Monitoring of Middle Atmospheric Water Vapour

Alistair Bell and Axel Murk

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Institute of Applied Physics

Microwave Physics Division

Sidlerstr. 5
CH-3012 Bern
Switzerland

Tel. : +41 31 634 89 11
Web : www.iap.unibe.ch
E-mail : iapemail@iap.unibe.ch

1 Summary

The Institute of Applied Physics (IAP) at the University of Bern has operated its 22 GHz microwave radiometer MIAWARA[1] for remote sensing of water vapor in the middle atmosphere since April 2002 (Deuber et al., 2004). In 2006 it was installed at the Zimmerwald Observatory near Bern and has since provided long-term observations of this essential climate variable in the stratosphere and lower mesosphere in the altitude range of approximately 20–70 km. The data is provided to the international Network for the Detection of Atmospheric Composition Change (NDACC) since its first year of observation. However, the data submission to NDACC had to be paused in 2021 due to hardware and software problems of the instrument.

The main objectives of this GCOS project were to maintain the continuity of the water vapour observations and to improve the quality of the results. This required the replacement of a failed low-noise amplifier and other consumable parts such as the microwave absorbers which are used for the calibration of the instrument. Another significant hardware upgrade concerned the digital FFT spectrometer in the back-end of the instrument. The old AC-240 spectrometer has reached the end of its life cycle and is no longer supported by the manufacturer. A recent study at the IAP also showed that its results are systematically biased compared to more recent models (Sauvageat et al., 2021). For these reasons it was replaced with a more recent spectrometer based on the Universal Software Defined Radio receiver (USRP X310), which provides a higher frequency resolution and a better linearity. Currently the old and the new spectrometer are operated simultaneously at MIAWARA to facilitate the homogenisation of the time series. After several months of parallel observations and a statistical comparison of the two data sets the AC-240 will be decommissioned.

Also the data processing routines for the radiometric calibration of the raw data and the retrieval of the atmospheric data products had to be updated substantially. The initial routines were dependent on an outdated MySQL data base which is no longer maintained. For that reason the calibration routines have been successfully updated and merged into the new calibration framework of the University of Bern microwave radiometers. This framework was initially developed for the NDACC Ozone radiometers GROMOS and SOMORA operated by IAP and MeteoSwiss, respectively, and its extensive data quality control and outlier detection has improved the accuracy of the retrieved Ozone profiles and the consistency of the time series from the two instruments (Sauvageat et al., 2022). It has been expanded to include the balancing calibration of MIAWARA.

The retrieval routines have also been updated for the latest version of the Atmospheric Radiative Transfer Software (ARTS) and Qpack, a Matlab environment which allows the user to perform radiative transfer calculations and optimal estimation with ARTS (Buehler et al., 2018; Eriksson et al., 2005). These make use of the newly calibrated data and a new climatological a-priori dataset created from the European Centre for Medium Range Forecasts (ECMWF) analysis data. The new retrieval routines are now functioning and able to provide retrievals of water vapour with an acceptable measurement response at an altitude of 40 Pa to 3 Pa (30 km to 70 km).

A reprocessed dataset of retrieval results from 2015 until 2021 has been published at the Bern Open Repository and Information System (BORIS) data portal. A conference presentation and a publication with this dataset are currently in preparation, and once they have passed the peer review process also the time series in the NDACC database will be updated.

[1]MIddle Atmosphere WAter vapour RAdiometer (MIAWARA)

2 Introduction

Water vapour is the most important natural greenhouse gas and has a large impact on the radiative budget and the chemistry of the atmosphere. Upper tropospheric water vapour is particularly important due to its strong radiative forcing. Therefore, long-term measurements of water vapour at all vertical levels are essential to understand and quantify climate change. The abundance of water vapour in the middle atmosphere is of great importance due to its influence on ozone chemistry, and because of its links with atmospheric dynamics and the concentrations of methane, which is another important greenhouse gas.

