Fast Fourier Transform Spectrometer

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***Abstract*—We review the development of our digital broad-band Fast Fourier Transform Spectrometers (FFTS). In just a few years, FFTS back-ends - optimized for a wide range of radio astronomical applications - have become a new standard for heterodyne receivers, particularly in the mm and sub-mm wavelength range. They offer high instantaneous bandwidths with many thousands spectral channels on a small electronic board (100 x 160 mm). Our FFT spectrometer make use of the latest versions of GHz analog-to-digital converters (ADC) and the most complex field programmable gate array (FPGA) 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.**

Our latest development step is a prototype compact FFTS board with a new 5 GHz 8/10-bit ADC and an outstanding instantaneous bandwidth of 2.5 GHz. An early version of the board has been successfully field-tested at the APEX telescope and we present a first spectrum observed in November 2008.

***Index Terms*—Fast Fourier Transform Spectrometer, FFTS, instrumentation, spectrographs**

I. INTRODUCTION

At the Max-Planck-Institute für Radioastronomie (MPIfR) we develop digital Fast Fourier Transform Spectrometer since ~6 years: Beginning with a bandwidth of just 2 × 50 MHz and 1024 (1k) channels in 2003 [1], 1.5 GHz with 8k channels in 2007 [2], [3], we are currently developing a wideband FFTS with an instantaneous bandwidth of 2.5 GHz and likely 32k spectral channels. This corresponds to an improvement in bandwidth by a factor of 50 over 6 years or ~400 MHz per year. Today, FFT spectrometers cover all the requirements of line observations in radio astronomy. They provide wide bandwidths for mm and submm-observations and very high spectral resolution (kHz range) for radio sky frequencies of a few GHz. The high dynamic range of today's ADCs (8/10-bit) allows using FFTS for planet observations with high background and strong maser lines. FFTS are very stable as measured by long Allan variance times; they are calibration- and aging free and can be easy manufactured. Our FFT signal processing is based on a generic approach, which makes it possible to generate FPGA cores with different bandwidths and spectral resolution on a short time scale. Unlike the usual window-FFT processing, we use a more efficient 4-tap polyphase filter-bank algorithm, with significant less frequency scallop loss, less noise bandwidth expansion, and faster sidelobe fall-off.

Manuscript received 20 April 2009.

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II. AFFTS: THE 32 × 1.5 GHZ BANDWIDTH ARRAY-FFTS

To serve the requirements of today's and future receiver arrays (e.g., CHAMP$^+$, LAsMA [4]), we have developed a compact (100 × 160 mm) FFTS-board [5] with an on-board standard 100 MBits/s Ethernet interface, which simplifies the combination of many boards into an Array-FFTS, just by integrating of a common Ethernet switch. For use at the APEX telescope [6], we have combined 32 FFTS-boards in four 19 inch crates (Fig. 1). The APEX AFFTS has been successfully commissioned one year ago. 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 AFFTS bandwidth can be extended to 58 GHz (32 × 1.8 GHz) by uploading a new FPGA processing core and new ADC synthesizer parameters.

III. XFFTS: THE NEW 2.5 GHZ BANDWIDTH FFTS

With the availability of first samples of E2V's 5 GS/s 8-bit ADC in mid 2008, we have started the development of a new eXtended bandwidth FFTS (XFFTS) board [5]. The goal of this project has been to realize a digitizer board, which is able to analyze 2.5 GHz of instantaneous bandwidth. Already in Nov. 2008 we performed observations with this new XFFTS at the APEX telescope: the first light spectrum towards the extragalactic nucleus NGC253 is displayed in Fig. 2.

Still during this development a 10-bit 5 GS/s ADC became available by E2V with an even wider analogue input bandwidth: This new device allows capturing frequencies up to 3.85 GHz. To allow higher spectral resolution (the first test board was limited to just 256 spectral channels due to FPGA resources) we designed a new XFFTS board around E2V's novel 5 GS/s 10-bit ADC and replaced the Virtex-4 FPGA by a Xilinx Virtex-5 SX240T – one of the highest performance FPGA devices available today. In Fig. 3 we show a photo of our new XFFTS board that is currently undergoing first lab tests. It very likely, that FPGA resources will allow to implement a full polyphase filter-bank FFT signal processing pipeline with 32768 spectral channels for the 2.5 GHz wide band mode. By using our optimized filter coefficients, this FFTS will have a spectral resolution (equivalent noise bandwidth) of 88.5 kHz. This wideband high-resolution FFT spectrometer development aims at operational readiness for SOFIA's early science flights with GREAT in 2010 [7].

