The Next Generation of Fast Fourier Transform Spectrometer

Bernd Klein*, Ingo Krämer, Stefan Hochgürtel, Rolf Güsten, Andreas Bell, Klaus Meyer, and Vitaly Chetik

Max-Planck-Institut für Radioastronomie, Bonn, Germany

* Contact: bklein@mpifr-bonn.mpg.de, phone +49 228 525-286

***Abstract*— We present our second generation of broadband Fast Fourier Transform Spectrometer (FFTS), optimized for a wide range of radio astronomical applications. The new digitizer and analyzer boards make use of the latest versions of GHz analog-to-digital converters and the most complex field programmable gate array chips commercially available today. These state-of-the-art chips have made possible to build digital spectrometers with instantaneous bandwidths up to 1.8 GHz and 8192 spectral channels.**

I. Introduction

The rapid increase in the sampling rate of commercially available analog-to-digital converters (ADCs) and the permanently increasing processing power of field programmable gate array (FPGA) chips has led to the technical possibility to digitize the baseband mixed intermediate frequency (IF) of heterodyne radio-receivers, and to transform the digital signal stream into a power spectrum in real-time. At the Max-Planck-Institut für Radioastronomie (MPIfR), this technology has been advanced over the last ~5 years: Beginning with a bandwidth of just 2 × 50 MHz and 1024 (1k) channels in 2003 [1], we have now developed FFTSs with instantaneous bandwidths up to 1.8 GHz and many thousands spectral channels (Fig. 1). Based on the announcement of once more faster ADCs and FPGAs with increasing processing capabilities, we are confident that FFTS' bandwidths can be pushed to ~3 GHz in the near future.

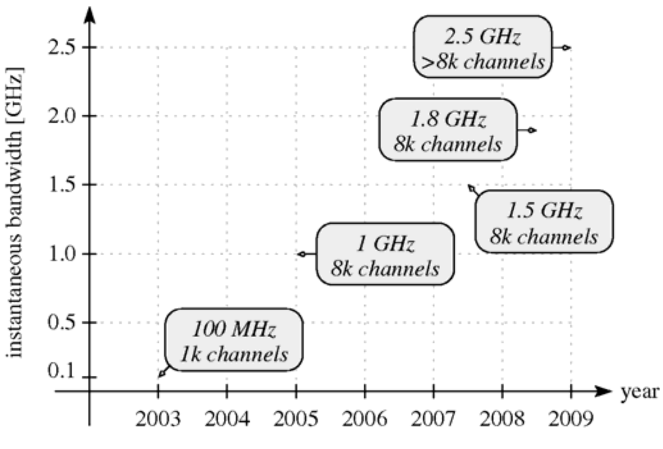

Fig. 3 FFTS developments at the Max-Planck-Institut für Radioastronomie.

II. The 1.5 GHz Bandwidth FFTS board

At the APEX telescope in Chile [2], we are successfully operating FFT spectrometers for more than 3 years ([3], [4]). They have proven extremely reliable and robust even under the harsh environmental conditions of a sub-mm facility at an altitude of 5100-m. Based on this experience we decided to launch the development of a second generation spectrometer based on ADC/FPGA technologies. For this, a compact FFTS-board has been designed at MPIfR which achieves wide instantaneous bandwidths (1.5 – 1.8 GHz) with several thousand spectral channels (up to 16k, depending on the bandwidth set-up). The board combines the latest version of GS/s ADC chips and the most complex FPGAs commercially available today. The wide analogue input bandwidth of the 8-bit ADC offers to sample the IF signals at baseband (DC to 1.5 GHz) or in the second Nyquist zone (1.5 – 3.0 GHz). A block diagram of the new FFTS-board is presented in Fig 2.