The Institute of Applied Physics of the University of Bern developed the 22 GHz radiometer MIAWARA for the monitoring of middle atmospheric water vapour in 2001, and has operated it continuously since September 2006 at the Zimmerwald observatory near Bern. There is also an identical instrument at the Sookmyung Women's University in South Korea, which has been in operation since 2006 in Seoul. In 2008, MIAWARA-C, a more compact and sensitive campaign instrument was developed. This has been deployed in the Arctic at the Ny-Ålesund Research Station on Svalbard, after successful campaigns in Germany, La Réunion, the USA and Finland. The data from these operational instruments contributes to the international Network for the Detection of Atmospheric Composition Change (NDACC).

The aim of the current GCOS project is to ensure the continuity of the long-term time series of the middle atmospheric water vapour over Switzerland. This includes necessary maintenance and hardware upgrades of the aging MIAWARA instrument, as well as a major software upgrade of the calibration and retrieval framework to make it compatible with the current data processing pipelines. This will facilitate and improve the analysis and quality control of the operational observations, and it will allow making the data products accessible for interested parties.

The project contributes to the GCOS Switzerland Strategy Pillar 1, Priorities 1.5 and 1.6: "Data analysis and data archives", and Pillar 2, Priority 2.1: "National collaboration and synthesis".

3 Methods and Activities

3.1 Instrument Maintenance and Hardware Upgrades

For the radiometric calibration of the instrument we procured different types of microwave absorbers from several manufacturers and characterised them in the laboratory. The one with a pyramidal geometry outperformed the previously used convoluted model and has been installed on the instrument, as use for the ambient target and the reference target. In addition, new radome materials were investigated to improve the thermal stability and weather protection of these critical elements. In addition, a defective low-noise amplifier in the receiver front-end was replaced by a spare part from the campaign instrument MIAWARA-C to continue with the observations.

For the transition from the outdated AC-240 FFT spectrometer in MIAWARA to a more recent USRP X310 Software Defined Radio receiver, a new computer was procured and configured to allow parallel operation of the two back-ends. This is important for the comparison of the linearity of the spectrometers and for the homogenization of the time series. The new PC and USRP spectrometer were installed on MIAWARA in September 2022 and have been delivering data since then. One of the main reasons for the upgrade was that we noticed in simultaneous observations of the 110.836 GHz ozone line with three different FFT spectrometers a systematic bias the AC-240 (Murk and Kotiranta, 2019).

Figure 1: A sideways view of the old ambient target absorber (left) and the instrument during a liquid nitrogen calibration (right). The new reference and ambient absorbers can be seen at the top left of this photo.

A detailed analysis of these observations indicated that this error is not only caused by a simple non-linearity of the AC-240, but also by a spectral leakage which will cause a negative bias of the retrieved atmospheric trace gas profiles (Sauvageat et al., 2021). In order to investigate whether these results also apply to the much weaker 22.235 GHz emission line of H2O the simultaneous observations with MIAWARA were calibrated using either a total power or a balanced calibration technique.

The USRP has two frequency agile receivers with a bandwidth of 200 MHz each. This is five times less than the 1 GHz bandwidth of the old AC-240, but it is nevertheless sufficient to retrieve water vapor in the middle atmosphere. Currently the two USRP receivers are tuned to the same center frequency to compare the linearity of the different spectrometers. It is possible to configure one of the USRP receivers in a frequency hopping mode. This extends the effective bandwidth of the USRP to 1 GHz, as we have already demonstrated in our wind radiometers WIRA and WIRA-C (Hagen et al., 2020).

The last milestone of this work package includes a final calibration with LN2 and the issue of a maintenance manual for the future operation of MIAWARA. The liquid nitrogen calibration was performed in March 2023 (see figure 1) which allowed a calibration of the brightness temperature of the radiometer when pointing in the different positions (to the sky measurement angle, the angle used as a cold target for regular calibrations, and the reference target) as well as a calculation of the receiver noise temperature, which is an important consideration for the sensitivity of the instrument. These calibrated spectra allowed to compare the radiometric performance of the different FFT spectrometers and of the new reference absorbers. The maintenance manual has also been written and issued (Bell et al., 2023a).

