A new generation of spectrometers for radio astronomy

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Abstract

We present a new generation of very flexible and sensitive spectrometers for radio astronomical applications: Fast Fourier Transform Spectrometer (FFTS).
The rapid increase in the sampling rate of commercially available analog-to-digital converters (ADCs) and the increasing power of field programmable gate array (FPGA) chips has led to the technical possibility to directly digitize the down-converted intermediate-frequency (IF) signal of coherent radio receivers, and to Fourier transform the digital data stream into a power spectrum in continuous real-time, with no gaps in the data. In the last years FPGAs have become very popular for building fast and reconfigurable hardware. State-of-the-art chips include several hundreds dedicated 18 bit x 18 bit multipliers which allow up to 80 billion multiplication and nearly 500 billion 36-bit additions, which gives these FPGA chips over 50 times higher performance than the latest Intel Pentium 4 processors. This extremely high computation power makes it possible to implement real-time FFTs to decompose a 1 GHz band into 32768 spectral channels.
In this paper we present the technological concept and first-light results of both our narrow-band 50 MHz FFTS with 1024 channels and digital down-converter techniques as well as the new broad-band 1 GHz FFTS with up to 32768 frequency channels. Both backends can be considered prototypical for spectrometer development for future radio astronomical applications.

Introduction

A wealth of information on the physical conditions of astronomical sources can be gathered using spectrometers. Today these spectrometers offer useable coherent bandwidth from a few MHz to 1-2 GHz, with a few thousand spectral channels capable of resolving narrow spectral lines of masers and the thermal line emission of gaseous clouds.
Since a few years, it has become possible to develop multifeed arrays in continuum (bolometers) as well as multipixel heterodyne receivers for spectroscopy, e.g. CHAMP [1]. Multifeed/-pixel receivers provide a more efficient method to observe large areas of the sky, gaining in observing time efficiency essentially by the number of receivers that can observe simultaneously. The huge impact of multifeed receiver on HI and in pulsar astronomy [2] is illustrated by the Parkes 21-cm system [3]. And at higher frequencies the 230 GHz multibeam receiver HERA at the IRAM 30-m telescope has been in high demand for wide-field molecular line mapping projects. Unfortunately, the spectrometers have not develop at the same pace as the receiver technology. Neither the number of spectral channels nor the number of spectrometers or the bandwidth have increased significantly for spectrometers with resolution in the few 10 kHz range, i.e. for velocity resolved line observations of Galactic sources at mm-wave.
The novel FPGA-based FFT spectrometer (FFTS) will offer new perspectives. Today, complex FPGAs are able to perform digital signal algorithm at clock rates up to 150 MHz. By parallelization single processing pipelines it becomes possible to implement 32K-point Fourier transforms for input data rates up to 2 GBytes/sec. The advantage of FPGAs are their wide availability, decreasing costs (both based on the large commercial interest) and increasing process capability (Moore's Law), which makes it very likely that FFTS can be pushed to broader bandwidth in the near future.

Spectrometer for radio astronomy

Since commercially available spectrum analyzers use frequency sweepers to obtain a broad-band spectrum, they are not sensitive enough for radio astronomical applications. Therefore, special instruments have been developed for coherent spectral analysis. For radio frequencies one can differentiate three basic types of spectrometers: filter banks, acousto-optical spectrometer, and autocorrelators. Early on, spectrometers were build using analog (bandpass) filters and detectors, which were then assembled into filterbanks. Later on, acousto-optical spectrometers (AOS) were developed which allowed for wider bandwidth and a larger number of spectral channels. Due to their acousto-optical design, they are however technically elaborate and difficult to stabilize.

