A novel spectrometer concept for microwave remote sensing of middle atmospheric trace constituents

Stefan C. Müller [a], Niklaus Kämpfer[a], Christian Monstein[b], Hansueli Meyer[b], Axel Murk[a], Vladimir Vasic[a],

[a]University of Berne, Institute of Applied Physics, Sidlerstrasse 5, 3012 Berne, Switzerland;
[b]ETH Zürich, Institute of Astronomy, Scheuchzerstrasse 7, 8092 Zürich, Switzerland

ABSTRACT

The Institute of Applied Physics of the University of Berne is active in the filed of remote sensing of middle atmospheric trace gases such as ozone and water vapor by microwave radiometry. From the measured pressure broadened spectral lines it is possible to retrieve the vertical distribution of the observed species. One of the radiometers is operating from an aircraft of the Swiss Air Force. For the spectral analysis it uses a broadband acousto-optical spectrometer with a total bandwidth of 1 GHz with 1725 channels, which allows retrievals of altitude profiles from about the flight height up to 60 km.

Unfortunately acousto-optical spectrometers proved to be critical under conditions encountered in an aircraft. For this reason the novel approach of using digital Fast Fourier Transform (FFT) spectrometers with a total bandwidth of 25 MHz and with the option to select either 2048 or 4096 channels and another FFT spectrometer with 16384 channels on 1 GHz bandwidth was chosen.

In this paper we present first measurements of atmospheric trace constituents using this novel approach with digital FFT spectrometers. We report on critical instrumental aspects such as system stability and linearity that are of fundamental importance for this application.

Keywords: FFT, AOS, spectrometer, atmospheric, trace constituents, microwave, radiometry

1. INTRODUCTION

Ozone depletion and greenhouse warming are two key areas in atmospheric research that request detailed information about the distribution of atmospheric parameters. Observations of key parameters is important in order to understand the relevant atmospheric processes and to detect changes of the individual species. A spectral region which is particularly well suited to detect atmospheric constituents is the microwave region.

This technique measures the weak radiation emitted by rotational transitions of molecules in the atmosphere. The spectral line of such transitions is pressure broadened what allows to retrieve an altitude profile of the species under investigation. The frequency resolution of the spectrometer determines to which altitude it is possible to retrieve the volume mixing ratio profiles and the overall bandwidth is a measure for the lower altitude limit.

The Institute of Applied Physics has built and operates several radiometers for stratospheric observations of ozone at 142 GHz[1] and water vapor at 22 GHz[2] from the ground and at 183 GHz[3] from aircraft. Up to now we measured the spectrum with acousto-optical spectrometers (AOS) with an overall bandwidth of 1 GHz and with 1725 channels and resolution of 1 MHz. Additionally a narrowband AOS with 50 MHz bandwidth and 2048 channels was used for the observation at line center. However this type of spectrometer was very sensitive to temperature fluctuations and vibrations as typically encountered in an aircraft. As an example before take-off ambient air enters the cabin and can cause temperature drops by up to 30 degrees when being in arctic regions. The AOS needs to warm-up for about 15 minutes and more to reach stable functionality after take-off as seen in figure 1 thus wasting measuring time during a campaign.

Therefore a new approach has been chosen by using digital FFT spectrometers. First tests with such instruments have been performed with a narrowband one with 25 MHz bandwidth on the one hand and with a broadband unit with 1 GHz bandwidth on the other hand.

Send correspondence to Stefan Müller: E-mail: stefan.mueller@mw.iap.unibe.ch, Telephone: +41316318923

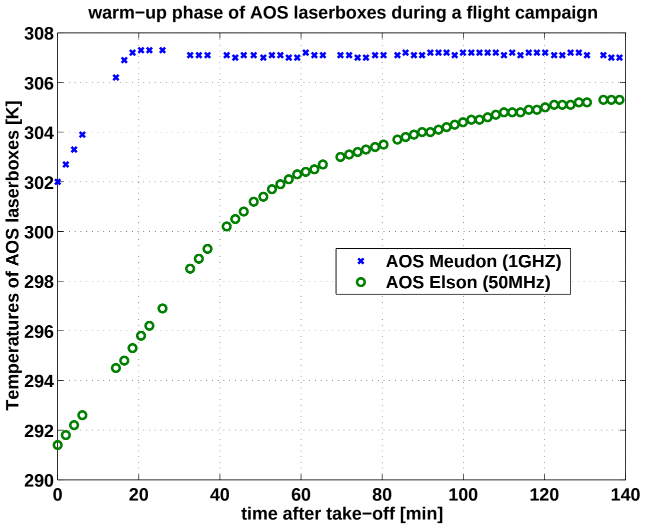

Figure 1. Typical warm-up phase of AOS during a flight. For the 1 GHz spectrometer it took about 15 minutes to reach temperature stability. For the narrowband it took much longer.