3.2 Update of the MIAWARA Data Processing Pipeline

At the beginning of the project the original calibration routines of MIAWARA were no longer functional which was partly due to their reliance on outdated MySQL databases. This problem has been solved with a major upgrade of the calibration routines for both instruments. They are now integrated into the new framework used for the data processing of other University of Bern microwave radiometers. It was initially developed for the 142 GHz ozone monitoring instruments GROMOS in Bern and SOMORA at the MeteoSwiss observatory in Payerne (Sauvageat et al., 2022). Besides an improved data quality control and extensive set of additional metadata it does not include any dependencies on the old MySQL databases and allows an easier access and archiving of the data at all levels. Since the water vapour and ozone instruments use different calibration techniques, the original routines of GROMOS/SOMORA had to be expanded to make use of both a tipping curve calibration and a balancing calibration to convert the signals measured on the radiometers into brightness temperatures. In addition, a new quality control mechanism feature was included in the calibration routine which performs a routine check of the standing wave errors on the different observing positions.

Also the retrieval routines were updated substantially to use the newly calibrated data and to be consistent with the atmospheric retrieval framework for the University of Bern microwave radiometers. The new retrieval software uses the radiative transfer software ARTS together with the Matlab package Qpack (Eriksson et al., 2005) to perform an optimal estimation (Rodgers, 2000) of the water vapour concentration. In essence, the retrieval algorithm simulates the expected brightness temperatures observed at the frequency of the microwave radiometer from an initial atmospheric state (a priori) and compares the observed brightness temperatures to the simulated brightness temperatures. The a priori (in this case water vapour profile) is perturbed in successive iterations to find an optimal estimate of the atmospheric state given the measurement and the a priori state, and the expected errors of both of these. For the a priori a new dataset has been created using ECMWF reanalysis data between 2010 and 2015.

The retrieved profiles are sensitive to the random and systematic errors of the observations, as well as to the a priori state and error estimations. To some extent the systematic measurement errors can be corrected in the retrieval, but this will also reduce the vertical range of the retrieval and it can introduce an additional bias of the retrieved atmospheric state. In order to optimize the parameters of the new retrieval a series of sensitivity tests have been conducted.

The last milestone of this second work package consists of the final release of the retrieval pipeline and reprocessed data. The calibration and retrieval routines are operational and have been uploaded to the git server of the University. The reprocessed data of the years 2015-2021 has been published at the Bern Open Repository and Information System (BORIS) data portal of the University (Bell et al., 2023b). The raw data is archived on the long term data storage of the University and can be made available upon request.

4 Results

In order to verify that the new calibration routines give comparable results as the old ones we applied them to a data set from 2014-2017, a period for which calibrations had been still performed with the outdated routines and stored on MySQL. Figure 2 gives an example of the observed spectral line at 22.235 GHz after a balanced calibration with the old and the new routines. It shows the brightness temperature (Tb) integrated over one day and corrected for the variable mirror elevation angles and tropospheric opacities.

The good agreement between the old calibrated spectra and the ones obtained with the new routines indicate that they are both working to a similar standard and should result in a similar retrieval performance.

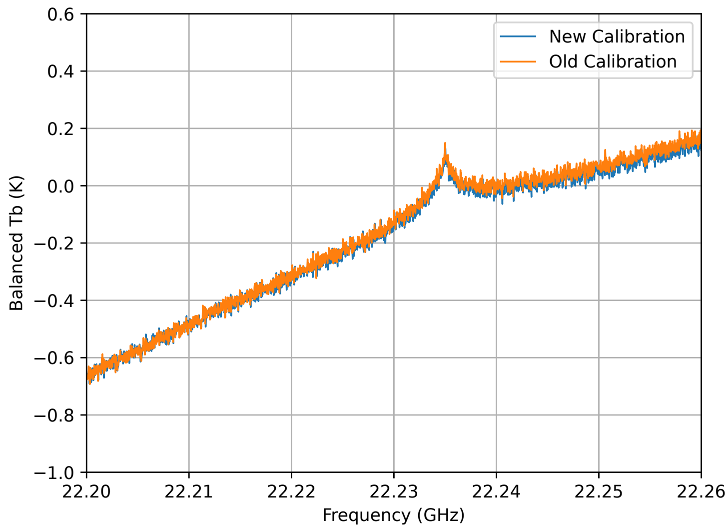


Figure 2: Example of the balanced brightness temperatures Tb from the MIAWARA recorded on 02/05/2014, calibrated with the new routine and as stored on the old MySQL database.

