Operational Monitoring of the Rain Rate by Ground-based Microwave Radiometry in Switzerland

Project duration: 14 months

Final report

Klemens Hocke (PI)

Institute of Applied Physics (IAP), University of Bern, Bern, Switzerland

Funding information: with the support of the Federal Office of Meteorology and Climatology, MeteoSwiss, in the framework of GCOS Switzerland

Figure 1. The HATPRO radiometer (left) was safely transfered from MeteoSwiss (Payerne) to the roof of the EXWI building of the University of Bern in November 2021. Axel Murk (IAP), Christoph Dätwyler (IAP) and Maxime Hervo (MeteoSwiss) discuss the calibration and the operation of the HATPRO radiometer at Bern (from left to the right). The water vapour and rain rate measurements of the outdoor HATPRO radiometer can now be compared with the coincident observations of the indoor TROWARA radiometer of IAP.

1 Summary

The project consisted of five work packages. WP-1 and WP-2 took care of the implementation of a new rain rate retrieval for the indoor Tropospheric Water Radiometer (TROWARA) at University of Bern. The PhD student Wenyue Wang successfully applied the new method for derivation of the rain rate to the observations of a two-channel microwave radiometer. Intercomparisons with data from nearby rain gauges and ECMWF reanalysis (ERA5) showed that the opacity at 31.5 GHz is most adequate to derive the rain rate with a high temporal resolution (10 seconds). A near-real time operational processing of the rain rate was established at Bern. The long-term time series of the rain rate of TROWARA was derived for the time interval from 2005 to now. Daily, monthly and yearly means of the rain rate at Bern are provided by the STARTWAVE database with open access in the internet. The new method and the validation results were published in a peer-reviewed journal. Generally, WP-1 and WP-2 showed that ground-based microwave radiometry is an independent new data source for long-term monitoring of the rain rate with an unpreceded temporal resolution.

WP-3 was dedicated to the application of the rain rate retrieval to the observations of the outdoor, commercial HATPRO microwave radiometer at Payerne. The postdoc Dr. Christoph Dätwyler found that the application of the rain rate retrieval is much more difficult for the HATPRO since the opacity measurements are often enhanced due to water films on the radome of the HATPRO, even 1 hour after rainfall. The long-Covid sickness of Christoph Dätwyler (since April 2021) slowed down the progress in WP-3, and Wenyue Wang overtook the task to process the Payerne HATPRO dataset with an algorithm, almost similar to the algorithm for TROWARA in Bern. However, there is an unacceptable, positive offset of the rain rate estimation of the HATPRO compared to coincident rain gauge measurements. The reason is not fully understood yet, possibly the bias is due to the water film on the radome during rain. On the other hand, we got encouraging results from WP-5 that the brightness temperature measurements at 31.5 GHz of the HATPRO at Bern agree very well with those of TROWARA at Bern. However, we will look in more detail of the HATPRO rain rate bias when we have collected more coincident rain rate observations of TROWARA and HATPRO at Bern.

Within WP-4, Wenyue Wang processed the available data of the HATPRO radiometers at Schaffhausen and Grenchen. As expected, the outdoor HATPRO radiometers at Schaffhausen and Grenchen seem to overestimate the rain rate, similar as the HATPRO at Payerne.

WP-5 consisted in the transfer of a HATPRO radiometer from Payerne to Bern. The transfer, the calibration of the HATPRO and the operation of the outdoor HATPRO parallel to the indoor TROWARA radiometer in Bern were very successful. The opacity measurements at 31.5 GHz agree very well but there is a difference in the derived integrated water vapour of the two instruments (caused by a bias of the 22 GHz channel of the HATPRO). We are sure that this measurement campaign will result in further important insights and publications. The PhD student Wenyue Wang will continue this work after the GCOS project.

The GCOS Switzerland Steering Committee requested us for an analysis and discussion if the new method (rain rate from ground-based microwave radiometry) can be an alternative to the existing rain gauge network. We don’t think so since the operation of a dense microwave radiometer network would cost too much money and time. However, since accurate rain rate measurements are still a challenge, it is important to have a further independent measurement technique. We have not yet explored the high frequency fluctuations in the rain rate time series of TROWARA. These fluctuations may contain valuable information about short-term convective processes during rainfall. Contrary to rain gauges, the microwave radiometer also inform about rain and cloud droplets within the troposphere. These observations can be used for cross-validation of the rain rate profiles obtained by atmospheric models and satellite measurements. Inspired by your question, we like to investigate the time series of integrated rain liquid water and cloud liquid water observed by ground-based microwave radiometers.

