Comparison of three high resolution real-time spectrometers for microwave ozone profiling instruments

Eric Sauvageat  
Institute of Applied Physics  
University of Bern  
Bern, Switzerland  
eric.sauvageat@iap.unibe.ch

Mikko Kotiranta  
Institute of Applied Physics  
University of Bern  
Bern, Switzerland  
mikko.kotiranta@iap.unibe.ch

Klemens Hocke  
Institute of Applied Physics  
University of Bern  
Bern, Switzerland  
klemens.hocke@iap.unibe.ch

R. Michael Gomez  
Remote Sensing Division  
U.S. Naval Research Laboratory  
Washington D.C., USA  
mike.gomez@nrl.navy.mil

Gerald Nedoluha  
Remote Sensing Division  
U.S. Naval Research Laboratory  
Washington D.C., USA  
gerald.nedoluha@nrl.navy.mil

Axel Murk  
Institute of Applied Physics  
University of Bern  
Bern, Switzerland  
axel.murk@iap.unibe.ch

Abstract—We present a comparison of digital real-time spectrometers used in ground-based radiometry for the profiling of trace gases in the middle-atmosphere. From January to June 2019, we performed parallel observations of the atmospheric ozone transition line at 110.836 GHz with three different spectrometers connected to the same front-end. It allows to compare and characterize the ozone spectra over an extended period of time and covering a wide range of meteorological conditions. We show that the spectra derived from the Acqiris AC240 is systematically biased compared to other state-of-the-art spectrometers. It has a different spectral slope and a negative bias at the line center on the order of 8 percent. The bias evolves with the atmospheric opacity and originates from various sources. Using some simple corrections, we show that the bias from the AC240 can be corrected during data processing which is of high interest for the numerous time series derived from this back-end.

Index Terms—Microwave radiometry, digital real-time spectrometers, ozone, water vapor, remote sensing

I. INTRODUCTION

High-resolution real-time spectrometers are widely used in radio astronomy and remote sensing of trace gases in the atmosphere. Thanks to the pressure broadening of atmospheric lines in the microwave region, such back-ends are often used in ground-based radiometry for the profiling of ozone, water vapor, carbon monoxide or winds in the middle-atmosphere. Today, most radiometers are using either digital Fast Fourier Transform (FFT) or Polyphase Filter Bank (PFB) spectrometers [1], [2].

The Acqiris AC240 was the first commercial FFT spectrometer that was used for remote sensing of the middle-atmosphere [3]. For more than a decade it was widely used to monitor ozone and water vapor, including in microwave radiometers of the global Network for the Detection of Atmospheric Composition Change (NDACC). However, different studies have noticed a bias in the time series derived from the AC240 compared to other measurements [4], [5]. In the meantime the AC240 is no longer supported by the manufacturer, and they are progressively being replaced with newer generation spectrometers. Nevertheless it is still important to understand the origin of this bias, and to reprocess the numerous past time series derived from this back-end with adequate corrections.

This is the goal of a measurement campaign setup between January and June 2019 at the University of Bern. We performed parallel observations of the ozone rotational transition line at 110.836 GHz using the AC240 and two different new generation digital spectrometers: the Acqiris U5303 and Ettus USRP X310. Preliminary results from this campaign have shown that the ozone spectra recorded from the AC240 showed a systematic bias compared to the spectra from the more recent U5303 and USRP. In particular, the AC240 showed a smaller amplitude at the line center and a flatter slope, caused by the strong line wing of oxygen at 118 GHz, than the other two spectrometers [6].

In our study, we further investigate these discrepancies by studying their sensitivity to the atmospheric conditions. We have devised a harmonized calibration routine enabling to compare the spectra depending on their brightness temperature and better identify the bias sources.

II. INSTRUMENTAL SETUP

During the measurement campaign, we connected three digital real-time spectrometers to a single radiometer front-end for simultaneous operation. As front-end, we have used the recently designed Microwave Ozone Profiling Instrument MOPI 5 described in [7]. It is a single sideband heterodyne receiver with a noise temperature of 550-625 K designed for ozone monitoring in the middle-atmosphere. It has been
developed at the University of Bern on behalf of the United States Naval Research Laboratory (NRL) to replace a previous instrument on Mauna Loa, Hawaii. As back-ends, the Acqiris AC240 (FFT), Acqiris U5303 (PFB) and Ettus USRP X310 (FFT) were used for simultaneous observations of a hot and a cold calibration target as well as the atmospheric ozone emission line at 110.836 GHz.