2. DIGITAL FFT SPECTROMETERS

An FFT spectrometer essentially consists of two parts: a fast analog to digital converter that samples the incoming signal and a **F**ield **P**rogrammable **G**ate **A**rray (FPGA) that calculates the FFT in realtime. The FPGA consists of millions of logical gates that are defined according to a user program loaded onto the FPGA. Calculating the FFT by hardware instead of software makes it extremely fast thus allowing to process the signal in realtime. Processtime must be as short as one scan of samples.

According to the Nyquist theorem

$$f_{\text{sampling}} \geq 2 \cdot f_{\max} \tag{1}$$

it is only possible to retrieve frequencies up to half ($f_{\max}$) of the sampling frequency f_{sampling}. It is therefore necessary to add a low-pass filter before the signal enters the spectrometer as shown in figure 2 in order to avoid aliasing effects.

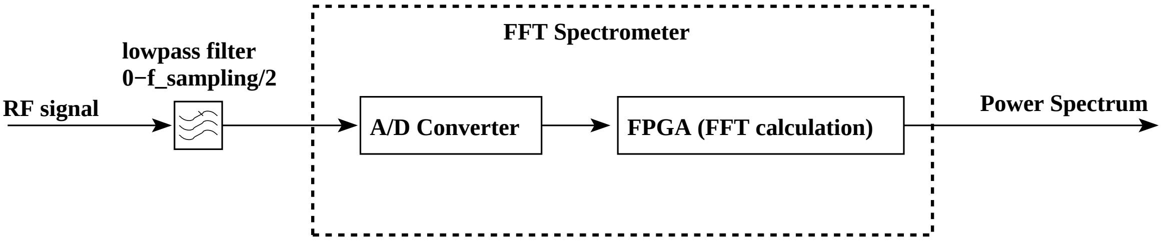

Figure 2. Principle of an FFT Spectrometer. The signal is sampled by a fast A/D converter and then processed by an FPGA that calculates the FFT.

A short description of the technical specifications of the FFT spectrometers is given in the tables 1 and 2. An image of the narrowband spectrometer from BEAM Ltd., which is realized on a commercially available PCI computer board, is given in figure 3. The broadband spectrometer has been developed in collaboration between ETH Zürich and Acqiris.

In case of the BEAM spectrometer it is possible to select either 2048 or 4096 channels. Applying an FFT on a sampled signal produces a power spectrum that consists of the spectrum and its mirror. Therefore some redundancy is present. That is what "FFT" mode does. "RFFT" mode uses a special algorithm "FFT of Single Real Function" from Numerical Recipes in C. This allows to use all 4096 points of the FFT and thus giving a doubling in resolution.

parameter	value	comment
A/D conversion	2 GSamples/sec	→ bandwidth 1 GHz
ADC resolution	8 bit	→ dynamic range 48 dB
number of channels	16384	
channelresolution	61.035 kHz	
integration onboard	1 ms - 70000 s	
windowing	programmable filter	
data output	32bit PCI interface	

Table 1. 1 GHz FFT spectrometer ACQIRIS.

parameter	value	comment
A/D conversion	50 MSamples/sec	→ bandwidth 25 MHz
ADC resolution	14 bit	→ dynamic range 74 dB
anti-aliasing filter	onboard	bandpass 1kHz - 23 MHz
number of channels	4096 (RFFT mode), 2048 (FFT mode)	
channelresolution	6kHz (RFFT mode), 12kHz (FFT mode)	
integration onboard	40 μsec - several sec	
data output	32/64bit PCI interface	

Table 2. 25 MHz FFT spectrometer BEAM.

