# Microwave remote sensing of stratospheric trace gases using digital Fast Fourier Transform spectrometers

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***Abstract*— The Institute of Applied Physics observes middle atmospheric trace gases, such as ozone and water vapour, by microwave radiometry. We report on the comparison of measurements using a novel digital Fast Fourier Transform and accousto optical spectrometers. First tests made on ground are presented as well as first experience about the use of such spectrometers under aircraft conditions.**

## I. Introduction

Two key domains in atmospheric research are global warming and ozone depletion. They require detailed information about the atmospheric state and their single parameters. Thus observations are important to understand processes and to detect changes. A well established technique to measure trace gases is microwave radiometry, which detects pressure broadened emission lines of atmospheric constituents. By a suitable retrieval process it is then possible to obtain an altitude profile of the observed species from the detected spectrum. The maximum and minimum altitude of the profile depends on resolution and bandwidth of the spectrometer in use.

The radiometers built and operated at the Institute of Applied Physics for groundbased and airborne observations of ozone and water vapor use traditional low resoluted filter banks or accousto optical spectrometers (AOS). With resolutions up to 24.4 kHz for the narrow band and a bandwidth of 1 GHz for broad band units the AOS are suitable for the determination of profiles from about 15 to 65 km altitude. One problem of this kind of spectrometer type is its sensitivity to temperature fluctuations and vibrations. Both situations are present during operations in an aircraft.

A new approach is the usage of digital Fast Fourier Transform (FFT) spectrometers. We dispose of a narrowband unit with a resolution of 12 kHz on 25 MHz bandwidth and also of a broadband one with 61 kHz resolution over 1 GHz. The last one was developed by ETH Zürich [1]. These novel spectrometers are employed in an aircraft instrument [2] in addition to the AOS for comparative measurements.

## II. Digital Fast Fourier Transform spectrometers

### A. Description

The principle of an FFT-specrometer is well known for a long time but realizable for real-time applications only since the developement of fast signal processors. As shown in figure 1 it consists of two parts. The first one is the analogue to digital converter for sampling the incoming signal. The sampling frequency $f_{\mathrm{sampling}}$ determines finally the bandwidth $f_{\max}$ of the spectrometer according to Nyquists theorem $f_{\mathrm{sampling}} \geq 2 \cdot f_{\max}$. The second part is the **F**ield **P**rogrammable **G**ate **A**rray (FPGA) a collection of logical gates that calculates the FFT by hardware what makes the operation very fast. The number of samples taken for one calculation determines the frequency resolution.

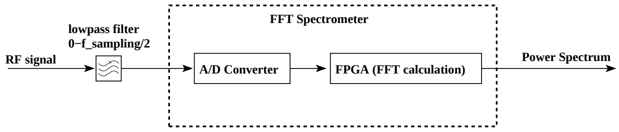


Fig. 1. Principle of an FFT spectrometer. The signal is sampled by a fast A/D converter and then processed by an FPGA that calculates the FFT in real-time.

Table I shows technical specifications of the two units in use at our institute.

| parameter | broadband Acqiris | narrowband Beam |
|---|---|---|
| distributers | ACQIRIS | BEAM Ltd. |
| ADC sampling rate | 2 GHz | 50 MHz |
| bandwidth | 1 GHz | 25 MHz |
| ADC resolution | 8 | 14 |
| number of channels | 16384 | 2048 |
| resolution | 61 kHz | 12 kHz |
| integration onboard | 16$\mu$s-70000s | 40$\mu$s-several s |

TABLE I

Technical specifications of the used FFT spectrometers.

### B. System requirements and tests

When observing a target, e.g. the atmosphere, calibration of the signal is done according to formula (1) using an absorber at ambient temperature as hotload and an absober in liquid nitrogen as coldload. $T_B$ is the brightness temperature of the radiation, $V$ is the measured output and indices $_H$ and $_C$ correspond to the hotload and the coldload.

$$T_B(\text{target}) = \frac{T_{B_H} - T_{B_C}}{V_H - V_C} \cdot (V(\text{target}) - V_C) + T_{B_C} \quad (1)$$

Thus we assume that the spectrometer's behaviour is linear. A second point is that the whole measurement system is in a stable state during one calibration cycle. So it is desired that the time of stability of the spectrometers is much larger than the one of the whole system.

*1) System stability:* First stability tests in the laboratory have been very encouraging. Allan variance measurements [3] as seen in figure 2 have given an Allan time of about 200 seconds for the narrowband spectrometer BEAM that is one order of magnitude greater than for our AOS that is specified with 30 seconds. The broadband spectrometer shows even more. Its Allan time is greater than 1000 seconds [1].