2.1 Introduction

The project contributed to the GCOS Switzerland Strategic Priority 3.1 (high-quality climate data). The overall aim was the operational monitoring of the rain rate by ground-based microwave radiometers at Bern, Payerne and Schaffhausen. The radiometers are operated by University of Bern and MeteoSwiss Payerne since 14 years and longer. Radiometry is a new and independent data source for monitoring of the rain rate with a temporal resolution of about 10 seconds. The rain rate measurements of ground-based microwave radiometers complement the rain gauge measurements. In difference to rain gauge measurements, radiometric observations are sensitive to virga precipitation and are possibly better comparable to satellite and radar measurements of precipitation. During the project, an operational processing of the rain rate was implemented and validated for the tropospheric water radiometer (TROWARA) at Bern. The time series of the rain rate at Bern was derived for the time interval from 2005 to now. The radiometer estimates of the rain rate agreed well with those of nearby rain gauges and ECMWF reanalysis (ERA5). A different situation was found for the HATPRO radiometer at Payerne. The effect of water films on the radome of the outdoor radiometer has to be considered during and after rainfall otherwise a positive bias would be obtained. We noticed this overestimation of the rain rate also when we processed the HATPRO datasets at Schaffhausen and Grenchen A HATPRO radiometer was transfered from Payerne to Bern in order to perform a cross-validation between coincident observations of the outdoor HATPRO and the indoor TROWARA radiometer.

2.2 Methods and activities

The radiometric estimate of the rain rate was firstly described in Mätzler and Morland (2008). With a few assumptions about the mean temperature, the temperature lapse rate and/or the height of the melting layer, it is possible to derive the rain rate at the surface by using the observed opacity at 31 GHz. The microwave emission of rain droplets is relatively strong, so that an onset of rainfall induces a sharp increase of the brightness temperature and the opacity. The radiometer is sensitive to small amounts of rain rate (drizzle), and a high temporal resolution of 10 seconds can be achieved. Compared to a rain gauge, the measurement volume of the radiometer beam is larger. Thus, ground-based microwave radiometry might be valuable for a validation of rain observations from satellites and weather radars.

During the GCOS project, the PhD student Wenyue Wang implemented the method of Mätzler and Morland (2008) for the indoor radiometer TROWARA at Bern. She also established a near-real time operational data processing of the rain rate. She derived the whole time series of rain rate at Bern since 2005 and intercompared the radiometric estimates of the rain rate with those of nearby rain gauges and ECMWF reanalysis (ERA5).

The GCOS postdoc Christoph Dätwyler took care of the rain rate retrieval for the observations of the outdoor HATPRO radiometer at Payerne. He firstly adjusted the algorithms of Mätzler and Morland (2008) to the different data format of the HATPRO radiometer. He compared the radiometric estimates of the rain rate wth coincident data from the rain gauge at Payerne. Then, he investigated the reasons for the observed differences between the HATPRO and the rain gauge at Payerne. Wenyue Wang improved the data processing for the HATPRO dataset at Payerne but

nevertheless an unacceptable, positive bias remained which is possibly due to the water film on the HATPRO radome during rain.
WP-4 yielded a positive bias of the rain rate estimation of the HATPRO radiometers which are operated by MeteoSwiss in Schaffhausen and Grenchen.
WP-5 consisted in the transfer of the HATPRO radiometer from Payerne to Bern where it is in parallel operation with the TROWARA radiometer. This campaign is unique since it delivers coincident data of an outdoor and an indoor radiometer looking at the same elevation angle (40 degrees) in the same direction (south). The intercomparison provides us new insights, e.g., about the biases of the rain rate and water vapour column density due to the water film on the radome of the outdoor radiometer.

