following figure (courtesy of Stuart Fox, extracted from final report of EUMETSAT ISMAR study). The absorption differences between the two implementations are quite small (less than 0.05%) and are attributed to different assumptions in the radiative transfer regarding the variation of absorption coefficient across an atmospheric layer.

We added the following text to Section 4.3: “Atmospheric absorption spectra from PyRTlib were compared with the equivalent computed from ARTS using the same absorption model, resulting in differences within 0.05% (Fox et al., 2023), which are attributed to different assumptions in the variation of absorption coefficient across an atmospheric layer.”

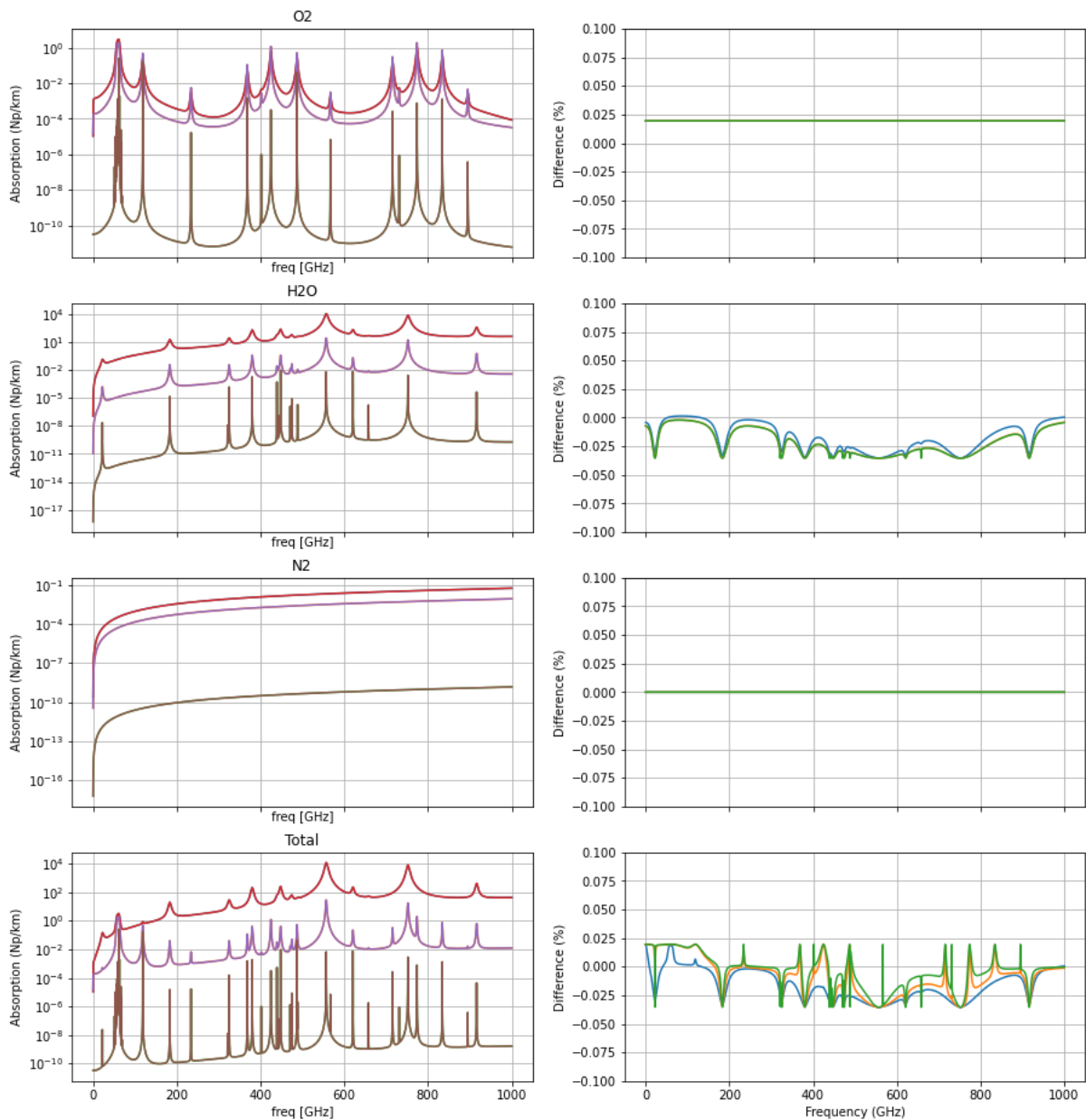


Figure 49 (from final report of EUMETSAT ISMAR study): Comparison of absorption coefficients at 3 atmospheric levels from ARTS and CNR using PWR21 spectroscopy. The left-hand column shows the absorption coefficients for each species, and the right-hand column shows the percentage difference between the ARTS and CNR values.