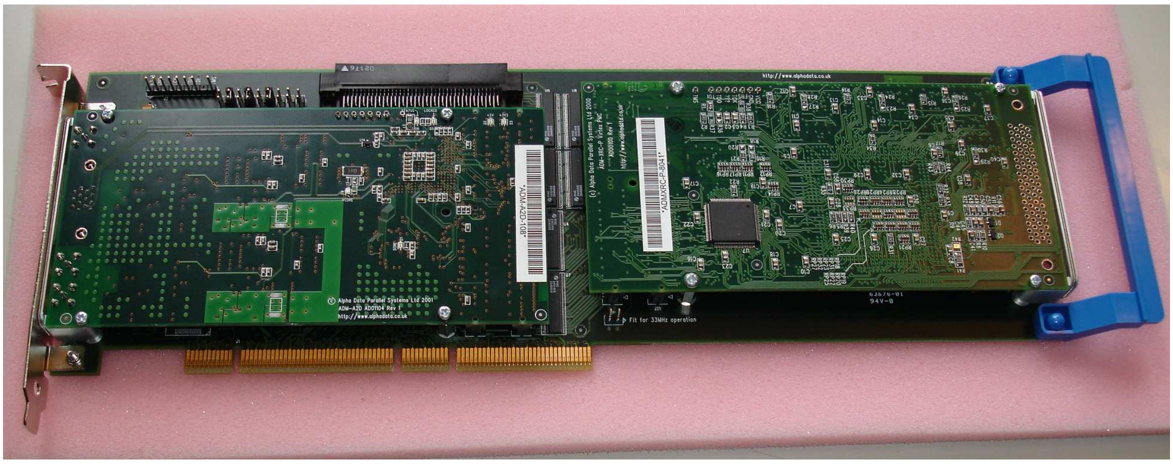

Figure 3. View of the narrowband FFT spectrometer BEAM. The left part is the A/D converter and the right part is the FPGA that calculates the FFT. Both parts are on a carrier board with PCI interface for data acquisition.

2.1. Tests of the FFT spectrometers

2.1.1. Channel characteristic

The frequency characteristics of all channels was measured by performing a frequency sweep over the whole range of individual channels with high frequency resolution. Figure 4 presents an example of such a sweep and illustrates the separation of the channels. The center frequency of one channel contains the whole power at this specific frequency. Two neighbouring channels overlap at half of the power (-3 dB) in each channel. The sidelobes are generated by a rectangular scanning window. The Fourier transformation of a rectangle is $\sin(\nu)/\nu$ where ν is the frequency. That explains also the channel isolation when the function $\sin(\nu)/\nu$ is equal to zero. The sidelobes are suppressed by about -13 dB and more. This channel characteristic is exactly what we expect from the simulation also shown in figure 4.

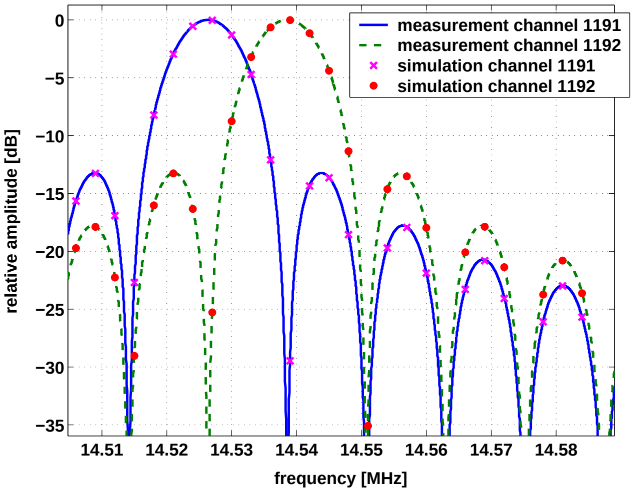

Figure 4. Channel characteristic of two neighbouring channels of the narrowband FFT spectrometer. Simulation and measurement fit exactly.

2.1.2. System stability

System stability was checked by measuring the Allan variance^4 of the spectrometer. For this test a stabilized noise source was connected to the spectrometer input and 10’000 measurements with half a second integration time were taken. As we can see in figure 5 the Allan time for the narrowband spectrometer is at 200 seconds. For the broadband spectrometer the Allan time was at about 2000 sec. This is an outstanding result when compared with the Allan time of 30 seconds of the AOS Meudon.