2.3 Results

2.3.1 Work Package 1 and 2

Wenyue Wang processed the rain rate from TROWARA observations since 2005. She derived time series of the daily, monthly and annual means of the rain rate. She intercompared the rain rate data from TROWARA, rain gauge and the meteorological reanalysis ERA5. The validation of the rain rate retrieval is part of her peer-reviewed article (Wang et al., 2021). The TROWARA rain rate data are available here:
https://startwave.mw.iap.unibe.ch/project/index.html

In addition, the rain rate time series of three days ago is shown at this web page. The rain rate of TROWARA is operationally processed with a daily cron job.

Figure 2 shows the scatter plots of monthly rain rates at Bern. The radiometric estimates is most accurate for the 31 GHz data. Here, we get a coefficient of determination R^2 of 0.73. The radiometric estimates could be further improved by a more realistic estimate of the melting layer height, e.g., from high resolution meteorological reanalysis.

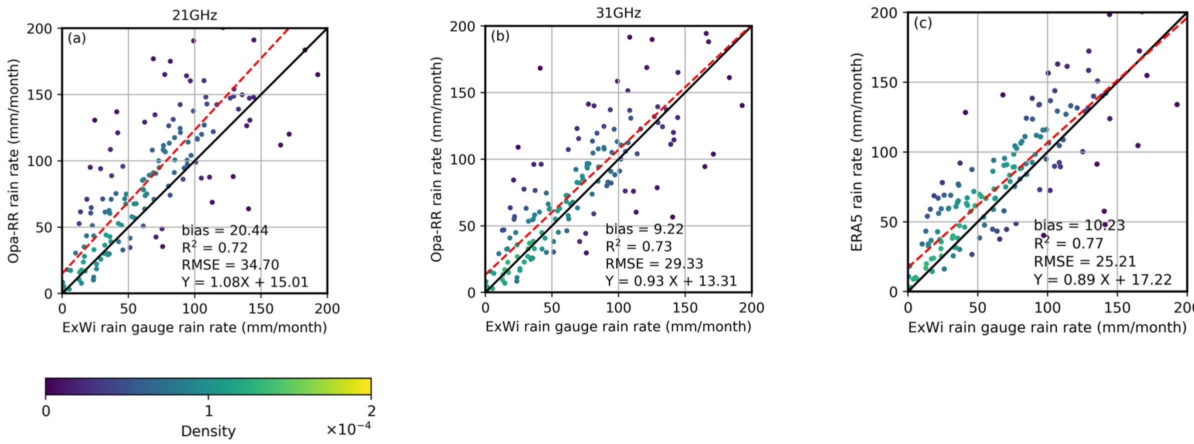

Figure 2. Scatter plots of monthly rain rates estimated by TROWARA radiometer (Opa-RR) and provided by ERA5 versus measured by the ExWi rain gauge over the period 2005 to 2018 in Bern. The solid black line shows the y = x line, and the red dashed line shows the linear regression fit line. The color shows the density of the data distribution calculated by Gaussian kernels (Wang et al., 2021).

The time series of monthly rain rate is shown for TROWARA, rain gauge and ERA5 in Figure 3. Generally, we find a good agreement between all data sets.

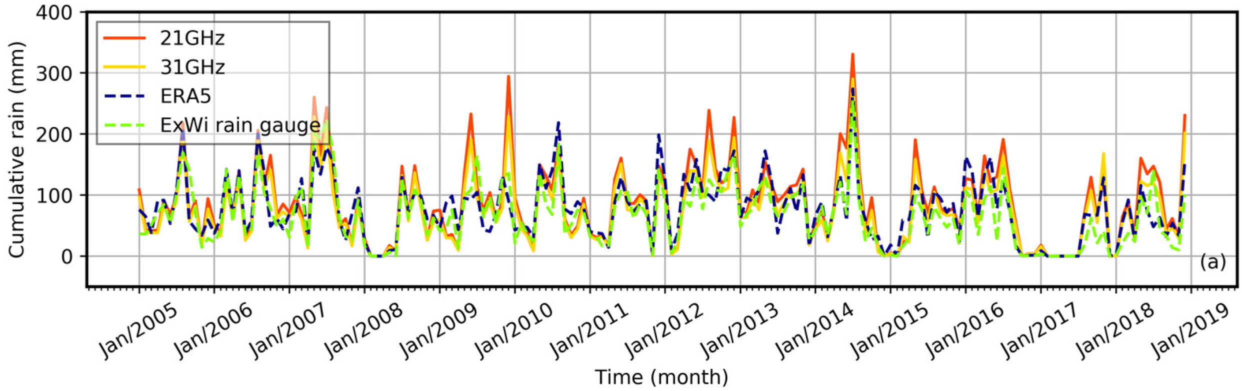

Figure 3. Monthly time series of the rain rate for TROWARA (Opa-RR) at 21 GHz (solid red), at 31 GHz (solid yellow), rain gauge (dashed green), and ERA5 (dashed blue) in Bern. It is assigned as 0 for months without rain or when data are missing (Wang et al., 2021).