The U5303 is a new generation spectrometer designed as a replacement for the outdated AC240. It has a larger bandwidth than the AC240 and an improved dynamic range thanks to more analog-to-digital converter (ADC) bits. Both instruments have the same number of channels (16384) which results in a slightly lower frequency resolution (Δν) for the U5303. The U5303 uses a PFB algorithm resulting in lower side-lobes and better channel separation without loss of sensitivity compared to the FFT algorithm used in the AC240. The USRP is a software defined radio platform which can be used for signal processing and which firmware can be customized according to the user needs. For this study, it was used with a 200 MHz bandwidth. While the focus of the study is mainly on the comparison of the two broadband spectrometers, it has been added for validation purposes (for more details, see [6]). The main spectrometers properties are summarized in Table I.

| Model         | Bandwidth | ADC Bits | Δν      | Type   |
|---------------|-----------|----------|---------|--------|
| AC240 Acqiris | 1000 MHz  | 8        | 61.04 kHz | FFT    |
| U5303 Acqiris | 1600 MHz  | 12       | 97.66 kHz | PFB    |
| USRP Ettus    | 200 MHz   | 14       | 12.21 kHz | FFT    |

### III. Measurement Campaign

Between January and June 2019, MOPI 5 operated on the roof of one of the buildings of the University of Bern (47N) in Switzerland. If we remove the time needed for technical maintenance, it provided more than 350 hours of parallel observations from the three spectrometers. Despite some technical difficulties due to the manual operation of the instrument, the MOPI 5 observations covered a broad range of atmospheric conditions distributed mostly over 4 months (January to April). Fig. 1 shows an example of time series recorded during the measurement campaign for the month of February 2019.

To investigate more thoroughly the bias noticed previously by [6], we have devised a common calibration routine for the three spectrometers. It allows to integrate the calibrated spectra depending on the weather conditions, i.e. based on their line amplitude or brightness temperatures ranges. Taking the U5303 as the reference, we separated the calibrated spectra into brightness temperature bins for the integration and used the same integration periods for the two other spectrometers for comparison. To provide a more accurate description of the bias seen on the AC240, we additionally defined the three specific parameters sketched in Fig. 2 and listed hereafter:

- Slope of the spectrum
- Continuum amplitude: it corresponds to the brightness temperature at which the slope line crosses the observation frequency (110.836 GHz)
- Amplitude at the line center: this is the difference between the peak amplitude value and the continuum amplitude.

#### A. Comparison of the integrated spectra

Fig. 3 shows a comparison of the integrated spectra from the 3 spectrometers for two different brightness temperature bins (out of 15) during the time period shown in Fig. 1. For the comparison, the spectra from the 3 spectrometers have been binned to a comparable resolution. With the more recent U5305 and USRP spectrometers, we see that the integrated spectra agree very well and are independent of the atmospheric conditions. On the contrary, the older AC240 shows a systematic bias which depends on the brightness temperature range. It shows a negative bias at the line center that is more pronounced in the case of lower tropospheric opacity (left panel of Fig. 3) than in the case of higher tropospheric opacity (right panel). Also, the slope difference between the AC240 and the U5303 varies.

![Fig. 1. Time series with 10 minutes averaged brightness temperature from the 3 spectrometers (top panel), the air pressure and temperature (middle panel) and precipitation and relative humidity (bottom panel) recorded in Bern.](image1)

![Fig. 2. Specific parameters used for the bias description. The shaded areas represent the frequency bands used to compute the slope of the spectra](image2)

![Fig. 3. Comparison of the integrated spectra from the 3 spectrometers for two different brightness temperature bins (out of 15) during the time period shown in Fig. 1. For the comparison, the spectra from the 3 spectrometers have been binned to a comparable resolution.](image3)
Fig. 3. Comparison of the integrated spectra recorded from the 3 spectrometers for a low (left) and high (right) atmospheric opacity. The bottom panels show the difference between the AC240 (orange) or USRP (green) and the reference spectrometer (U5303).

Fig. 4. Hourly integrated differences between AC240 and U5303 for the three parameters sketched in Fig. 2. The colors represent the different months. On the right panel, the red (blue) vertical dashed line indicates the temperature of the hot (cold) calibration target while the black line shows a typical non-linearity curve that could be expected.

according to the atmospheric conditions, getting smaller at higher atmospheric opacity.

B. Evolution and origins of the bias

To study the evolution of the bias with the brightness temperature, we computed the three specific parameters for the two broadband spectrometers on hourly integrated spectra recorded during the whole measurement campaign. The absolute differences between the parameters computed on the AC240 and the U5303 are shown in Fig. 4.

It highlights the strong dependency of the bias on the brightness temperature and it shows that this dependency is consistent through the whole measurement campaign. Also note that the bias is quite high in regards to the type of observations performed with these back-ends ($\approx 8 - 12\%$ for the line amplitude).