As highlighted in section 3, the installation of the new USRP spectrometer on MIAWARA and the simultaneous observations with the old AC-240 has allowed us to investigate the suspected bias between the two back-ends. Figure 3 shows the spectra of the old AC-240 and the two USRP receivers. The spectra were integrated for one day, and they are smoothed by binning 50 USRP channels and 10 AC-240 channels, giving the same frequency resolution for both spectrometers. This example was calibrated using a total power scheme where the atmospheric observations at a low elevation angle are calibrated against the ambient temperature absorber and a cold sky view close to zenith. This type of calibration is usually very sensitive to non-linearities, which are evident by the offset between the calibrated spectra in figure 3. More important for atmospheric retrievals are the systematic spectral baseline errors which are visible on the blue line of the AC-240 observation at an offset of ±25 MHz from the line center. These spectral artifacts can lead to significant errors on the retrieved atmospheric profiles, and it is obvious that they do no longer occur with the new USRP spectrometer. This test demonstrates the superior performance of the new USRP spectrometer, which can be explained by the higher resolution of its A/D converter and the improved implementation of the FFT without numerical truncation errors.

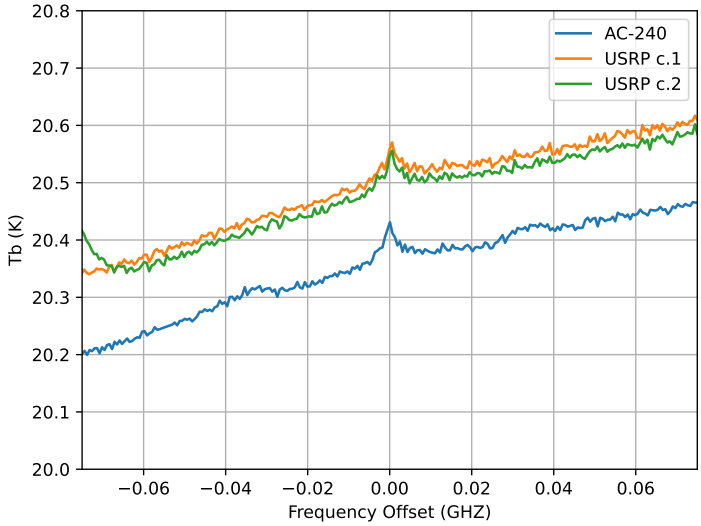


Figure 3: Comparison of spectra from the AC-240 and the two USRP channels after a total power calibration using the cold sky and the ambient temperature target.

In order to mitigate the non-linearity errors seen with the AC-240 and previous spectrometers, the routine observations with MIAWARA and all similar NDACC instruments make use of a balanced calibration. Figure 4 gives an example of simultaneous measurements of MIAWARA with the AC-240 and USRP spectrometers after a balanced calibration integrated for one day. Also in this case the AC-240 spectrum has a bias and a reduced line amplitude compared to the two USRP channels, which is consistent with the previous study with a 110 GHz ozone radiometer by Sauvageat et al. (2021). These findings are also relevant for all other microwave radiometers in NDACC which are using the AC-240 spectrometer.