2.3.2 Work Package 3

Christoph Dätwyler organized video conferences of the project partners Klemens Hocke and Axel Murk (IAP) and Alexander Haefele and Maxime Hervo (MeteoSwiss Payerne). The brightness temperature and opacity measurements of the outdoor HATPRO radiometer at Payerne were analysed in detail. The rain rate retrieval has been implemented and tested for the Payerne data. The derived rain rate values are greater than those of the rain gauge at Payerne. The overestimation of the rain rate was reduced by Wenyue Wang, when she improved the rain rate retrieval for the HATPRO at Payerne. The new retrieval starts with the measured 31 GHz brightness temperature (while Christoph Dätwyler started his retrieval later with the opacity values). The algorithms of Wenyue Wang are closer to those of TROWARA. However, the positive bias of the HATPRO rain rate, compared to a rain gauge, is still not acceptable as Figure 4 shows.

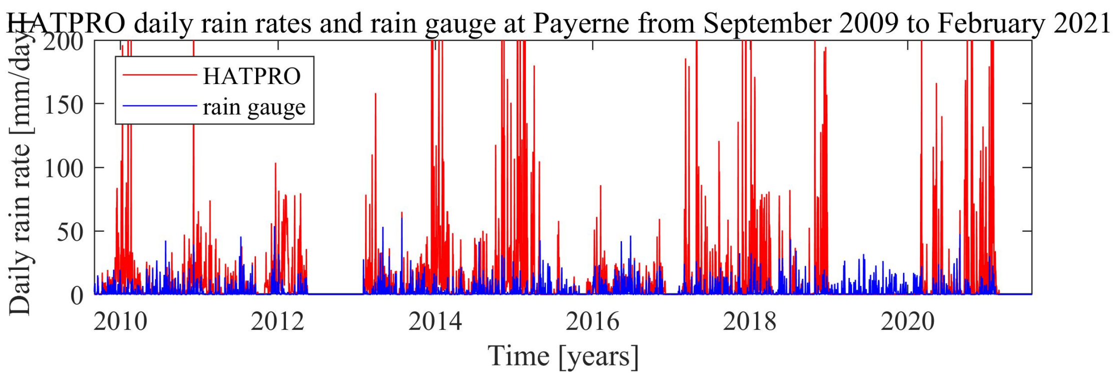

Figure 4. The rain rate estimated by the outdoor HATPRO radiometer in Payerne (red) is cleary overestimated compared to the coincident rain gauge measurements (blue).

Another finding is that the observed opacity after a rainfall is sometimes enhanced due to a water film and droplets on the radome of the HATPRO radiometer (Figure 5). It is unclear why this effect sometimes occur and sometimes not. Thus, a reliable correction of this positive bias of the outdoor radiometer in the past observations is a challenge. However, the new generation of HATPRO can better remove the water film on the radome by using a stronger fan.