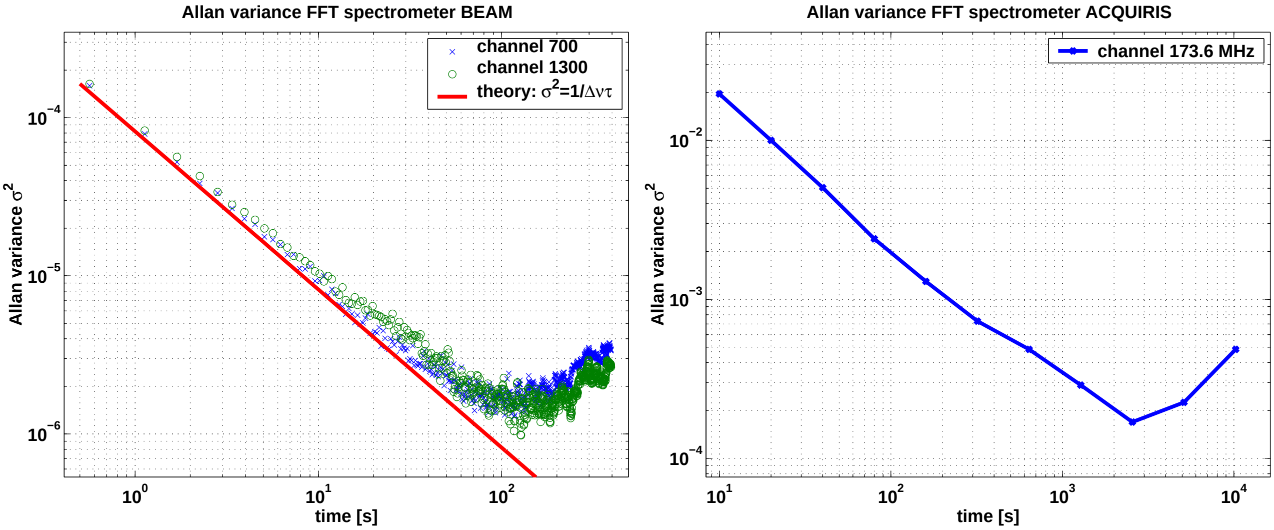

Figure 5. Allan variance of individual channelsof the BEAM (left) and ACQIRIS (right) FFT spectrometers.

The same measurements can be used to check if noise is reduced correctly when integrating for longer time. According to equation 2 the noise should decrease with $1/\sqrt{\tau}$. Here V is the detected spectrometer output, $\Delta\nu$ is the channelbandwidth and τ is the integration time.

$$\sigma = \frac{\Delta V}{V} = \frac{1}{\sqrt{\Delta\nu \cdot \tau}} \tag{2}$$

This theoretical curve in figure 5 compares very well with the measurement results.

Measurements with a stable CW test signal proved an excellent frequency stability and accuracy of the FFT spectrometers. The AOS, on the other hand, show a temperature dependent frequency drift and require periodic calibration of the frequency axis with a comb generator.

2.1.3. Linearity

The linearity was measured using a noise source at the input that could be attenuated in well defined steps. The results in figure 6 show a linearity on a range of 60 dB input power for the narrowband spectrometer. The broadband spectrometer shows an excellent linearity over its dynamic range of 48 dB.