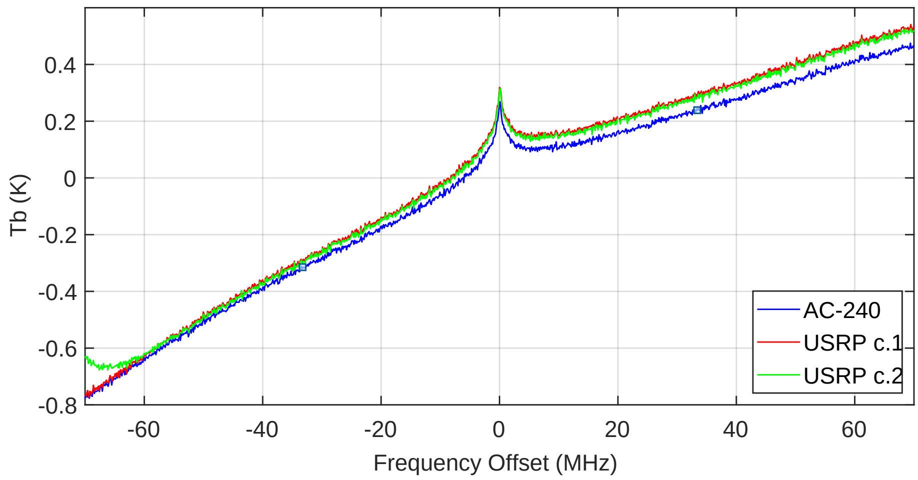
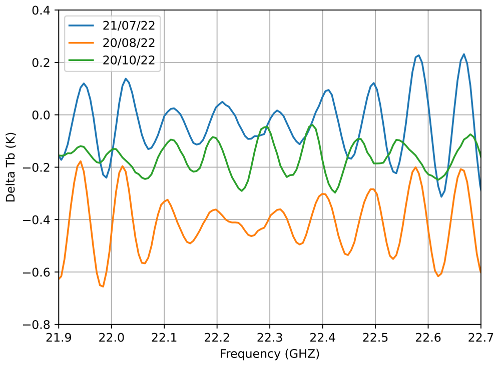
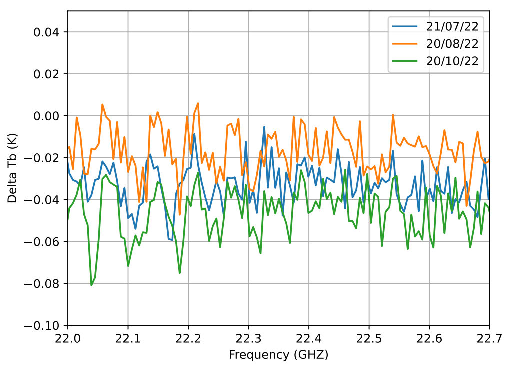


Figure 4: Comparison of spectra from the AC-240 and the two USRP channels after a balanced calibration against a zenith view partially blocked by the reference absorber.

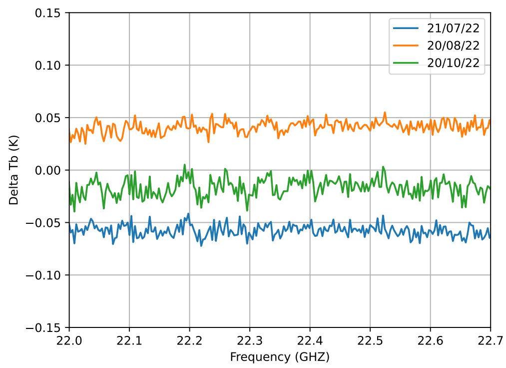
Standing waves arising from reflections are a known issue for microwave radiometers (Deuber and Kämpfer, 2004). For the MIAWARA, the most problematic of these was thought to come from the reference calibration load, however, they may also arise from reflections from the ambient target or other surfaces inside the radiometer. In order to minimise their impact, the radiometer mirror is successively shifted back and forth by a distance of a quarter wavelength of the observation frequency. Averaging over the two measurements has been shown to correct for the effects of standing waves (Gustincic, 1977). The change in mirror position also allows to investigate the magnitude and origin of the standing waves in the different measurement cycles. For that purpose the raw data from the two mirror positions is not averaged, but subtracted from each other. In this case the standing waves result in a frequency dependent baseline ripple with an amplitude that depends on the reflectivity of given scene (reference target, ambient target, sky, etc). This analysis method has been integrated into the calibration routine and will be used in the future as quality control for the status of individual spectra or the health of the calibration targets.