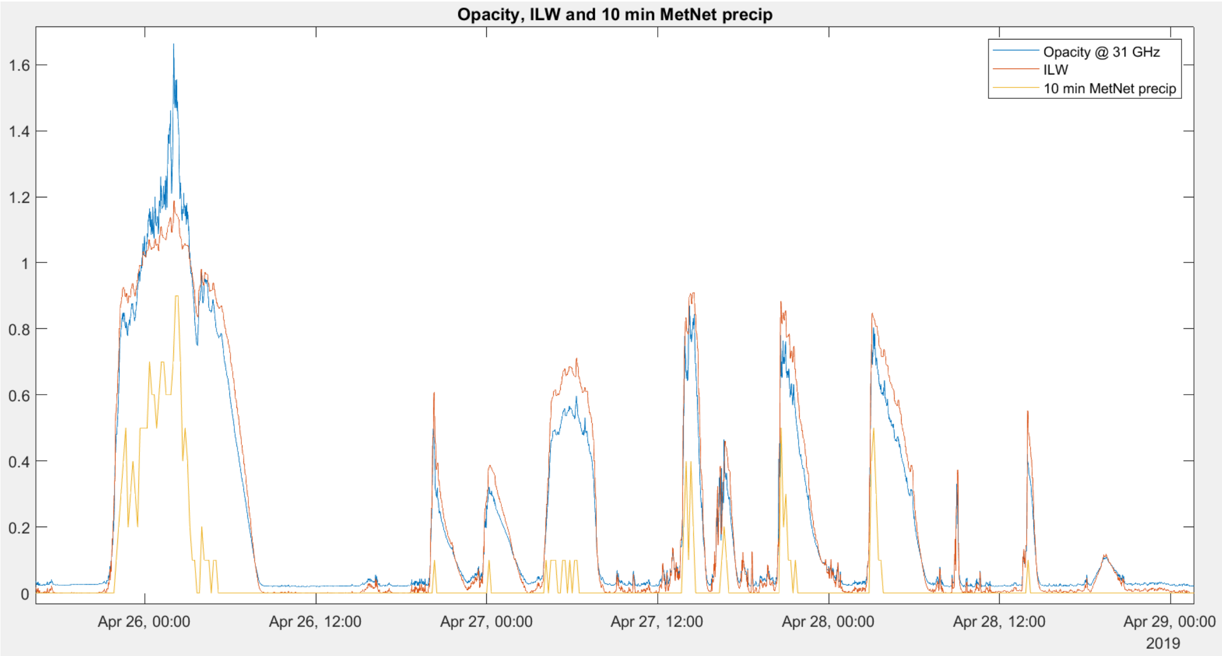

Figure 5. Opacity and integrated liquid water (ILW) of the HATPRO at Payerne are sometimes enhanced for several hours after rainfall while the rain gauge of MetNet (lower curve) does not indicate precipitation. The three curves have scaled values.

2.3.3 Work Package 4

Within WP-4, Wenyue Wang applied her retrieval of the rain rate from the HATPRO radiometer data at Payerne also to the datasets of the HATPRO radiometers at Schaffhausen and Grenchen, but as expected, the outdoor radiometers overestimate the rain rate also at these locations.

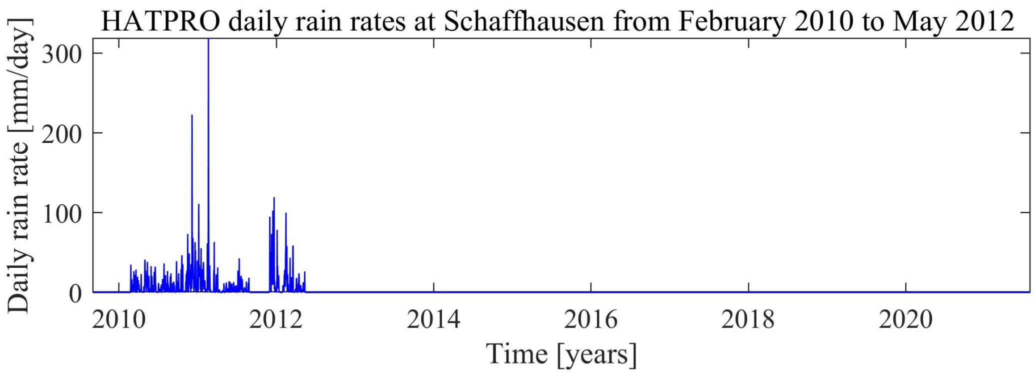

Figure 6. Rain rate estimation of the HATPRO radiometer at Schaffhausen (there were less measurements available than we initially expected).