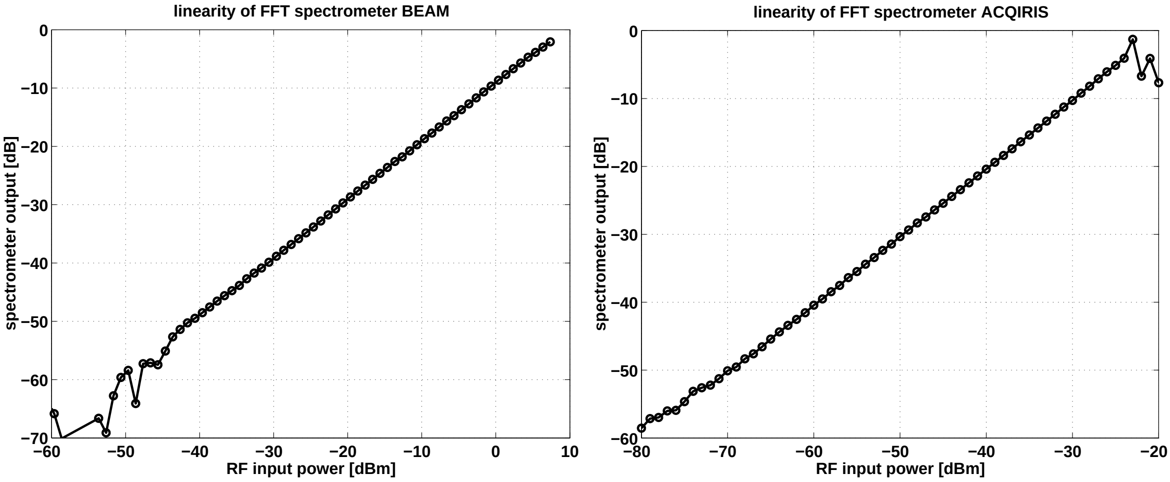

Figure 6. Linearity measurements of the narrowband on the leftside and the broadband FFT spectrometer on the rightside.

3. SPECTROMETER INTERCOMPARISON WITH ATMOSPHERIC OBSERVATION

3.1. Description of the measurements with an Ozone radiometer

In order to compare the suitability of different spectrometer types a spectrometer comparison campaign has taken place at the University of Berne in summer 2005. During this campaign different spectrometers were connected to one specific radiometer that is used to measure ozone within the frame of the *N*etwork for the *D*etection of *S*tratospheric *C*hange NDSC. A list of the four spectrometers that were used for this comparison is given in table 3.

type	manufacturer	bandwidth	channels	Resolution
FFT	Acqiris	1 GHz	16384	61 kHz
FFT	BEAM Ltd	25 MHz	2048	12 kHz
AOS	Observatoire de Meudon	1 GHz	1725	1 MHz
AOS	Elson Research Inc.	50 MHz	2048	75 kHz

Table 3. List of the spectrometers used for a comparison between AOS and FFT measuring stratospheric Ozone.

The *GRO*und-based *M*illimetre-wave *O*zone *S*pectrometer (GROMOS) measures Ozone at 142.175 GHz with a conventional filterbank with 48 channels. It is a total power radiometer using hotload-coldload calibration as illustrated in figure 7. An atmospheric spectrum is calibrated by using a hotload (absorber at 314 K) and a coldload (absorber in liquid nitrogen). The signal is mixed down to an intermediate frequency of 3.7 GHz. Power splitters divide the signal which is then converted down to the different input frequency bands of the spectrometers. In addition to the original filterbank spectrometer two different AOS and FFT spectrometers were connected to the radiometer frontend. Data acquisition has been time synchronized between each spectrometer.

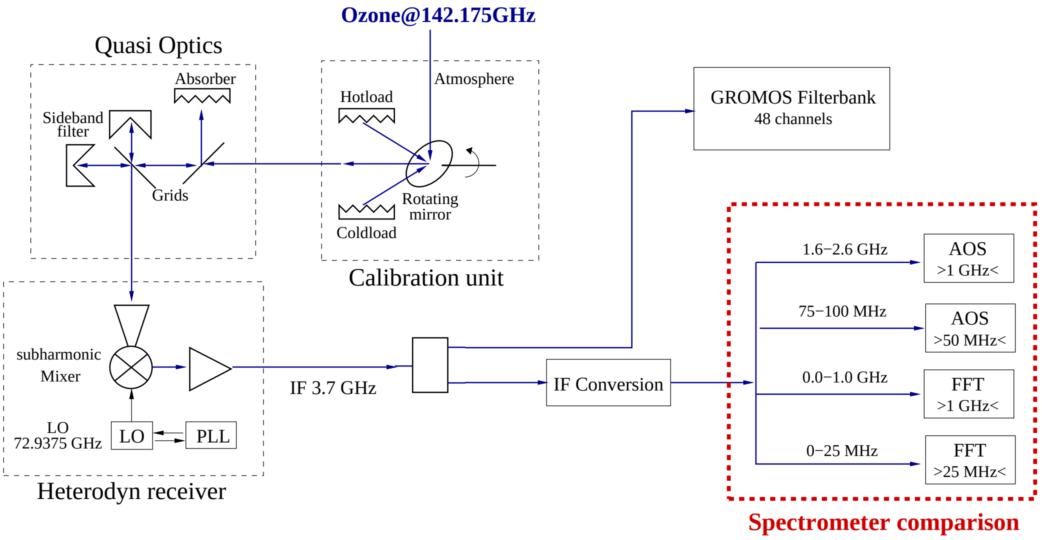

Figure 7. Scheme of the spectrometer comparison at the ozone radiometer GROMOS.