Fig. 4 also suggests that the bias is a combination of multiple errors sources. The bias in the continuum amplitude indicates a typical non-linearity problem of the AC240 which can be described by a small gain compression. If we approximate the non-linear transfer characteristic with a quadratic equation, the resulting calibration bias is negligible if $T_B$ is close to either of the two calibration load temperatures. The black line in the right-hand-side of Fig. 4 shows the modelled calibration bias for this first order approximation, which provides a reasonable fit of the observations. While non-linearities could well explain the continuum difference, it fails to explain the biases seen on the slope and line center amplitude. We have investigated multiple possible explanations, among which the quantization errors due to the reduced number of ADC bits as well as the effect of the FFT channel response $|\sin(x)/x|^2$. However, they could not explain such differences between the spectrometers. It seems that the AC240 spectrum experiences
A significant spectral leakage leading to a scaling of the brightness temperature throughout the whole bandwidth. We can reproduce this effect on the U5303 using (1):

$$T_B' = (1 - \alpha)T_B + \alpha T_{B,\text{mean}} + \Delta T_{B,\text{nonlin}}$$  \hspace{1cm} (1)

where $T_B'$ is the scaled brightness temperature using a scaling factor $\alpha$ and the mean brightness across all channels $T_{B,\text{mean}}$ while the non-linearities $\Delta T_{B,\text{nonlin}}$ have been modelled from the black curve in Fig. 4.

The combination of the spectral leakage and the effect of non-linearities are shown in Fig. 5 for two atmospheric opacities and three different cases: the original bias (orange lines), the modified bias with $\alpha \approx 8\%$ with (green) and without (red) the non-linearity effect. We can see that the combination of both effects is able to reduce the bias between the AC240 and the U5303. The non-linearity seems to limit the broadband bias observed when the brightness temperature moves away from the calibration temperatures while the scaling factor is effective at reducing the slope and the line center amplitude biases. A constant scaling factor value is found to work best for the whole range of brightness temperature observed during this time period. Although not shown here, the results are similar when applying the same non-linearity effect and scaling factor on the other periods of the measurement campaign. The origin of the scaling factor remains unclear and further investigations are needed.

IV. CONCLUSION AND OUTLOOK

The main goal of this contribution was to investigate the systematic bias previously observed between the calibrated spectra recorded by the AC240 spectrometer and the more recent spectrometers U5303 and USRP. The broad range of parallel observations obtained during the measurement campaign shows that the AC240 is consistently biased compared to the other two spectrometers. The bias is dependent on the weather conditions and seems to be a combination of non-linearity and an unknown spectral leakage on the AC240. The origin of this leakage is under investigation but we show that the bias can be well reproduced by applying a constant scaling factor of 8% and accounting for non-linearity.

We are planning further measurements in order to broaden the range of measurements and better constrain the source of the scaling error. It will also be needed to extend this study to other atmospheric lines (e.g. ozone at 142 GHz and water vapor at 22 GHz) and to different receiver noise temperatures before providing a correction for the numerous spectra measured by the AC240.

REFERENCES

[1] A. O. Benz et al., “A broadband FFT spectrometer for radio and millimeter astronomy,” Astronomy & Astrophysics, vol. 442, no. 2, pp. 767–773, 2005.
[2] B. Klein et al., “High-resolution wide-band fast Fourier transform spectrometers,” Astronomy & Astrophysics, vol. 542, pp. 1–6, Jun. 2012.
[3] S. Müller, A. Murk, C. Monstein, and N. Kämpfer, “Intercomparison of Digital Fast Fourier Transform and Acoustooptic Spectrometers for Microwave Radiometry of the Atmosphere,” IEEE Transactions on Geoscience and Remote Sensing, vol. 47, no. 7, pp. 2233–2243, Jul. 2009.
[4] S. Studer, K. Hocke, M. Pastel, S. Godin-Beekmann, and N. Kämpfer, “Intercomparison of stratospheric ozone profiles for the assessment of the upgraded GROMOS radiometer at Bern,” Atmospheric Measurement Techniques Discussions, vol. 6, pp. 6097–6146, 2013.
[5] G. F. Nedoluha, R. M. Gomez, B. C. Hicks, J. Helmoldt, R. M. Bevilacqua, and A. Lambert, “Ground-based microwave measurements of water vapor from the midstratosphere to the mesosphere,” Journal of Geophysical Research: Atmospheres, vol. 116, no. D2, 2011.
[6] A. Murk and M. Kotiranta, “Characterization of digital real-time spectrometers for radio astronomy and atmospheric remote sensing,” in Proceedings of the International Symposium on Space THz Technology, Gothenburg, Sweden, vol. 15, 2019.
[7] M. Kotiranta, R. M. Gomez, G. Nedoluha, N. Kämpfer, and A. Murk, “Receiver development for the microwave ozone profiling instrument mopi 5,” in 2019 IEEE International Geoscience and Remote Sensing Symposium, 2019, pp. 8952–8955.