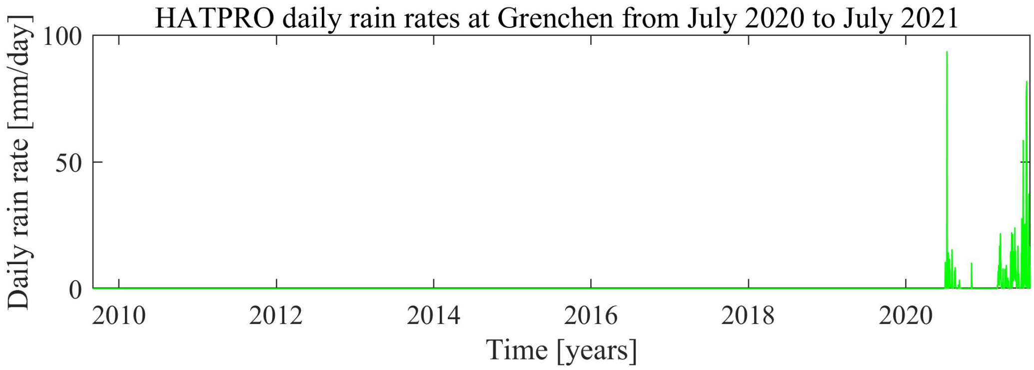

Figure 7. Rain rate estimation of the HATPRO radiometer at Grenchen. The processing of the measurements at Grenchen was not part of the work task of WP-4. Thus, it is a bonus provided by Wenyue Wang.

2.3.4 Work Package 5

In November 2021, the second generation radiometer HATPRO of MeteoSwiss Payerne was transfered to the University of Bern. MeteoSwiss Payerne got a new generation HATPRO.

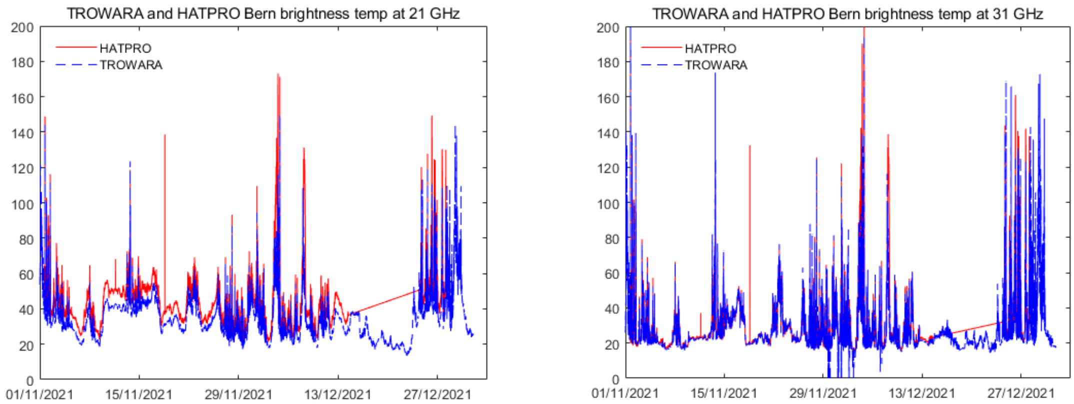

Figure 8. Parallel observation of the brightness temperature (K) by the outdoor HATPRO and the indoor TROWARA radiometer at Bern. Surprisingly, the measurements at 21 GHz differ by up to 10 K (left side) while the measurements at 31 GHz agree well (right side).

The parallel operation of the outdoor HATPRO and the indoor TROWARA radiometer at Bern is very interesting for cross-validation of the observations, particularly when it rains and the radome of the outdoor radiometer is wet. The parallel observation of the two radiometers permits the assessment of influences of water films on the measurements of the HATPRO.

Data analysis of the first weeks of coincident observations of the brightness temperature at Bern yield the important result that the HATPRO radiometer obviously overestimates the brightness temperature at 21-22 GHz (Figure 8). Consequently, this overestimations leads to a strong positive bias of the integrated water vapour (IWV) which is shown in Figure 9.