3.2. Atmospheric measurements

Measurements of stratospheric ozone by using FFT spectrometers were performed during the spectrometer intercomparison campaign. Figure 8 shows examples for each used spectrometer, on the lefthand side broadband AOS and FFT spectrometers and on the righthand side narrowband AOS and FFT spectrometers. The broadband FFT spectrometer appears to be noisier than the AOS due to the higher resolution. When its channels are binned to the same resolution as the AOS, however, the FFT spectrum has significantly less noise and measurement artifacts than the AOS.The same behaviour can be observed for the narrowband FFT and AOS spectrometer as well. In the broadband AOS spectrum there is a noisy part at 142.6 GHz and also some peaks e.g. at 142.1 GHz. In contrast to the FFT spectra which showed the same behavior over the whole intercomparison campaign, this was not the case for the AOS ones.

Spectra from the ACQIRIS type FFT spectrometer in figure 9 show an artifact in the spectrum with extremely long integration time. The input band is from 0-1000 MHz and on multiples of 125 MHz (at 142.3 and 142.42 GHz in the plot) we can see small peaks coming from an internally generated clock signal. A periodical calibration of the board has brought some improvement. Additionally we can identify frequencies of the mobile phone network at around 900 MHz (at 141.75 GHz in the plot).

Figure 10 shows a comparison of all spectrometers at line center integrated over the same measurement period. The different spectra show certain offset in intensity, which indicates a certain degree of nonlinearity. This can also be caused by the different IF conversion chains.

3.2.1. Inversion: Retrieval of ozone profiles

Inversion of a spectra is done by optimal estimation method.[5] We used the inversion software Qpack[6] and the forward model ARTS.[7] The profile shown in figure 11 was inverted from a spectra of the FFT spectrometer ACQIRIS. The profile shows clearly the maximum of ozone at 32 km with a volume mixing ratio of 9 ppm. In the comparison between the AOS and FFT profile in figure 11 both types show the maximum of ozone on the same altitude level. In the range between 40 and 60 km the FFT sees some more ozone but at lower heights we have a really good matching.

4. CONCLUSION AND OUTLOOK

We have shown that digital FFT spectrometers used in conjunction with microwave radiometers offer a new and promising approach to measure atmospheric transition lines in the microwave part of the spectrum. A comparison with other spectrometers such as acousto optical spectrometers and conventional filterbanks revealed that FFT spectrometers are superior