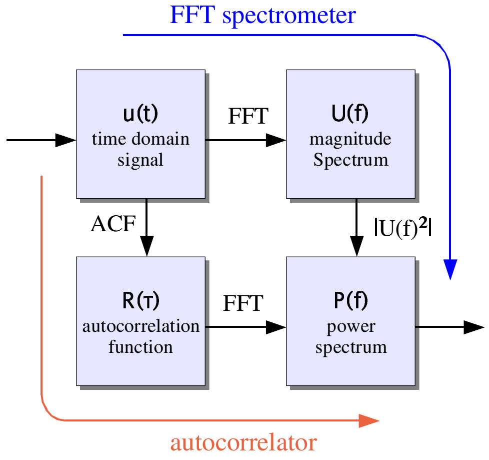

Fig 1 Visualization of the "Wiener-Khinchin-Theorem"

The most common spectrometer in use are digital autocorrelators (AC). This technology is based on the Wiener-Khinchin-Theorem, stating that the power spectrum of a signal is the Fourier transform of its autocorrelation function (ACF), as illustrated in Fig 1. The advantage of this indirect method is the possibility to accumulate the ACF even before the Fourier transform produces the final power spectrum, which reduces the number of and thus enables the calculation of the FFT in the early days. The ACF is computed by multiplication of the periodically time-shifted signals, followed by a summation of these. If one limits the sampler resolution to 1 or 2 bit, these three operations (shift, multiplication, addition) can be reduced to simple logical elements, and the ACF can be integrated in a customize silicon chip. The reduction to 1 or 2 bit (mostly 3-level) data sampling however results in a reduced sensitivity. Despite this disadvantages, AC have until recently been the only way to reduce the computation intensive Fourier transform, so that bandwidth of order 1 GHz were possible to be handled.

The narrow-band FFT Spectrometer

The narrow-band FFTS was joint development between the Radioastronomisches Institut (University Bonn) and the Max-Planck-Institut für Radioastronomie (MPIfR). This first FPGA-based FFTS was projected as a prototype to demonstrate this novel processing techniques and to serve as a backend for a new 7-beam 21-cm receiver for the 100-m Effelsberg telescope, which is currently under construction at the MPIfR. Based on a commercially available PMC/PCI bus board, this spectrometer transformed a time sampled signal to a 1024 channel spectrum with up to 50 MHz bandwidth. As a specific feature, this spectrometer uses undersampling techniques to avoid analog IF-mixing, which causes instabilities due to temperature and aging effects. In addition, digital down converter (DDC) chips on the board allow a zooming to spectral features of particular interest. Fig. 2 illustrates the frequency diagram for the realized narrow and broad band mode. Further details are described in [4,5,6].

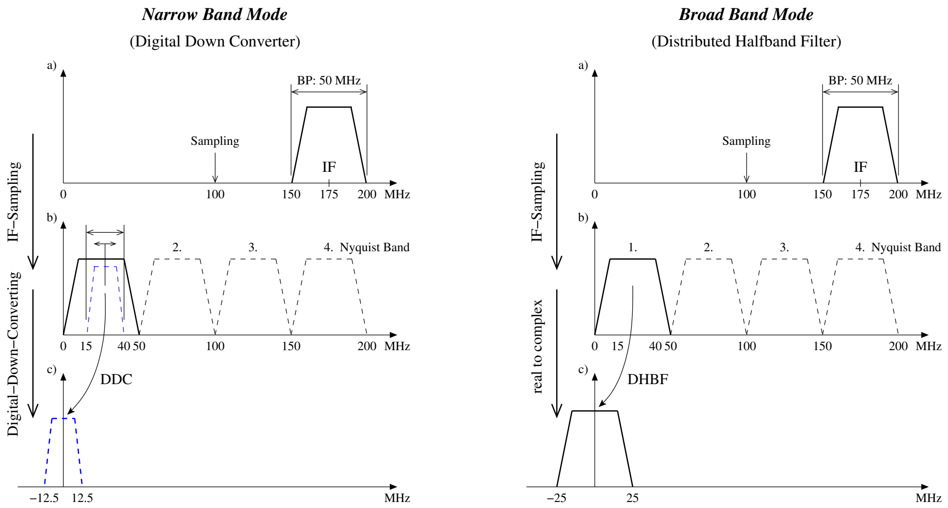

Fig 2 Concept of IF-downconverting to baseband by using undersampling techniques. The limited 150-200 MHz IF-band can be full acquired in the 4th Nyquist zone by sampling at 100 MHz. Since the Fourier transform works most efficiently with complex (I,Q) input signals, a digital halfband filter (broad band mode) and DDCs (narrow band mode) are used to convert the baseband to frequencies centered around 0 MHz. In addition, the DDCs offer to select sub-bands with tunable center frequencies.

