Characterization of Digital Real-Time Spectrometers for Radio Astronomy and Atmospheric Remote Sensing

Axel Murk, Mikko Kotiranta

Abstract— **High resolution real-time spectrometers are widely used for radio astronomy and atmospheric remote sensing. Today these are mostly realized by high-speed digital signal analyzers. In this contribution we compare the radiometric performance of different commercially available digital Fast Fourier Transform (FFT) and Polyphase Filter-Bank (PFB) spectrometers. It is found that the radiometric noise of the individual channels corresponds for both types very well to the theoretical value, but that the FFT and PFB spectrometers have a different behavior when channels are binned. We also report on spectroscopic linearity issues in one of the older FFT spectrometers.**

Index Terms—**Digital signal processing, microwave radiometry, radio astronomy, remote sensing, real-time spectrometer.**

I. INTRODUCTION

High resolution real-time spectrometers are needed for both radio astronomy and atmospheric remote sensing. In the past discrete filter banks, acousto-optical spectrometers (AOS) or chirp-transform spectrometers (CTS) were used for this purpose, but with the advances of fast analog-to-digital converter (ADC) and field programmable gated array (FPGA) circuits it became possible to process sufficiently wide bandwidths in real-time using digital signal analyzers. One of the first commercially available models was based on the AC240 digitizer from the company Acqiris. It uses an 8-Bit ADC and calculates a Fast-Fourier Transformation (FFT) with 16384 channels over a bandwidth of 1 GHz [1][2]. More recent digital spectrometer models have ADCs with higher sampling rates to process bandwidths of 4 GHz or above. They can be also equipped with ADCs with more bits of resolution, which improves the spurious free dynamic range of the instrument.

The first digital spectrometers used a standard FFT analysis, which results in a channel response of $|\sin(x)/x|^2$. This relatively high spectral leakage can be reduced by tapering the time domain signals with an optional window function. But since this also leads to a coarser frequency resolution and a significant loss of sensitivity it is in most cases preferred to operate the FFT spectrometer without a window function.

Most modern digital spectrometers process the time domain data with a digital polyphase filter bank (PFB) algorithm instead of an FFT. This results in a channel response with a much faster sidelobe roll-off and almost ideal channel separation compared to an unwindowed FFT. Equally important, it does not lead to a significant loss of sensitivity [3].

The Institute of Applied Physics (IAP) at the University of Bern operates a variety of microwave radiometers for remote sensing of the Earth's atmosphere. This includes observations of ozone, water vapor, wind and temperature in the stratosphere where the pressure broadening of the emission lines allows to retrieve vertical profiles of these quantities. A high linearity and a well-known channel response of the spectrometer are essential for these observations. Over the years we replaced all filter banks, AOS and CTS of our radiometers with digital FFT and PFB spectrometers. In this paper we compare the noise performance and linearity of these commercially available digital back-ends.

II. SPECTROMETER COMPARISON

Table I gives an overview of the spectrometers which were included in the comparison.

TABLE I
SPECTROMETER PROPERTIES

Model	Bandwidth [MHz]	Channels	ADC Bits	Type
AC240 Acqiris	1000	16384	8	FFT
U5303 Acqiris	1600	16384	12	PFB
AFFTS 1500 RPG	1500	8129	8	PFB
AFFTS 100 RPG	100	16384	8	PFB
XFFTS 500 RPG	500	32489	10	PFB
USRP X310 Ettus	200	16384	14	FFT

The AC240 was introduced in 2005 and resulted from a collaboration between the company Acqiris and the Swiss universities ETHZ and FHNW [1]. The available processing resources which were available on the Virtex-2 FPGA at that time did not allow to calculate the FFT over this bandwidth and resolution without any truncation errors. These lead to small numerical artifacts and nonlinearities on the accumulated data which are only noticeable after long integration times. Nevertheless, the AC240 has been successfully used by different groups for atmospheric remote sensing and radio astronomy. This outdated hardware is no longer available and

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has been replaced by the Acqiris U5303. For this powerful dual channel signal acquisition board ETHZ, FHNW and IAP developed with Acqiris and advanced PFB spectrometer firmware. It has a much better dynamic range and does not produce any numerical truncation errors. It also includes several advanced features such as I/Q signal processing with amplitude and phase corrections, cross correlation, and a Kurtosis analysis for RFI mitigation [4]. The capabilities of this new spectrometer will be reported elsewhere in an upcoming publication.

The AFFTS is the first generation of PFB spectrometers developed at the Max-Planck Institute for Radio Astronomy (MPIfR). Its successor XFFTS from MPIfR is capable to process a wider bandwidth with a higher resolution and a better dynamic [3]. It is distributed with firmware for different bandwidths by the company Radiometer Physics (RPG) [5].