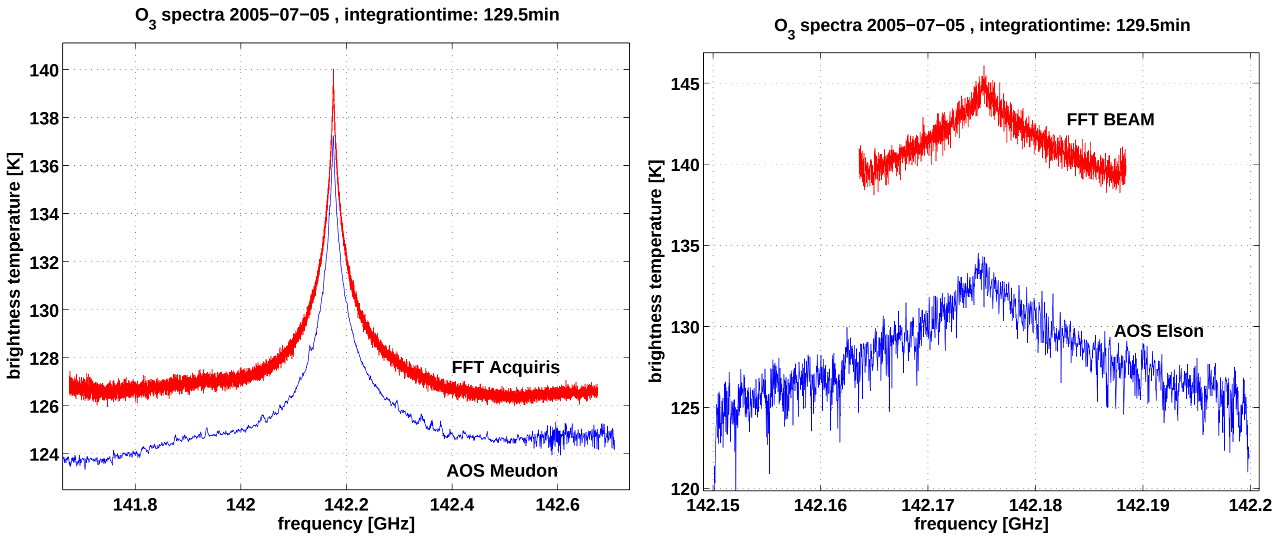

Figure 8. Spectra taken with all spectrometers on 2005-07-05. On the lefthand side the comparison of both broadband spectrometers. On the righthand side both narrowband spectrometers. Integrationtime was the same for all. The larger noise level of the FFT spectrometer is due to smaller channel bandwidth.

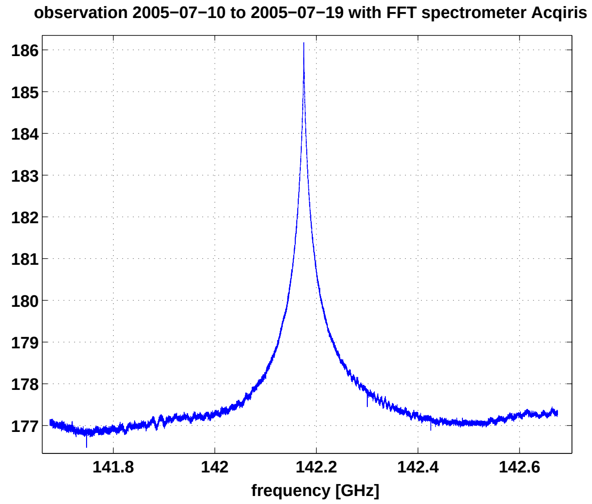

Figure 9. Long integration with FFT Acqiris. Spikes at 142.3 GHz and 142.42 GHz and 141.75 GHz disturb the spectrum at the input band. They are coming from a 125 MHz clock source onboard the spectrometer and from the mobile phone network around 900 MHz which interacts with the IF signal.

to the others concerning stability and resolution in addition to their size and lower costs. Identified peaks in the spectrum could be explained by internal clock signals and are not critical for the rest of the measurements.

An offset in measured absolute brightness temperature between individual spectrometers of several Kelvins has been detected. This effect might be caused by nonlinearities and needs further investigations. Further tests of the FFT spectrometer will be conducted in aircraft in November 2005 thus revealing the suitability under aircraft conditions.

ACKNOWLEDGMENTS

This work has been supported through the Swiss National science foundation under grant 200020-107665. The technical development of the 1 GHz FFT was financed by the Swiss Kommission für Technologie und Innovation (KTI) grant number 6421.2 IWS-IW and by the Swiss National science foundation under grant 200020-105366.

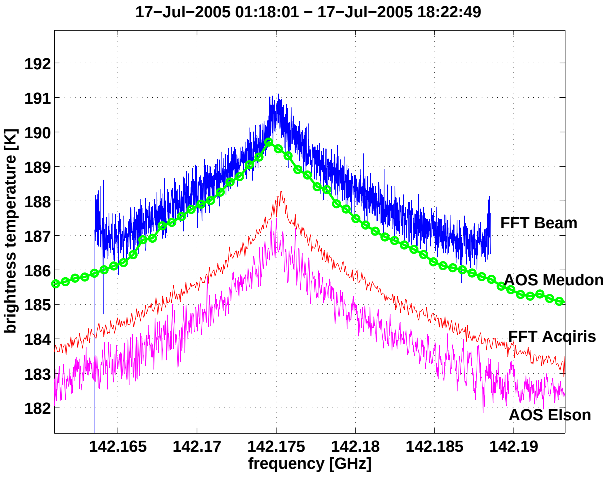

Figure 10. Comparison of all spectrometers at line center. An offset in brightness temperature is measured between all spectrometers. In the spectrum of the broadband Meudon AOS the peak at line center is rounded because of the limited resoluton of 1 MHz. With the narrowband Elson AOS it is not resolved because of the frequency instability of this instrument.