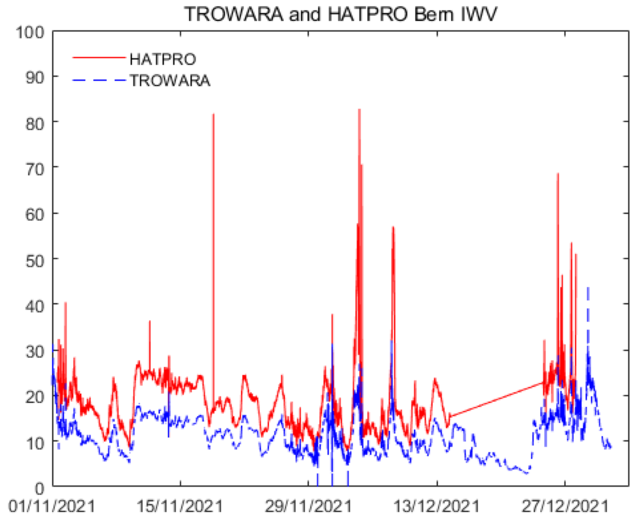

Figure 9. The estimate of integrated water vapour (IWV in [mm]) of HATPRO has a strong positive bias compared to TROWARA. IWV values greater than 20 mm are not reasonable during winter at Bern. Further, TROWARA is well validated by GNSS (Hocke et al., 2021), so that the HATPRO measurement must be wrong.

Fortunately, the biases of the brightness temperature at 21 GHz and IWV have no influence on the rain rate estimate of the HATPRO. The rain rate estimation relies on the 31 GHz channel which is in a fine agreement for HATPRO and TROWARA. However, we will investigate in more detail if this agreement is also valid when it rains.

2.3.4 Answers to the questions of GCOS (Ziffer 4.1, a,b,c)

We thank you for the questions which are very helpful to rethink our research targets and the project. This enables a progress in our future activities, e.g., in the framework of ACTRIS-CH.

a) Ground-based microwave radiometers cannot be an alternative to the existing dense networks of rain gauges and radars in Switzerland. However, it is valuable to have ground-based microwave radiometry as an additional independent measurement technique since precipitation measurements are generally difficult and imperfect. The measurement volume of the radiometer beam is comparable to the weather radar beam. So, coincident rain measurements of a weather radar and a microwave radiometer are invaluable. In addition, the radar and the radiometer provide not only information about the rain rate at the ground (as a rain gauge) but they provide information about rain liquid water and cloud liquid water within the troposphere. A rain gauge cannot inform about virga precipitation. Thus, microwave radiometers and radars can provide more informations about precipitation in the atmosphere. These informations are valuable for validation of vertical precipitation profiles in weather and climate models as well as for intercomparison with satellite measurements. Further, ground-based microwave radiometry has an unprecedented temporal resolution of about 10 seconds. The long-term monitoring of the rain rate with such a temporal resolution yields new knowledge about short-term processes of rainfall. In future, we like to analyse the high-frequency fluctuations of the rain rate, we like to evaluate rain liquid water path and cloud liquid water path, and we like to perform intercomparisons of radiometer, radar, model and satellite.

b) A two channel microwave radiometer as TROWARA is not sensitive to the snow rate. A micro rain radar as we have it at University of Bern might be better for assessment of the vertical profiles of snowfall.
c) Yes, ground-based microwave radiometers have the potential for calibration of the rain measurements of weather radars if the radiometer is operated close to the radar. As already mentioned in a), the large measurement volume of a radiometer beam supports intercomparisons of precipitation data from radiometer, radar, model and satellite. There is an operational network of microwave radiometers in Europe (EUMETNET) which may provide rain rate, rain liquid water path and cloud liquid water path in future.

2.4 Conclusions and limitations

WP-1, WP-2 and WP-5 were very successful. The operational data processing of the rain rate observed by the indoor microwave radiometer TROWARA has been implemented and validated. We were able to show that the new measurement technique for the rain rate is reliable. The results were published in a peer-reviewed article and shown at the international GAW and GCOS symposium in Switzerland in 2021. In addition, we got many ideas for future improvements and data analysis of the high-resolution time series of rain rate at Bern. WP-5 gave us the important result that the brightness temperature at 31 GHz agrees well for TROWARA and the outdoor HATPRO radiometer. We need more data of rain intervals at Bern in order to quantify if the HATPRO at Bern agrees with TROWARA for rainy conditions.

Further, we found that the retrieval of integrated water vapour (IWV) of the HATPRO at Bern is not possible because of a wrong measurement of the 21-22 GHz brightness temperature which is about 10 K too high. This could be caused by nonlinearities of the calibration process of the HATPRO.