The USRP X310 is a software defined radio (SDR) platform developed by Ettus Research [6]. Its on-board FPGA can be used for signal processing through the open source GNU Radio software framework, but it is also possible to develop customized firmware for it with the LabVIEW Real-Time environment from National Instruments. We have used this option to develop a FFT spectrometer firmware with 200 MHz processed bandwidth. As an option the SDR can zoom into a spectral region with higher frequency resolution, or the bandwidth can be extended by frequency switching at the cost of integration time in each spectrum. This spectrometer is currently used in one of our operational radiometers for the observation of stratospheric winds [7].

A. *Channel Response*

Fig. 1 compares the measured channel response of the PFB spectrometers AFFTS and U5303 with the FFT spectrometer AC240 without a window function. It shows the significant sidelobes of the FFT, which are above -15 dB. According to [3] the AFFTS and XFFTS should have a similar sharp roll-off to less than -50 dB as the U5303. It is currently not clear whether the observed shoulders starting at the -30 dB level are an artefact of phase noise in this measurement, or a firmware bug in this specific early AFFTS model which was available at IAP for this measurement.

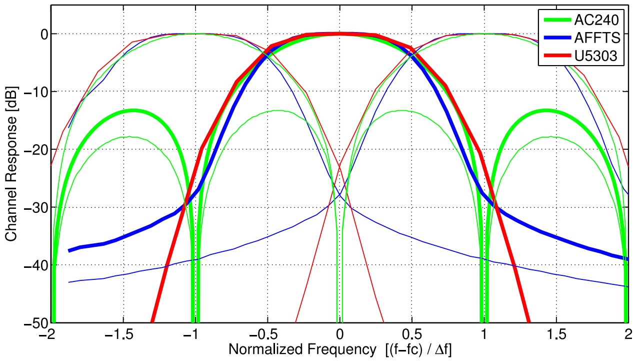

Fig. 1. Channel response of the FFT spectrometer AC240 compared to two PFB spectrometers with significantly lower sidelobes. The frequency axis is normalized with the channel spacing, and the response of neighboring channels is shown in thinner lines of the same color.

B. *Radiometer Setup*

The two Acqiris spectrometers AC240 and U5303 and two USRP X310 were connected to a single radiometer frontend to allow simultaneous observations of hot and cold blackbody calibration targets or atmospheric emission lines. The radiometer is a single sideband heterodyne receiver with an uncooled WR-10 low noise amplifier (LNA), and it is tuned to the 110.8 GHz ozone line. It also includes two noise diodes which can be injected before the LNA for calibration purposes and to verify the linearity of the system. One of the two USRP receivers was tuned to a weaker CO line at 115.3 GHz. This SDR channel USRP-B was operated with 20 instead of 200 MHz bandwidth and had thus a ten times higher frequency resolution than USRP-A. Figure 2 shows the schematic block diagram of the radiometer which is described in more detail in [8]. The overall system noise temperature of the setup was around 550 K in the ozone band and 650 K around the CO band which is beyond the nominal frequency band of the LNA.
The AFFTS and XFFTS spectrometers were not integrated in this 110 GHz radiometer setup.

C. *Spectral Line Observations*

Figure 2 compares the calibrated ozone spectra which were measured simultaneously by the AC24, U5303 and USRP spectrometers. For this figure the channels of the different spectrometers were binned to a comparable resolution.

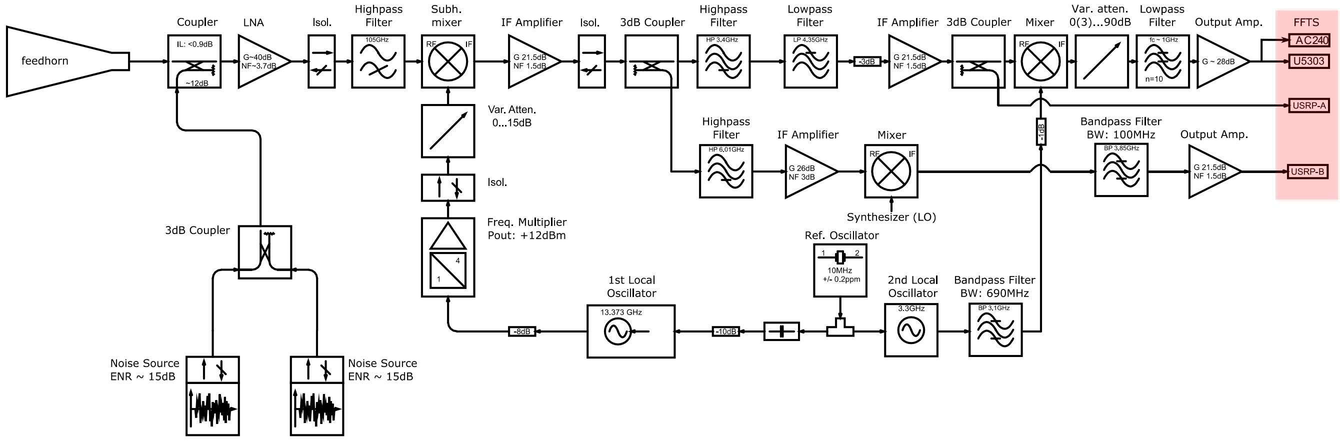

Fig. 2. Block diagram of the 110 GHz radiometer which was used for the spectrometer comparison.