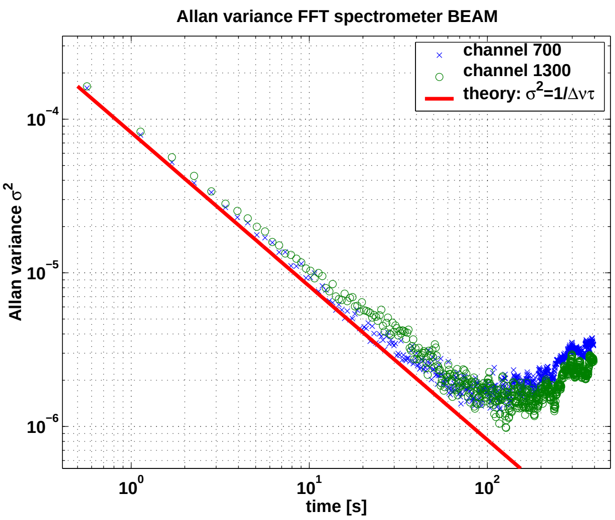


Fig. 2. Allan variance of individual channels of the narrow band FFT spectrometer BEAM.

*2) Linearity:* Another important point is the linearity of the system. For a proper calibration of the instrument we need linearity between the two reference loads and the atmospheric measurement. The test has been done using a noise source that could be attenuated in well defined steps and then observing one channel. The result shown in figure 3 with the broadband unit gives a deviation from linearity that is less than on 1 % over a range of more than 40 dB.

*3) Frequency axes:* A big advantage of the FFT spectrometers is the well known frequency axes and the good separation between the channels. This is seen in figure 4. The sidelobes are suppressed by 13 dB and originate from the Fast Fourier Transformation of a rectangular function. It can be described by the function $\sin(x)/x$. For each place on the axes where $\sin(x) = 0$ a new channel begins. Theory and measurement fit exactly.

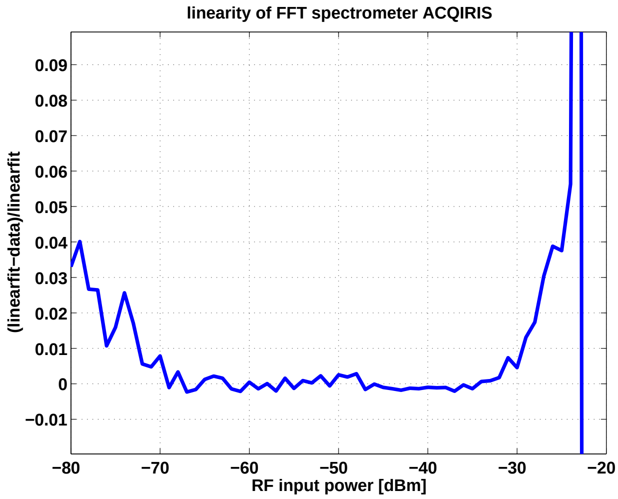


Fig. 3. Relative difference of the data and its linear fit from a linearity measurement of the broadband FFT spectrometer.

On the contrary our AOS has a nonlinear frequency axes due to geometrical reasons. In our case calibration of the axes is done using a comb generator with a signal each 100 MHz and then the channel frequencies are defined with a polynomial fit. Additionally the frequency axes is dependent on temperature what results in drift effects especially in an environment like inside an aircraft with changing temperatures. One can propose to calibrate often with the comb generator, but this will also result in a loss of measured spectra.

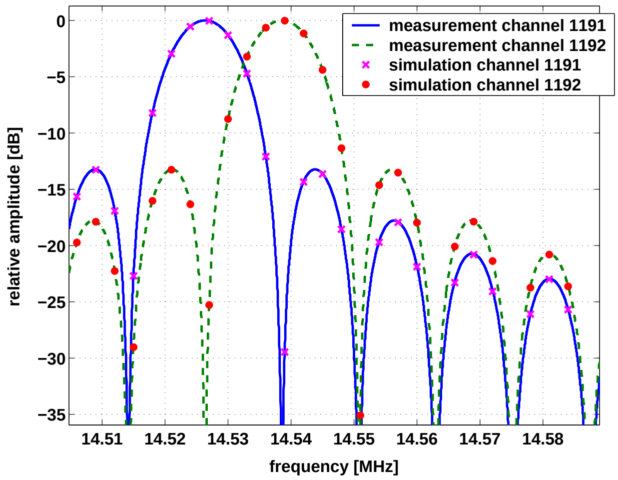


Fig. 4. Measured characteristic of a channel of the FFT spectrometer Beam compared to a simulation.