(a) Reference target



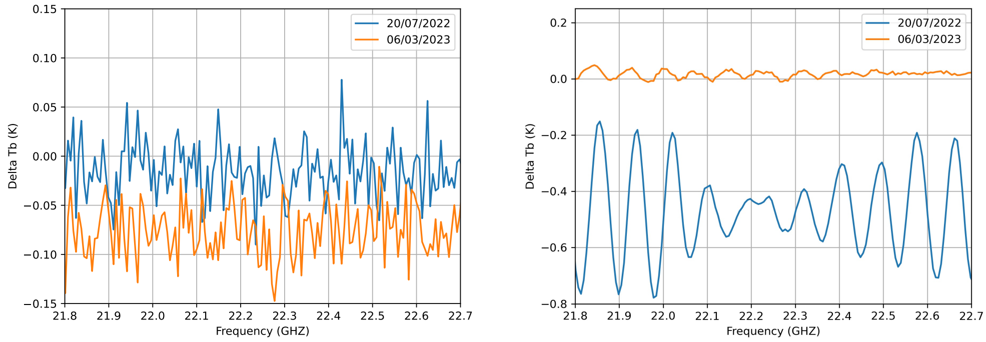
(b) Ambient target



(c) Cold sky view

Figure 5: Examples of the calibrated differences in signal from the two mirror positions when viewing different targets.

Figure 5 gives examples of such standing wave spectra for three different days after an integration time of 24 h. The largest amplitudes are observed for the reference target. The last measurement on 20 Oct. 2022 was after the replacement of the degraded absorber, and it has thus the smallest amplitude (a). The standing wave amplitude from the ambient



(a) Ambient target

(b) Reference target

Figure 6: Examples of the calibrated differences in signal from the two mirror positions when viewing different targets after both before and after work had been carried out in March 2023.

target is about an order of magnitude smaller (b). From the cold sky view close to zenith we would not expect any standing wave errors, but even here we can notice a very faint periodic signature (c). It could be caused by diffraction at the rim of the mirror, but its effect will be negligible compared to the standing wave error from the reference target.

After the absorbers for both the hot and reference target had been replaced, it was essential that the standing waves present in both observations be checked to ensure that hot and reference observations would not be degraded following the maintenance work. As can be seen in 6, the amplitude of the standing waves arising from the hot target and reference target decreased- significantly so in the case of the reference target- implying that there will be less likely to be artifacts arising from reflections in these observations. The improvement may come from the improved state of the absorbers, which can be seen in figure 1. As well as signs of the absorber material becoming degraded due to aging, the hot reference absorber had also become shaved where the rotating mirror in the instrument had been rubbing against it. This flattened off the pointed tips of the absorber, making the surface more irregular and degrading the absorbing properties of the material which come in part from the pyramidal shape.

Using liquid nitrogen as a calibration target for the radiometer provides the significant benefit of an absolute calibration standard. Unlike routine calibrations that rely on the tipping curve method to estimate the cold-sky temperature, absolute calibration does not need to be calibrated against another quantity. As a result, it yields a more reliable calculation of the system noise temperature, a critical quantity related to the instrument's sensitivity. The plot depicted in Figure 7 reveals that over the ten days surrounding the liquid nitrogen calibration, the system noise temperature calculated from the regular calibration routine closely aligns with the more reliable liquid nitrogen calibration value. However, it should be noted that unsettled weather during the two days at the end of this period caused a degradation in data quality, resulting in the system noise temperature value deviating further from the LN2 value than on other days.

The liquid nitrogen target proved useful for the absolute calibration of both the line observation and reference target. The signal from the line measurement is frequency dependent, the shape and intensity of which comes from the atmospheric state. The signal from the reference target is a combination of signal from the at zenith, which is frequency-

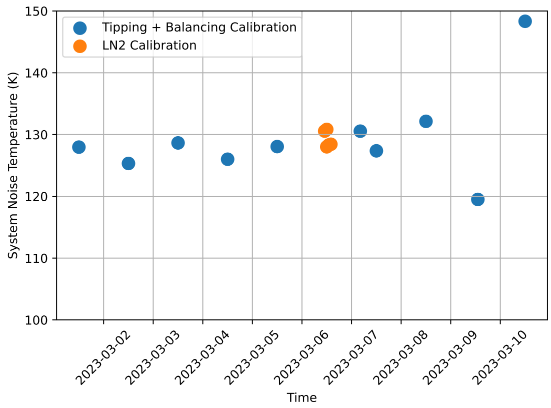


Figure 7: System noise temperature of the MIAWARA radiometer calculated in the regular calibration cycle and with a liquid nitrogen calibration.