The spectra of the USRP and U5303 coincide very well with each other. The AC240 spectrum, however, has a systematically smaller line amplitude than the two other spectra. Also the slope on the AC240 spectrum, which is caused by the line wing of a strong oxygen line at 118 GHz, has a different inclination than with the two other spectrometers.

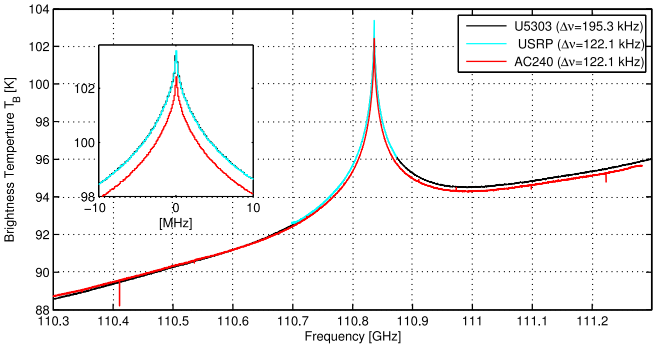

Fig. 3. Ozone line observed simultaneously with three different FFT spectrometers. The zoom in the inset highlights the systematic bias of the AC240 spectrometer.

The observed behavior cannot be explained by a simple analog gain compression effect in the AC240 input circuit. Such non-linearities would lead to an overall offset over the full bandwidth, including the line wings. This was also verified by comparing the signal levels for different combinations of hot and cold load measurements in which either one, two or none of the noise diodes is switched on. The excess noise ratio (ENR) of the noise diodes remains the same for all spectrometers independent whether they are turned on over the hot or cold input signal, which indicates that the bias of the AC240 only occurs for spectral line signals. It is also not possible to explain the bias with the $|\sin(x)/x|^2$ channel response of the FFT. For that reason we suspect that this systematic error is caused by the numerical rounding errors, which might lead to a higher spectral leakage which is not observed in the channel response measurements with the CW signal. We are planning to investigate this in the future by an analysis of the bias between the ozone spectra under different weather conditions, i.e. for different line amplitudes and distances from the two reference temperatures, as well as by additional laboratory measurements.

D. Radiometric Noise

According to the radiometer equation a noise signal with an expectation value of its power $\langle P \rangle$ can be observed with a standard deviation σ_P depending on the the integration time τ and the fluctuation bandwidth Δf_{neq}:

$$\sigma_P \,/\, \langle P \rangle \;=\; 1/\sqrt{\Delta f_{neq}\;\tau}$$

For an ideal FFT spectrometer without a window function the theoretical fluctuation bandwidth Δf_{neq} is identical with the channel spacing Δf. In order to investigate whether this criterium is met with the spectrometers under test we recorded time series of several thousand spectra with integration times of either 50 ms or 1 s. In order to distinguish between radiometric noise and instrumental drift we first subtract consecutive spectra from each other before we calculate the standard deviation. Because of this differentiation the result needs to be scaled by a factor of $\sqrt{2}$ to obtain the correct value of σ_P. This test is very similar to a standard Allan variance measurement [9], but here we are focusing only on the radiometric noise at short integration times to assess the efficiency of the spectrometers. The Allan time τ_A, where the instrumental drift dominates over the radiometric noise, will be in most cases determined by the radiometer front-end.

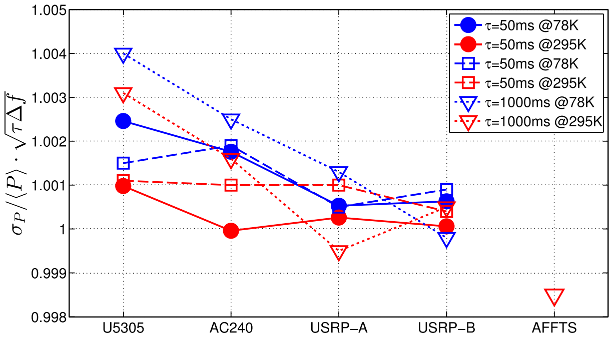

Fig. 4. Normalized radiometric noise of the different spectrometers measured with different integration times while observing a hot or a cold target.