## C. Radiometric tests

A first test was done looking with the heterodyne receiver AMSOS [2] at 183 GHz to to a microwave absorber immersed in liquid argon. The theoretical value of the boiling temperature of argon is 86.7 K taken into account the actual pressure situation. The result in figure 5 shows a good matching of the broadband AOS and FFT spectrometers and 1 K lower for the narrowband. But all values are too high in comparison to theory. A possible explanation is that only 99% of the antenna beam looks into the argon and 1% or less captures some of the ambient temperature. It is not yet clear where the offset between narrowband and broadband come from.

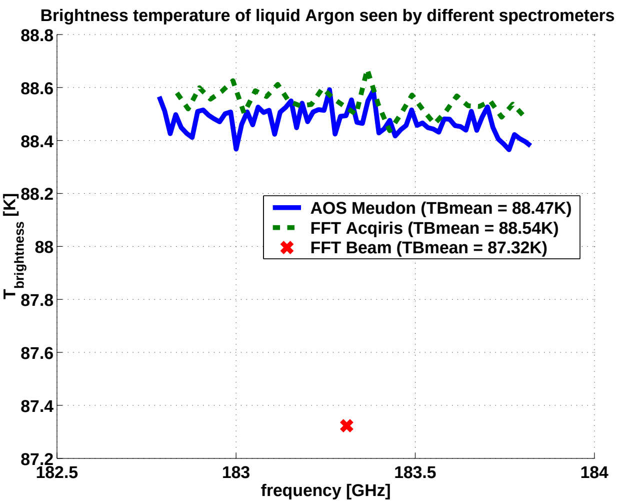


Fig. 5. Brightness Temperature of liguid argon seen by different spectrometers. Channels are binned to a bandwidth of 20 MHz for FFT Beam, 32 MHz for FFT Acqiris and 15 MHz for AOS Meudon.

## III. Atmospheric Measurements

### *A. Spectrometer intercomparison in summer 2005*

During summer 2005 first measurements of stratospheric ozone with the ground-based radiometer GROMOS at 142 GHz have taken place during a spectrometer intercomparison campaign [4]. The scheme is shown in figure 6. In a first step the frequencyband is mixed down to an intermidiate frequency (IF) of 3.7 GHz. Then is splitten up in four paths and again downconverted to the specific input band of each spectrometer. Together with the two described FFT spectrometers two AOS and a conventional filterbank were attached to the radiometer. One AOS was a broadband from Observatoire de Meudon and a narrowband from Elson Research Inc.. An offset in measured brightness temperatures between the FFT and AOS spectrometers has been detected in figure 7 but line amplitude and line form between all of them including filterbank was equal as can be seen in figure 8. The origin of the offset was caused by nonlinearites in the different IF chains.

As a consequence of that all IF chains of the airborne radiometer AMSOS [2] have been checked and adapted for the measurements from aircraft described in section III-B.

### *B. Measurements from aircraft during SCOUT-O3 campaign*

In november 2005 the Institute of Applied Physics participated with a Learjet of the Swiss Air Force at the SCOUT-O3 campaign in Darwin, Australia. With the radiometer AMSOS [2] it is possible to measure either $H_2O$ at 183.3 GHz in the upper sideband (figure 11) or $O_3$ at 175.4 GHz in the lower

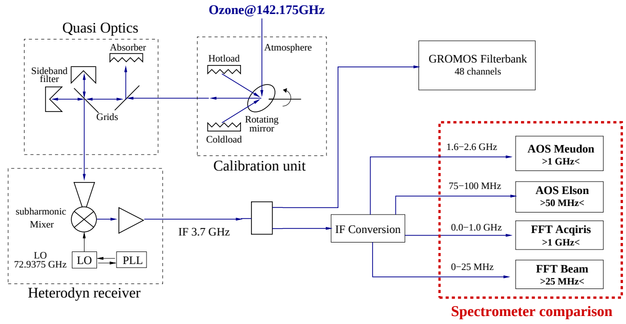


Fig. 6. Scheme of the radiometer GROMOS during intercomparison campaign in summer 2005.