dependent (though colder than the line measurement), and an assumed frequency-independent contribution from the absorber. The calibration of these two observations revealed that the line measurement was consistent with expectations, displaying a strong signal from the water vapour line at the central frequency and a contribution from the troposphere that resulted in a slightly broader peak at a slightly higher frequency. However, the reference observation exhibited an unexpected frequency-dependent signal, as seen in figure 8. A large oscillation between 21.8 GHz and 22.1 GHz was observed, followed by a linear decrease that revealed the weak line signal, and another oscillation feature at 22.5 GHz. Despite this unexpected behavior, the shape of the reference observation has been instrumental in determining the likely bandwidth limit for the retrieval algorithm. The linear decrease can be easily accommodated by a fit, but the oscillations pose a greater challenge.

The calibration of the spectra in the line and reference position with the liquid nitrogen and ambient target also allowed a further comparison of the performance of the two spectrometers. As highlighted earlier, the artifact present in the AC-240 spectrometer at distances of around 25 MHz from the central bandwidth of the spectrometer (22.235 GHz) can be seen on both the reference and line observation, whereas these are not present on the observations made with the USRP back-end. This is further evidence of the improvements in the calibrated spectra, and likely improvements in the quality of retrieved data made with this back-end.

As previously stated, the updated calibration and retrieval routines for MIAWARA are now fully operational. They were used to reprocess the time series of water vapour concentrations between 2015–2021 which is shown in figure 9. The expected features of the middle atmosphere water vapour annual cycle are clearly visible, with an increase in the concentrations during the warmer summer months and a decreases in winter. The profiles are also in accordance with the expected peak between 100 Pa and 10 Pa.

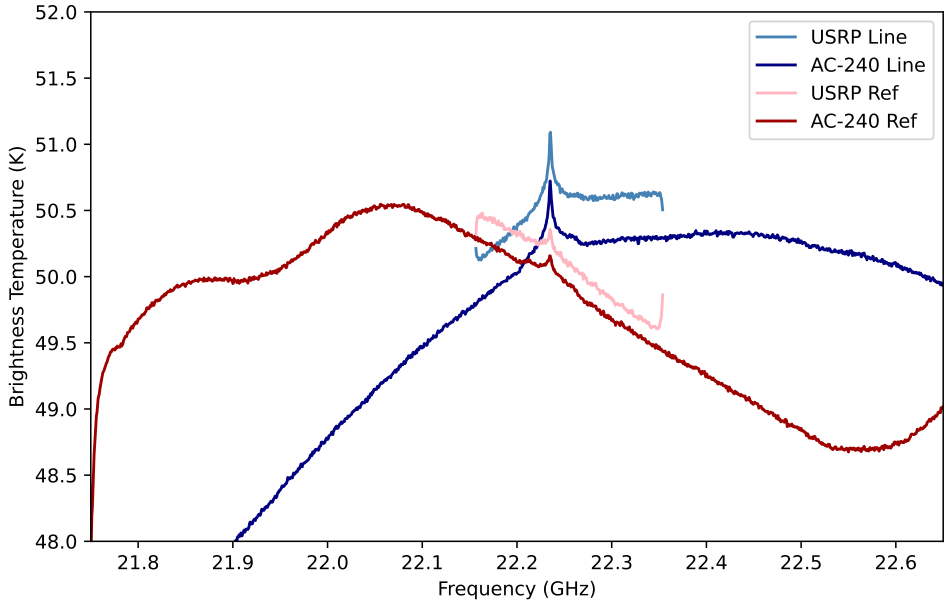


Figure 8: The line and reference signal from both the AC-240 and the USRP spectrometer, calibrated with LN2 on the 6th March 2023 following upgrades to the absorbers.