The outcome of WP-3 was delayed because of the long-Covid sickness of the GCOS postdoc Christoph Dätwyler since April 2021. He found that the rain rate retrieval is generally more difficult for the outdoor radiometer HATPRO compared to the indoor radiometer TROWARA. The data analysis has to consider a positive bias of the rain rate due to a water film on the radome. MeteoSwiss Payerne constructed a small water protection roof above the HATPRO which could be a solution for the future. In addition, the new generation of the HATPRO radiometer has a better fan which removes the water film on the radome. The PhD student Wenyue Wang improved the algorithms for the HATPRO retrieval leading to a smaller bias of the rain rate at Payerne (WP-3). However, the HATPRO rain rate estimation is still unacceptable compared with a rain gauge. A similar positive bias of the rain rate estimation also occurred for the HATPRO radiometers at Schaffhausen and Grenchen (WP-4).

2.5 Outreach work and publications

We generated two peer-reviewed publications related to the GCOS project:

Hocke, K.; Bernet, L.; Wang, W.; Mätzler, C.; Hervo, M.; Haefele, A. Integrated Water Vapor during Rain and Rain-Free Conditions above the Swiss Plateau. *Climate* 2021, *9*, 105. https://doi.org/10.3390/cli9070105

Wang, W.; Hocke, K.; Mätzler, C. Physical Retrieval of Rain Rate from Ground-Based Microwave Radiometry. *Remote Sens.* **2021**, *13*, 2217. https://doi.org/10.3390/rs13112217

The near-real time time series of rain rate of the TROWARA radiometer are provided by our startwave web page:
https://startwave.mw.iap.unibe.ch/project/index.html

Wenyue Wang gave a poster presentation at the Swiss National GAW/GCOS Symposium GAW in August 2021. The title is: Physical Retrieval of Rain Rate from Ground-Based Microwave Radiometry.

The GCOS activities contribute to a major part of Wenyue Wang's PhD thesis which will be finished in 2025. Wenyue Wang also submitted a paper about precursors of rainfall at Bern to the journal Remote Sensing and already got four positive review reports which she will respond in begin of May 2020.

2.6 Outlook

Wenyue Wang currently writes an intercomparison study of the outdoor radiometer HATPRO and the indoor radiometer TROWARA at Bern. This article will be a further result of WP-5.

Generally, we continue the research about the rain rate after the end of the GCOS project. For example, the PhD student Wenyue Wang will derive time series of rain liquid water path and cloud liquid water path from ground-based microwave radiometers. This new data product can be compared to observations from weather radars, micro rain radar, models and satellites.

The close cooperation with MeteoSwiss Payerne during the GCOS project will be continued within ACTRIS-CH.

We have submitted in April 2022 an SNSF proposal about virga precipitation (for a PhD student). This will ensure the work on rain rate observations of our micro rain radar (MRR) at Bern. Cross-validations of MRR, TROWARA and HATPRO are desirable.

2.7 Acknowledgment

We thank GCOS for funding, managing and extending of our rain rate project. This project is very important for the engagement of IAP-Bern in precipitation research. This research branch was strongly reduced at IAP because of the retirement of Professor Christian Mätzler. However, during the past years the IAP restarted the precipitation research, e.g., new master and PhD students, new projects such as ACTRIS-CH and GCOS, and new data processing of our observations from MWR, MRR, ceilometer and other instruments. We are grateful to Christian Mätzler for his works and advices about the rain rate retrieval from radiometer data. The PI Klemens Hocke thanks all project partners from IAP Bern and MeteoSwiss Payerne for the excellent cooperation and the excellent work atmosphere.

References

Hocke, K.; Bernet, L.; Wang, W.; Mätzler, C.; Hervo, M.; Haefele, A. Integrated Water Vapor during Rain and Rain-Free Conditions above the Swiss Plateau. *Climate* 2021, *9*, 105. https://doi.org/10.3390/cli9070105

Mätzler, C.; Morland, J. Advances in Surface-Based Radiometry of Atmospheric Water; IAP Research Report 2008-02-MW; Institut für Angewandte Physik, Universität Bern, Bern, Switzerland, 2008.

Wang, W.; Hocke, K.; Mätzler, C. Physical Retrieval of Rain Rate from Ground-Based Microwave Radiometry. *Remote Sens.* 2021, *13*, 2217. https://doi.org/10.3390/rs13112217