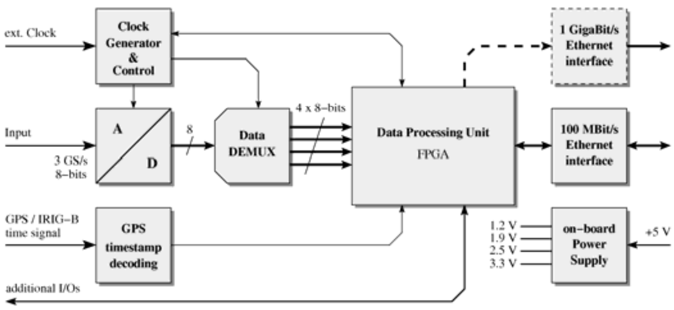

Fig. 4 Block diagram of the new MPIfR 1.5 GHz digitizer/analyzer board. The board can be equipped with a single- or dual-input ADC (ADC083000 or ADC08D1500). The optional GigaBit Ethernet interface allows high speed data acquisition with transfer rates up to 85 MBytes/s, which are required for pulsar or transient searches.

The compact FFTS-board (100 × 160 mm) operates from a single 5 Volt source and dissipates less than 20 Watt, depending on the actual configuration in terms of bandwidth and number of spectral channels. Precise time stamping of the processed spectra is realized by an on-board GPS/IRIG-B time decoder. Furthermore, the 10-layer boards include a programmable ADC clock synthesizer for a wide range of configurations (bandwidth: 0.1 – 1.8 GHz), making the spectrometer flexible for different observation requirements.

III. A-FFTS – An Array FFTS for APEX

To serve the requirements of today's and future receiver arrays (e.g., CHAMP$^+$, LAsMA, [5]), the new FFTS-boards include a standard 100 MBits/s Ethernet interface, which simplifies the combination of many boards into an Array-FFTS (A-FFTS), just by integrating of a common Ethernet switch. For use at APEX, we have build a 32 × 1.5 GHz A-FFTS in four 19" FFTS-crates (Fig. 3). Up to eight FFTS-boards can be housed in one FFTS-crate together with power supplies (4 × 5 Volt / 20 Amperes) and one FFTS-controller.

Fig. 5 Photograph of our 19 inch FFTS-crate, equipped with eight FFTS-boards and one FFTS-controller unit. The modular concept allows combining multiple crates to build large FFTS arrays.

The FFTS-controller is responsible for the distribution of global synchronize signals, e.g., the reference clock for the on-board ADC synthesizer or the GPS/IRIG-B timing information. In addition, the FFTS-controller displays housekeeping information on the four lines LCD, like board IP numbers, temperatures of the ADC and FPGA chips as well as the power level of the IF inputs.

The APEX A-FFTS has been successfully commissioned in spring 2008 [5]. In the current configuration, it provides a total bandwidth of 32 × 1.5 GHz = 48 GHz and 256k (32 × 8k) spectral channels. If requested, the A-FFTS can be extended to 58 GHz (32 × 1.8 GHz) total bandwidth by uploading a new FPGA processing core and a new ADC synthesizer setting. A first light spectrum of the novel FFTS-board towards Orion-KL is displayed in Fig. 4.

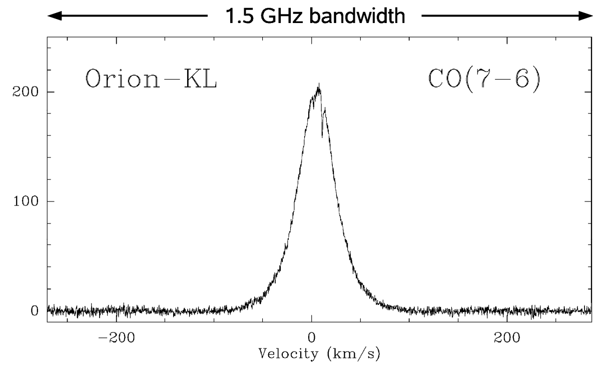

Fig. 6 First light spectrum of the new MPIfR-based 1.5 GHz bandwidth FFTS board towards the hot core Orion-KL. The high-excitation CO(7–6) transition at 806 GHz was observed with the central pixel of the CHAMP$^+$ array at APEX (24. October 2007).