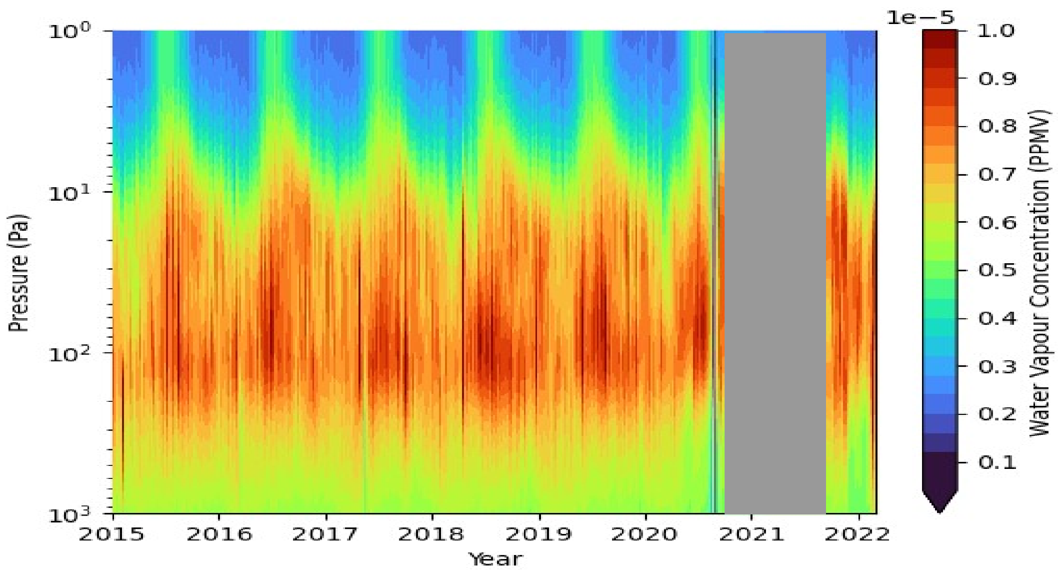


Figure 9: Water vapour as retrieved with the MIAWARA radiometer from Zimmerwald, BE, between 2015 and 2022. Grey areas correspond to instrumental down-time.

5 Conclusions and Outlook

The replacement of a broken amplifier and of the degraded reference absorbers were finished in 2022 and 2023, respectively, as well as the integration of an USRP X310 FFT spectrometer. Parallel observations of the old and the new spectrometer verified the bias of the old AC240. These parallel measurements will continue in order to be able to homogenize the MIAWARA time series, and eventually also correct the one of other H2O radiometers in NDACC.

The new calibration routines for MIAWARA were finished in 2022. They are now independent of the outdated MySQL database and include, besides other improved quality controls, also an analysis of the standing wave errors. The raw data, as well as the calibrated and integrated spectra, are now stored in a standardized way on the long term research storage facility of the University of Bern. Also the new retrieval routines for MIAWARA were finalized in 2023 and released together with the calibration routines on the git server of the University. A reprocessed dataset with retrieval results from 2015-2021 has been published on the Bern Open Repository and Information System (BORIS) data portal of the University. These retrieval results and other aspects of the MIAWARA upgrade will be presented at the IUGG conference in July 2023 and submitted to a peer reviewed journal. Once they have passed the peer review it is planned to reprocess the data back to 2005 and to update the entire time series on the NDACC database with the results from the new retrieval. It is also planned to enable the automated rapid delivery of daily water vapor profiles to NDACC, which is already done routinely for the ozone radiometer.

6 Outreach work, publication of data and results

An abstract on the MIAWARA developments and presentation of the new time series has been accepted by the IUGG conference, which will take place in Berlin in July 2023. In addition to a publication on the upgrade of the instrument and retrieval status we are considering a study which combines the retrieval results of the water vapor and ozone instruments of the University of Bern. Another topic of interest is whether changes in middle atmospheric water vapour resulting from large volcanic eruptions (such as Hunga Tonga, which erupted in December 2021) are present and can be sensed by the radiometer. This has been already demonstrated with another NDACC radiometer on Mauna Loa (Nedoluha et al., 2022).

The new calibration and retrieval framework is well documented in the following publications and technical technical reports, which are available including the full data set on `https://boris.unibe.ch` (Sauvageat, 2022).

7 Acknowledgements

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