The 1 GHz bandwidth / 32768 channel FFT Spectrometer

The broad-band FFTS is based on the currently most powerful digitizer/analyzer board available from Acqiris, Switzerland (Fig. 5). It incorporates two 1 GS/sec ADCs which feed a XILINX Virtex 2 Pro70 FPGA chip. By combining both ADCs in an interleave manner (180 deg phase-shift), the board is capable to sample an analog input signal at 2 GHz clock rate which results in a 1 GHz Nyquist bandwidth.
A spectrometer core for this card was offered by RF Engines Ltd. (RFEL) and integrated by the MPIfR digital group [7]. The spectrometer core is based on RFEL's HyperSpeed Fast Fourier Transform (FFT) technology. It receives 8-bit samples from the two ADC at a continuous sample rate of 2 GHz, and then processes this data in a sequence of four steps:
First, a Half Band Filter converts samples to a complex I/Q-format, and reduces the sample rate by a factor of two (decimation), which eases the subsequent processing requirements. This is followed by the application of a windowing function (Blackmann-Harris), which weights the data in order to control the filtering performance of the FFT. The window coefficients are user programmable at run-time, allowing the performance characteristics of the spectrometer to be modified for changing operational scenarios.
The 32K-point HyperSpeed FFT core from RFEL forms the central element of the system, performing the conversion from the time-domain to the frequency-domain, and it includes bit reversing to sort the data in natural frequency order. The FFT is built using a highly parallel architecture in order to achieve the very high data rate of 2 GBytes/sec.
The final step of processing contains the conversion of the frequency spectrum to a power representation, and successive accumulation of these results. This accumulation step has the effect of averaging together a number of power spectra, thereby reducing the background noise and improving the detection of weak signals. This step also reduces the huge amount of data produced by the prior stages, and eases any subsequent interface bandwidth requirements and processing loads. The output from the spectrometer core is in a 32-bit floating-point format, which allows data to be efficiently post-processed by standard desktop computers. The processing sequence is shown in Fig. 3.

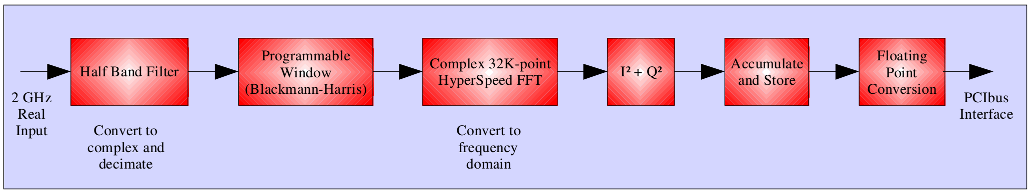

Fig 3 A block diagram of RF Engines 2 GHz Spectrometer Core for FPGA.

The broad-band FFTS is currently successfully operated at the new Atacama Pathfinder EXperiment (APEX) telescope and produces high resolution (30.5 kHz) spectra at a bandwidth of 1 GHz. Fig. 4 shows the spectrometer setup at APEX.