IV. Advanced FPGA signal processing

As already described in [3], the complete signal processing pipeline (conversion from time domain to an integrated power spectrum) fits in one complex FPGA (Xilinx Virtex-4 SX55) on the board. The spectrometer core for the FFTS-board is an in-house development by MPIfR and – based on a generic VHDL approach – without the use of commercial libraries. Unlike the usually applied window in front of the FFT to control the frequency response, a more efficient polyphase pre-processing algorithm has been developed with significantly reduced frequency scallop loss, faster side lobe fall-off, and less noise bandwidth expansion. Fig. 5 illustrates the FPGA signal processing: After the polyphase filter, which we have implemented as a pipelined version of the Weighted Overlap-Add (WOLA) method, the FFT is realized using a highly parallel architecture in order to achieve the very high data rate of 3 GBytes/s or more. The next step of the processing contains the conversion of the frequency spectrum to a power density representation and successive accumulation of these results. This accumulation step has the effect of averaging a number of power spectra, thereby reducing the background noise and improving the detection of weak signals. In addition, this step also reduces the huge amount of data produced by the prior stages and eases any subsequent interfacing for the data analysis. The final step is the conversion from 64-bit integer representation to 32-bit floating-point format.

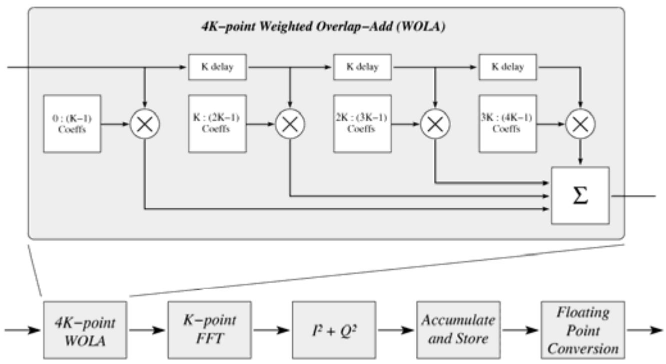

Fig. 7 Block diagram of the polyphase signal processing pipeline.

We have optimized our polyphase filter coefficients for spectroscopic observations. The goal was to find a good trade-off between the frequency resolution and an optimal use of the limited FPGA resources. The equivalent noise bandwidth (ENBW) is generally used to characterize the frequency resolution. The ENBW is the width of a fictitious rectangular filter such that the power in that rectangular band is equal to the (integrated) response of the actual filter. Our ENBW is adjusted to 1.16 × the channel spacing, which is the total bandwidth divided by the number of spectral channels. The frequency response of three adjacent frequency bins and the corresponding ENBW for the central bin is illustrated in Fig. 6. Following the above definition, the spectral resolution of our standard FFTS-board with 1.5 GHz bandwidth and 8k channels is 212 kHz.

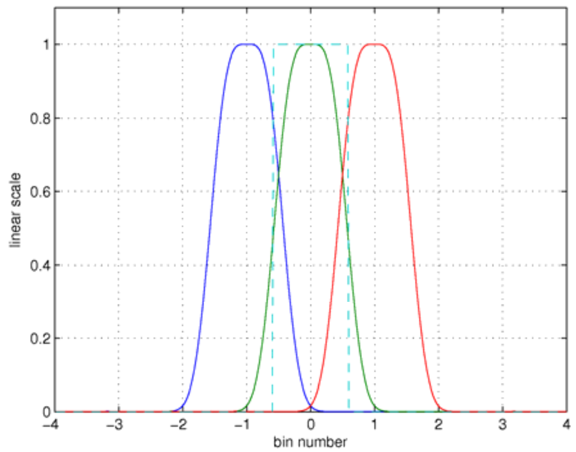

Fig. 8 Frequency response of the optimized FFT signal processing pipeline. The diagram shows three adjacent frequency bins. The dashed lines illustrate the equivalent noise bandwidth for the corresponding spectral bin.