Section 5 outlines extensions. This brings up the issue of the software version. The manuscript must be linked to a specific version. This likely requires a plan to “versionify” the software and document changes between each version.

Correct, we missed version number in Section 5, although it was reported in introduction (Line 200). Thanks for spotting it, we modified the text as follows:

“This paper presents PyRTlib version 1.0, a Python library...”

As mentioned above, PyRTlib source code is stored on a GitHub repository, a version control system tool that keeps track of all the code changes. Furthermore, the PyRTlib repository applies several actions every time the code is modified to test the quality of the code and the installation process and to ensure that PyRTlib is working properly.

Exploring the modelling uncertainty is novel and highly useful and should be better covered by the manuscript.

Agreed. The following information, as well as additional text to better cover the uncertainty modelling, was added to the revised manuscript, referring to the original papers for further details.

Some open questions here:

- Is there an uncertainty estimate for exactly all parameters affecting absorption cross-sections? If not, what parameters are covered?

The absorption model uncertainty is based on Cimini et al, 2018 (<https://doi.org/10.5194/acp-18-15231-2018>), where a sensitivity test to parameter uncertainty was performed to identify a reduced set of dominant contributions. This led to a reduced set of 111 parameters.

- Is it possible to extract these uncertainties and their covariance?

Yes, the 111x111 uncertainty covariance matrix from Cimini et al, 2018 is accessible through the PyRTlib code (as well as supplement files of the original paper: <https://doi.org/10.5194/acp-18-15231-2018>).

- How are the parameter uncertainties mapped to Tb uncertainty? Just perturbations or a more advanced approach? Can the full covariance matrix of Tb uncertainty (the information required for OEM retrievals) be obtained?

Yes, the full covariance matrix of Tb uncertainty is provided in output (e.g., Figure 9 of Cimini et al. 2018). This is obtained by propagating the 111x111 uncertainty covariance matrix through the RT Jacobians (computed by brute force).

I have not tried to install and run PyRTlib. Neither have I cared about minor language issues in detail.

Various comments:

- Why is radiative transfer written with capital R and T in the title? Even if alluding to PyRTlib, this causes more confusion than help.

Agreed. We used capital letters to recall those in PyRTlib name, but we concur it could be confusing. Capital letters have been changed to lowercase.

- The review of forward models is nice but makes the Introduction long. Place in an appendix?

We see the point, but prefer to leave the review of forward models in the introduction to introduce all the features that PyRTlib provides and does not provide. Hope this is OK.

- Line 152: AMSUTRAN is only used for the microwave region, not all fast parameterisations.

Correct. Thanks for spotting this out. We change the text as follows (underlined text is newly added/changed):

“The core of RTTOV is a fast parameterisation of layer optical depths due to gas and liquid water absorption. Profiles of layer-to-space transmittances computed by the line-by-line code AMSUTRAN (Turner et al., 2019) are the basis for the training of the fast parameterisation in the microwave region.”

- Line 156: Geer et al (2017) not the best reference here; better is gmd.copernicus.org/articles/14/7497/2021/gmd-14-7497-2021.html

Thanks for this suggestion. Citation has been modified accordingly.

- Line 194: Not all observation geometries are handled by a plane-parallel model; limb sounding can not be represented.

Correct. We added the following to the end of Line 194 (underlined text is newly added/changed):

“(zenith, nadir, slant), except for limb sounding geometry (not currently implemented in PyRTlib).”

- Line 231: As Eq 2 is written, s is the distance from the observation point, not the propagation distance.

Agreed. Text modified as to: “s indicates the distance from the observations point along the line-of-sight”

- Eq 4: Not correct to use = here. Consider this also for Eq 5.

Agreed. Eq. 4 has been modified accordingly. For Eq. 5 we added:

$$B_f(T_{MR}) = \frac{\int_a^b B_f(T(s)) \alpha_f(s) e^{-\tau_f(0,s)} ds}{e^{-\tau_f(0,a)} [1 - e^{-\tau_f(a,b)}]}$$

- Line 268: The value 99% is irrelevant (with this thinking, nitrogen should be the dominating absorber).

Of course, gas concentration itself does not explain its absorption. In fact, we also specify that “account for most of the gas absorption in the MW spectrum.” So, we prefer to keep it unchanged to make it clear that no relevant gas (in terms of concentration and absorption) is neglected.

- Line 291: It is not very clear what has actually been implemented.

Three models for liquid water absorption are implemented and can be chosen alternatively by the user: one is from Liebe et al. (1993), which updates earlier versions (Liebe et al. 1991), and the other from Rosenkranz (2015). We clarified this in the revised manuscript as described in the next answer below.