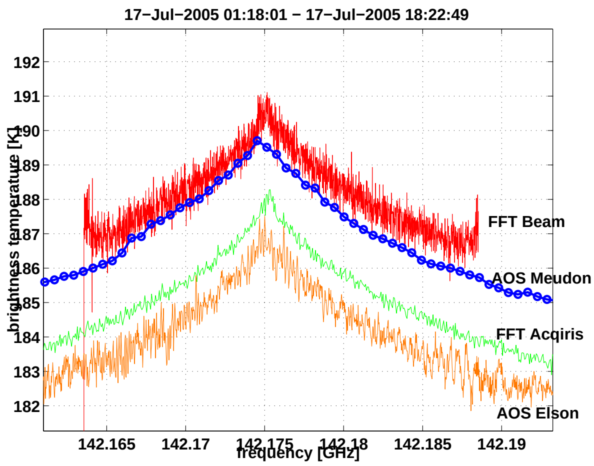


Fig. 7. Comparison of narrow and broadband AOS and FFT spectrometers at line center. An offset in brightness temperature is measured between all spectrometers.

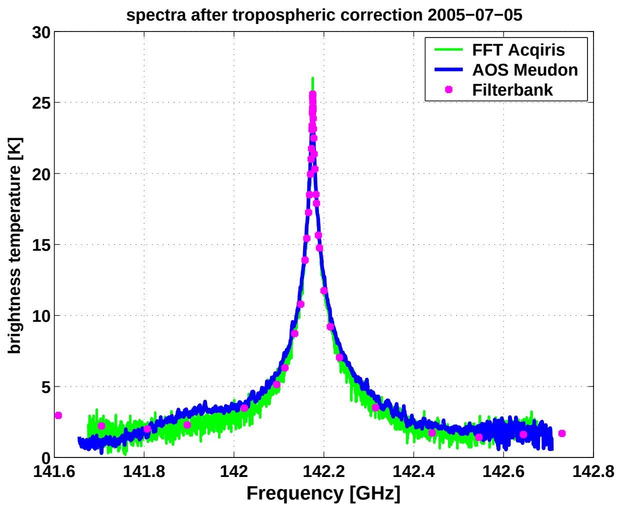


Fig. 8. Comparison of line amplitude and line form between broadband AOS, FFT and a 48 channel filter bank.

sideband (figure 9). The ripple in the ozone spectrum is due to standing waves in the input optics of the receiver. The channels in the high resoluted FFT spectrometers are binned together to around 1 MHz. Both examples show a good matching for both spectrometer types but with the AOS we see a higher brightness temperature in the ozone line as with the FFT. The differences plotted in figure 12 and 10 can give us an advice to this offset. Good matching would mean that there would be only the rest noise around 0 K. What we notice is on the left and on the right side a rise of 1-2 Kelvin. The discrepancy originates at the last downconversion. For downconversion to the input band of 0-1 GHz we need a steep roll-off filter next to the LO Frequency, in our case 3.2 GHz and also at the end of the analyze band at 4.2 GHz. Is this not the case, we get unwanted components of other frequency bands as shown in figure 14. Unfortunately this affected the ozone line in the measurement. What we see with the FFT Acqiris is a mix of brightness temperature from the ozone line of 57 Kelvin and from the part at the lower frequencies of around 48 Kelvin that reduces the ozone line. The aprupt rise in the center of figure 12 is caused by wrong calibration the of the frequency axis of the AOS, which is also visible in figure 13. We can clearly see the line shifted to the left of the theoretical center at 183.310 GHz by contrast to the FFT spectrometers. This shows the problems of frequency instability on the AOS but can be corrected afterwards.

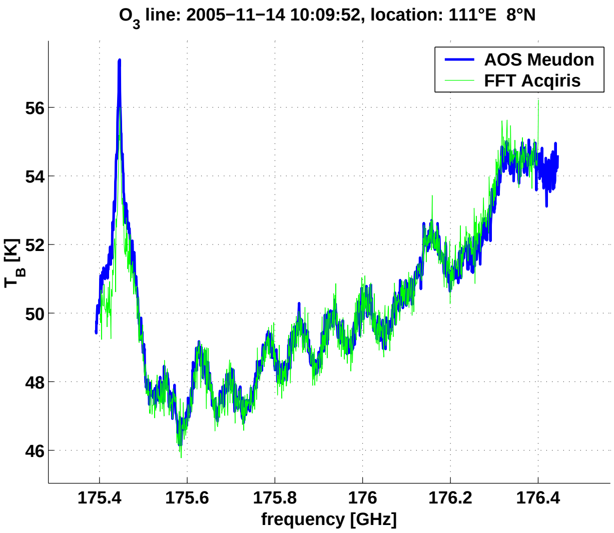


Fig. 9. $O_3$ line at 175 GHz. The channels of both spectrometers are binned to approximately 1 MHz.