The Allan variance is usually plotted on a double logarithmic scale, which does not allow to identify small deviations from the nominal noise bandwidth. Fig. 4 shows the normalized radiometric noise for a single spectrometer channel. To improve the statistics of the measurement it was calculated as an average of the normalized noise over all spectrometer channels. Anomalous channels at the edge of the spectrometer bandpass or which are affected by spurious signals were excluded from the average since they would bias the result. The remaining thousands of channels did not indicate any systematic variations of the normalized noise over the bandwidth, even if the total powers vary over several dB of magnitude over the spectrometer bandwidth.

The values in Fig. 4 deviate only by a few ppm or less from unity. This indicates that the noise performance of the FFT spectrometers is almost identical with the theoretical value. For the PFB spectrometers this behavior is not self-evident since the channel response and noise performance will depend on the selected window functions. With the AFFTS a value of about 0.9985 is observed, which means that the fluctuation bandwidth is by a factor 1.003 wider than the channel spacing. According to [3] the PFB has been designed for a nominal noise equivalent bandwidth of 1.16 of the channel spacing, i.e. we should observe an even smaller level of radiometric noise. However, since this measurement was obtained only with a 1s integration time we cannot rule out that this measurement was not affected by instrumental drift. Also for the U5303 the measurements with 1 s integration time have a noticeably higher normalized variability than with 50 ms, which indicates that the Allan variance curve deviates already at these integration times from the expected behavior of $1/\sqrt{\tau\ \Delta f}$.

Another interesting feature in Fig. 4 is the fact that the normalized radiometric noise on the cold load seems to be systematically higher than on the ambient load. This could probably be explained by quantization noise of the received thermal radiation, or by short term fluctuations due to standing waves from the instable LN2 surface of the cold load.

E. Channel Binning

In most applications several spectrometer channels will be binned together to reduce the noise and the number of channels. It is thus of interest to know whether the radiometric noise is reduced according to the square root of the number of binned channels.

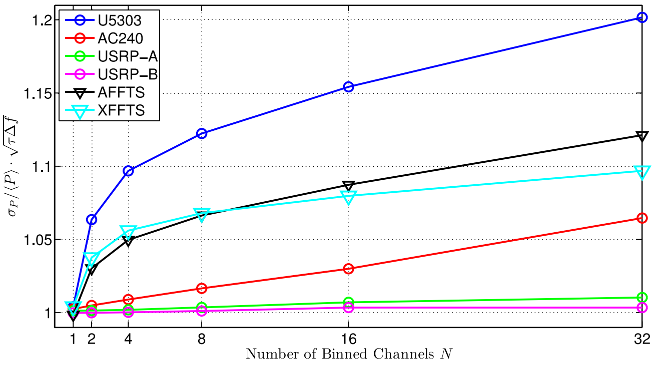

Fig. 5. Normalized radiometric noise of the different spectrometers depending on the number of binned channels.

A similar analysis was performed in [9] for the AOS of the HIFI instrument on the Herschel spacecraft. Since the AOS channels have a significant overlap the noise between adjacent channels is correlated. As a result, binning of N channels does not reduce the noise by a factor of $\sqrt{N}$.

With an ideal digital FFT spectrometer the noise in adjacent channels should be uncorrelated. Figure 5 shows the normalized radiometric noise of the different digital spectrometers depending on the number of binned channels. The two FFT spectrometers USRP-A and USRP-B with an analyzed bandwidth of 200 MHz and 20 MHz, respectively, behave under channel binning very similar to the ideal case. With the AC240 the noise seems to be reduced less efficiently by the binning and a linear increase of the normalized noise with the number of binned channels is observed. Part of this could be probably explained by the increasing influence of gain variations similar as in an Alan variance plot, but his effect should be rather small since these measurements were conducted with a very short integration time of 50 ms. The largest deviations are observed for all PFB spectrometers, in particular for the first two channels that are binned. This indicates a significant correlation of the noise in adjacent channels, which is surprising since the channel response of these spectrometers is very close to an ideal rectangular filter shape.

III. CONCLUSIONS

Digital spectrometers with high frequency resolution have become a key technology for radio astronomy and microwave remote sensing. In this paper we characterized and compared the radiometric noise performance, channel response, binning artifacts and linearity of a different FFT and PFB spectrometers. For the outdated FFT spectrometer AC240 we observed a significant spectroscopic nonlinearity, which leads to a scaling error of the observed emission lines. It will be important to understand the systematics of this effect in more detail and to find a way to correct this systematic error in the already existing long-term atmospheric data series which were collected with this type of spectrometer.

More recent FFT and PFB spectrometers do not suffer from this effect. The PFB models provide an excellent channel response and low spectral leakage, which is especially important if the observations are disturbed by narrow band radio interferences. However, our tests also indicate that the different PFB models suffer from correlated noise between adjacent channels. As a result the noise reduction by channel binning is less efficient than for a standard FFT spectrometer. The reasons for this effect are currently not understood and will need further investigations.

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