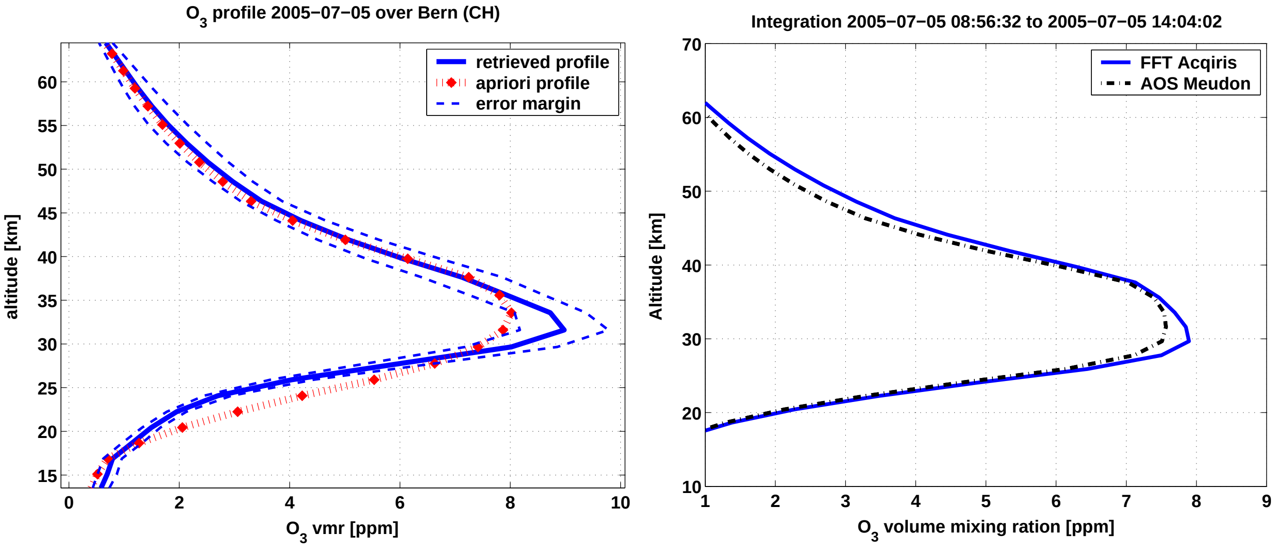

Figure 11. Left: Ozone profile over Bern taken on 2005-07-05 and measured by the 1 GHz FFT spectrometer Acqiris. Right: Comparison of profiles generated by an FFT and an AOS spectrum.

REFERENCES

1. Y. Calisesi, “Ground-based microwave radiometry of ozone profiles,” in *Proceedings of the third GAW-CH Conference*, 2002.
2. B. Deuber, N. Kämpfer, and D. G. Feist, “A new 22-GHz Radiometer for Middle Atmospheric Water Vapour Profile Measurements,” *IEEE Transactions on Geoscience and Remote Sensing* **42**, pp. 974 – 984, May 2004.
3. V. Vasic, D. G. Feist, S. Müller, and N. Kämpfer, “An airborne radiometer for stratospheric water vapor measurements at 183 GHz,” *IEEE Transactions on Geoscience and Remote Sensing* **43**, pp. 1563–1570, July 2005.
4. R. Schieder and C. Kramer, “Optimization of heterodyne observations using allan variance measurements,” *Astronomy & Astrophysics* **373**, p. 746, July 2001.
5. C. D. Rodgers, *Inverse Methods for Atmospheric Sounding: Theory and Practice*, vol. 2 of *Series on atmospheric,*

oceanic and planetary physics, World Scientific Publishing Co. Pte. Ltd., P O Box 128, Farrer Road, Singapore 912805, 2000.

6. P. Eriksson, C. Jimenez, and S. A. Buehler, “Qpack, a general tool for instrument simulation and retrieval work,” *J. Quant. Spectrosc. Radiat. Transfer* **91**, pp. 47–64, May 2005.
7. S. A. Buehler, P. Eriksson, W. Haas, N. Koulev, T. Kuhn, and O. Lemke, “Arts-1-0 user guide,” tech. rep., University of Bremen, Mar. 2003.