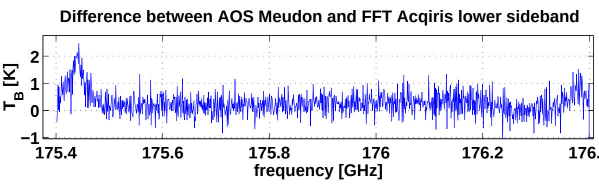


Fig. 10. Difference between broadband FFT and AOS spectrometer in the lower sideband.

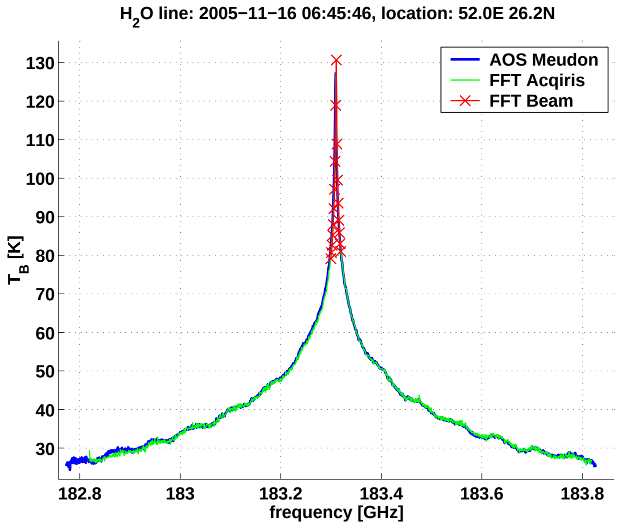


Fig. 11. $H_2O$ line at 183 GHz. The channels of the spectrometers are binned to approximately 1 MHz.

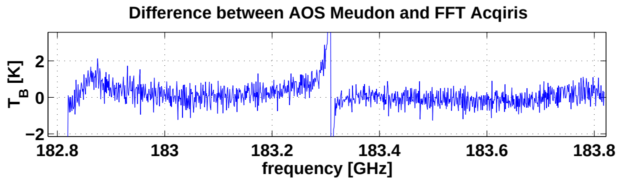


Fig. 12. Difference between broadband FFT and AOS spectrometer in the upper sideband.

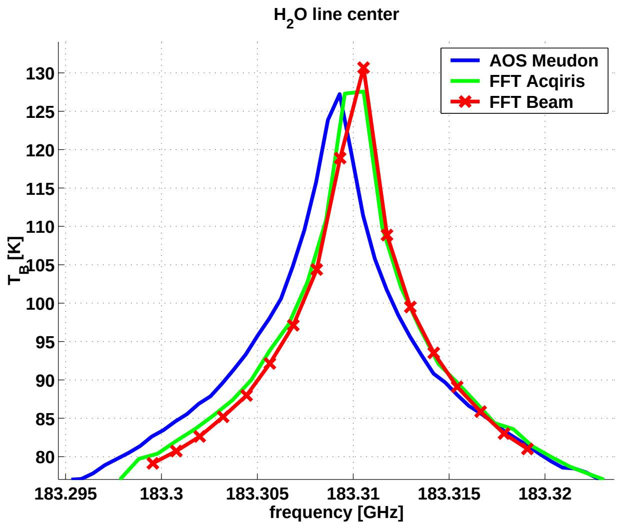


Fig. 13. $H_2O$ line center. The channels of the spectrometers are binned to approximately 1 MHz.

## IV. Conclusion

The novel technique of Digital Fast Fourier Transform spectrometers is a promising alternative to conventional accousto optical spectrometers. They are superior concerning resolution and stability and they proof to be linear to a high degree. First measurements of stratospheric ozone and water vapour from

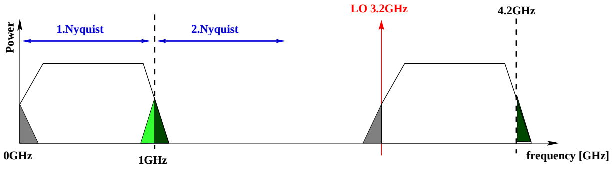


Fig. 14. Difficulties in downconversion to the first Nyquist band. If the LO frequency extend into the analyzed band, the part filled in gray color will be folded into the spectrum and will disturb it. If the bandpass filter covers more than the first Nyquist band the part from the neighboured Nyquist band (dark green) will also be folded into the spectrum (light green).

ground as well as from aircraft during SCOUT-O3 campaign in november 2005 were very successful.


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