- Lines 291-292: Why is this model optional? This implies that the other models are mandatory. Is this model just applied at freezing temperatures?

The model from Rosenkranz (2015) is optional in the sense that it can be chosen alternatively to the default one (Liebe et al. 1993). It is applied to any temperature as it was developed to be

applicable up to 60°C, but specifically recommended for low temperatures. We rephrased the manuscript as follows for the sake of clarity:

“Another model, as in Rosenkranz (2015), is also implemented for the liquid cloud absorption. This model was developed to be applicable up to 60°C, but it is specifically recommended for temperatures as low as -25°C for modeling the absorption of supercooled liquid water particles. Therefore, currently three models for liquid cloud absorption are available within PyRTlib and can be alternatively selected by the user.”

- Eq. 7: Does including refraction for a plane-parallel model make sense? Is it not more important to include the Earth’s curvature than refraction? Is including Eq. 7 actually an improvement when applied in a plane-parallel model?

The plane-parallel approximation is the default option in PyRTlib. However, when the refraction is optionally activated, the ray path is modelled assuming a spherically stratified atmosphere (i.e., 1D atmosphere), as specified in the original manuscript (line 324), which does consider the Earth’s curvature. We added text to clarify this aspect in Section 2.3 of the revised manuscript.

- Eqs 8-12: Why this level of detail here? Sticks out compared to other parts. And refraction is of relatively minor concern for the model.

We concur Eqs. 8-12 are detailed. As mentioned in the acknowledgements, the development of PyRTlib was partially supported by ESA through a project focusing on atmospheric propagation. In this context, the definition of dry and wet refractivity terms may be ambiguous, and thus we prefer to state explicitly the equations implemented as default option.

- Sec 3.1: Are there any issues with quality and missing data when reading from the Wyoming archive?

For all public datasets available in PyRTlib, we added a simple quality check to control whether the profile is suitable to be used into the radiative transfer equation (e.g., monotonic pressure decrease). Currently this is handled by issuing a warning to the user, although we plan to improve the quality check and error handling in future releases.

- Around here, it becomes clear that the radiative transfer part takes RH as input. Is this a good choice? For freezing temperatures, RH can also be defined with respect to ice. There is a lack of agreement between parameterisations of RH with respect to liquid for freezing temperatures. A user can think that if she/he imports data in RH all is fine, but there is an uncertainty in the mapping from RH to absolute humidity due to two points raised above.

Correct. RH was chosen as the code was originally developed to process radiosonde data, which only provides RH. The user can choose whether to use RH defined with respect to ice or liquid at freezing temperatures through the “Tconvert” argument (see documentation <https://satclap.github.io/pyrtlib/en/main/generated/pyrtlib.utils.mr2rh.html>). Whether input, “Tconvert” is used as threshold temperature below which saturation water pressure is calculated over ice instead of liquid water.

- Example codes: One or two example codes are motivated to exemplify how the program is used in practice. The extra examples contribute relatively little (basic things such as the import of packages and plotting get repeated, taking unnecessary space). For the rest, refer to the user documentation.

We thank the reviewer for this comment. The repeated packages import has been removed and we also removed unnecessary code from listing examples, while maintaining the original objective of making the code reproducible and obtaining the same results reported in the figures.

- Line 556: “Nicely” is vague, and not really true (there are apparent deviations from the 1-1 line).

Agreed. We modified the sentence as follows: “Figure 7 shows that RT simulations with both absorption models tend to align with observed TB over the whole range of variations for all MWRP channels,…”

- Fig. 7: PyRTlib does not apply any bandpass. Can this not be relevant for this comparison?

Correct, PyRTlib does not apply bandpass. This is on our list for future improvements. Although monochromatic vs band-averaged simulations may differ appreciably, especially along the sharp wing of the O₂ complex, we believe bandpass is not the cause of the features in Figure 7. Indeed, similar differences were already noted between bandpass simulations with Rosenkranz 1998 and ground-based MWR observations at 51-54 GHz from independent instruments in different environments (De Angelis et al, 2017; <https://doi.org/10.5194/amt-10-3947-2017>). This is briefly discussed at lines 556-563 of the original manuscript (now at lines 752-759).

The manuscript is relevant for GMD but requires revision before publication. The text needs better to introduce the actual forward model and its documentation. On the other hand, the background and overall motivation for developing PyRTlib could be shortened (not to extend the length of the manuscript). Some of my comments question design choices. Take these comments as input for discussion and reflection, and not as a demand for making changes to the code at this point.

All the comments were well received, and we believe they improved the manuscript overall. We thank the reviewer for the useful tips and the valuable time dedicated to it.