Based on our generic approach, we have generated a set of different FPGA cores for the new FFTS-board:

1 × 1.5 GHz bandwidth, 1 × 8192 spectral channels, ENBW: 212 kHz (default core)
1 × 1.8 GHz bandwidth, 1 × 8192 spectral channels, ENBW: 225 kHz
1 × 750 MHz bandwidth, 1 × 16382 spectral channels, ENBW: 53 kHz
1 × 500 MHz bandwidth, 1 × 16382 spectral channels, ENBW: 35 kHz
1 × 100 MHz bandwidth, 1 × 16384 spectral channels, ENBW: 7 kHz (in lab test)
2 × 500 MHz bandwidth, 2 × 8192 spectral channels, ENBW: 71 kHz (in lab test)
2 × 250 MHz bandwidth, 8-tap polyphase filter bank, 512 channels, high speed data dumping, application: pulsar search

V. THE 2.5 GHZ BANDWIDTH FFTS DEVELOPMENT

With the availability of first samples of E2V's 5 GS/s 8-bit ADC, we start the development of a new advanced FFTS-board. The goal of this project is to develop a digitizer board, which is able to analyse 2.5 GHz of instantaneous bandwidth in 32k spectral channels (ENBW: < 100 kHz). E2V's 5 GS/s ADC incorporates 4 ADCs at 1.25 GHz which can be flexibly interleaved to a 2 × 2.5 GS/s or a 1 × 5 GS/s virtual ADC. The large analogue input bandwidth of the track-and-hold amplifier of this ADC offers the ability to use the full Nyquist bandwidth of 2.5 GHz. The ADC provides 8 separate low-voltage differential data busses to transfer the huge amount of data (5 GBytes per seconds) to one or more FPGA. In Fig. 7 we show a photo of our test board, including the 5 GS/s ADC and a Virtex-4 SX55 FPGA. To reach the final number of 32k spectral channels, the Virtex-4 will be replaced by two or more powerful Virtex-5 devices.

This wideband high-resolution FFT spectrometer development aims at operational readiness for SOFIA's early science flights with GREAT [6] in summer 2009.

Fig. 9 Currently in development: The 2.5 GHz bandwidth FFTS. The board makes use of a first sample of E2V's 5 GS/s 8-bit ADC.

CONCLUSION AND OUTLOOK

The potential advantages of our next generation of FFT spectrometers are summarized:

- They provide high instantaneous bandwidth (up to 1.8 GHz; 2.5 GHz currently in development) with many thousands frequency channels, thus offering wide-band observations with high spectral resolution without additional IF processing.
- The new polyphase FFT signal processing pipeline provides a nearly loss-free time to frequency transformation with significantly reduced frequency scallop, less noise bandwidth expansion, and faster sidelobe fall-off.
- FFTS provide very high stability by exclusive digital signal processing. Allan-Variance stability times of several 1000 seconds have been demonstrated routinely.
- Low space and power requirements – thus safe to use at high altitude (e.g., APEX at 5100-m) as well as (potentially) on spacecrafts (e.g., SOFIA) and satellites.
- Production costs are low compared to traditional spectrometers through the use of only commercial components and industrial manufacturing.
- The superior performance, high sensitivity and reliability of our FFTS have been demonstrated at many telescopes world-wide, including APEX (Chile), CSO (Hawaii), the IRAM 30-m telescope (Spain) and the 100 meter Effelsberg observatory (Germany).

The announcement of new ADCs with higher samples rates and wider analogue input bandwidths together with the still increasing processing power of future FPGA chips (Moore's Law), makes it very likely that FFTS can be further pushed to broader bandwidths in the next years.

Due to the high interest from the astronomical community, from universities and from the industry, we have decided to outsource the production and distribution of our FFT spectrometer: the standard FFTS (1.5 GHz bandwidth with 8192 spectral channel) is manufactured now in licence by Radiometer Physics GmbH, Germany. For further information, visit:

http://www.radiometer-physics.de

2008-09-25, BK

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