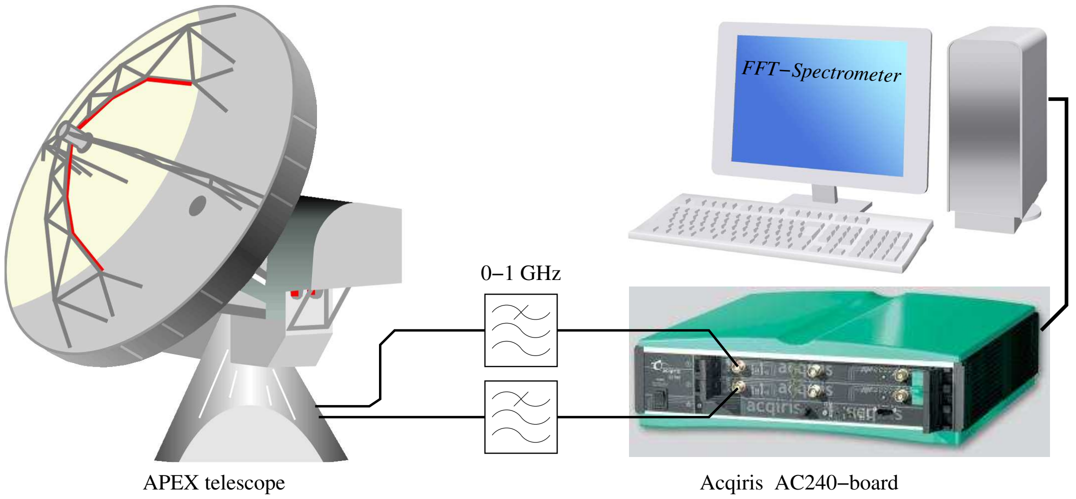

Fig 4 The broad-band FFTS installed at the APEX telescope is able to cover a frequency-bandwidth of up to 2 x 1 GHz using two commercially available ADC/FPGA digitizers.

Summary of results and key points

The potential advantages of FPGA-based FFT spectrometer compared with past spectrometers can be summarized as follows:

- High bandwidth (1 to a few GHz in the future) with up to 32K spectral channels in a single FPGA chip
- Full signal sampling with 8-bit (broad-band FFTS) and 14-bit (narrow-band FFTS), no additional calibration by means of implicit total power measurements, thus higher sensitivity and stability in comparison with autocorrelators and acousto-optical spectrometers
- Very high stability via pure digital signal processing (Fig. 6)
- Modular design with calibration-free digitizer/analyzer boards, thus simple reproducibility
- Low space and power requirements – thus safe to use at high altitude (e.g. APEX at 5100-m) as well as on spacecrafts and satellites
- Low price compared to traditional spectrometers through use of commercial parts:
  currently ~20 k€ per GHz bandwidth
- The new FFTS are well proven at the 100-m Effelsberg telescope as well as at APEX (Fig. 7)

Fig 5 Acqiris ADC/FPGA board AC240

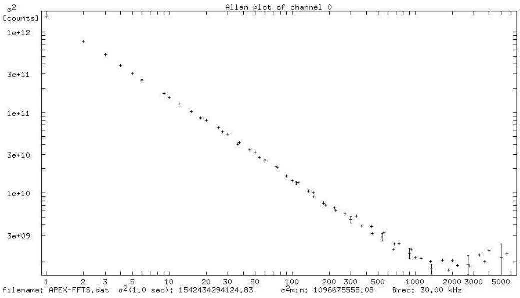

Fig 6 Measured Allan Variance of APEX FFTS, showing high stability resulting in possible integration times of up to 1000 seconds. Almost twice the time of good autocorrelators.

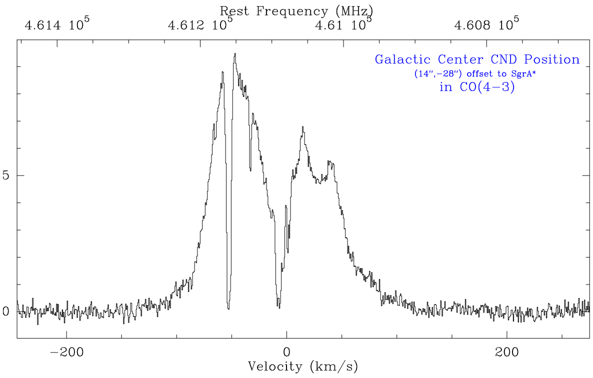

Fig 7 One of the first spectra in the CO (4-3) line obtained with the APEX FFTS in combination with the FLASH receiver in the 460 GHz atmospheric window on a position (14",-28") offset the galactic center (SgrA) within the Circum-Nuclear-Disk (CND). Prominently visible are the absorption features caused by line-of-sight molecular clouds, which extends out to ~ ± 130km/s.*

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