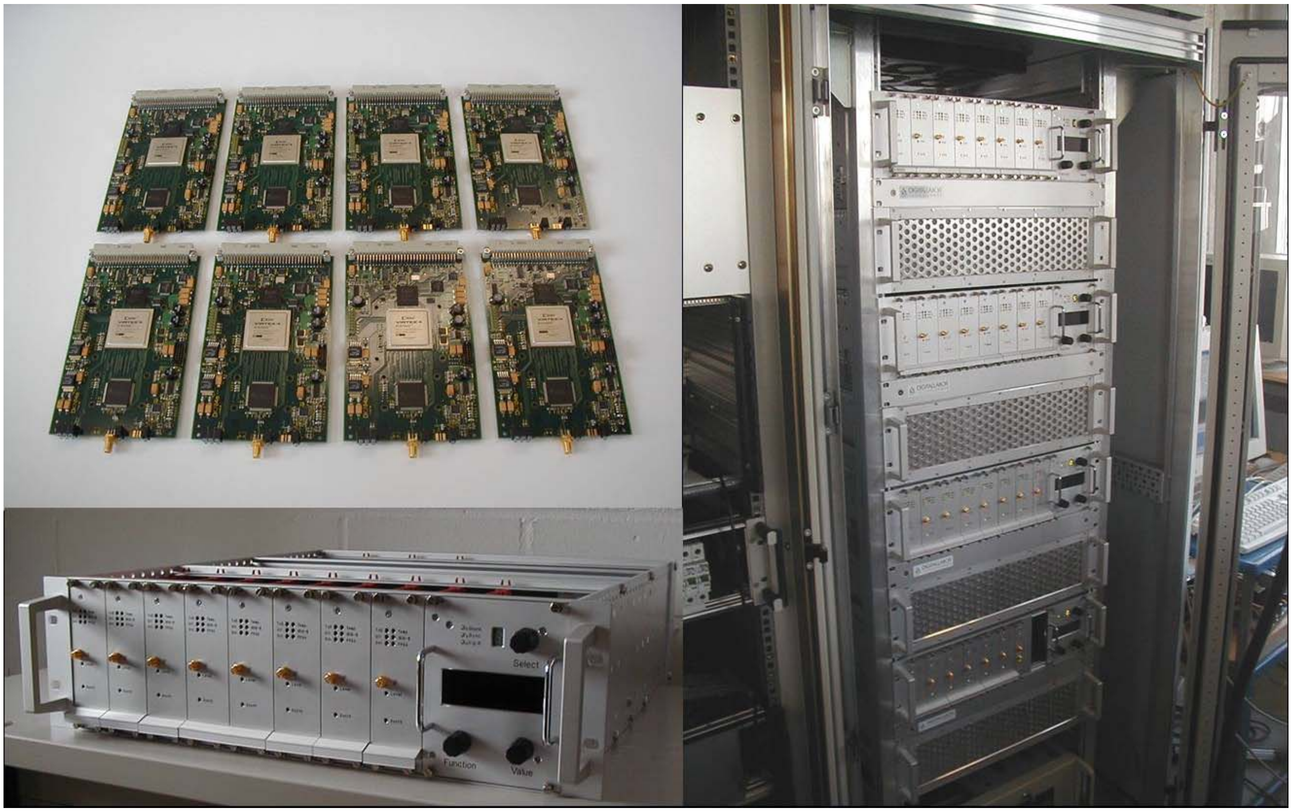

Fig. 1. The APEX wideband AFFTS consists of four FFTS-crates, each equipped with 8 FFTS boards and one FFTS-controller with LCD unit. The frequency resolution (equivalent noise bandwidth) for the standard board configuration with 1.5 GHz bandwidth and 8192 spectral channels per board is 212 kHz.

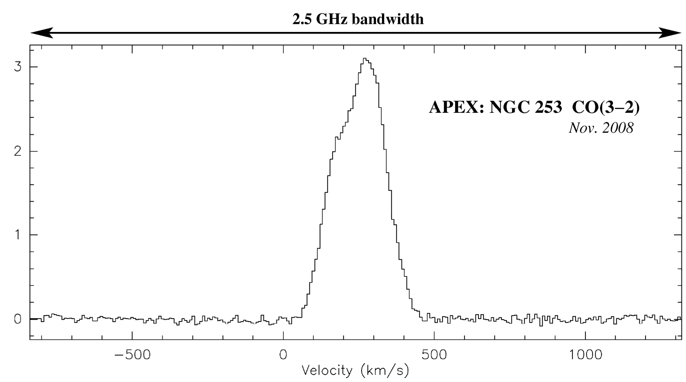

Fig. 2. First light spectrum of the new MPIfR 2.5 GHz XFFTS board towards NGC 253. The CO(3-2) transition at 345 GHz was observed with the APEX-2 facility receiver in November 2008.

Fig. 3. Currently in lab tests: The new 2.5 GHz bandwidth XFFTS, making use of a first sample of E2V's 5 GS/s 10-bit ADC and the high performance Xilinx Virtex-5 SX240T FPGA.

IV. Summary & Outlook

The potential advantages of our digital broadband Fast Fourier Transform Spectrometer are summarized:

- They offer high instantaneous bandwidth up to 2.5 GHz with many thousands frequency channels, thus offering wide-band observations with high spectral resolution. This simplifies the IF processing enormously, in terms of stability, aging, power dissipation, size and costs.
- FFTS provide very high stability by exclusive digital signal processing. Spectroscopic Allan variance times of several thousands seconds have been demonstrated routinely.
- Our optimized 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 side lobe fall-off.
- Low space and power requirements allow to operate FFTS at high altitude (e.g., APEX at 5100-m) as well as on airborne observatories (SOFIA) and future satellites.
- FFTS production costs are low compared to traditional spectrometers through the use of exclusively commercial components and industrial manufacturing.
- The superior performance, high sensitivity and reliability of our FFTS have been demonstrated at many observatories world-wide, e.g., APEX (Chile), CSO (Hawaii), the IRAM 30-m (Spain) and the MPIfR 100-m Effelsberg telescopes. In addition, FFTS are used in atmospheric research and in radiometer laboratories.

Based on our reconfigurable FFTS technology, we have recently developed a read-out system, operating in frequency domain, for arrays of Microwave Kinetic Inductance Detectors (MKIDs). First measurements show no deterioration of the noise performance compared to low noise analog mixing. Thus, this technique allows capturing several hundreds of detector signals with just one pair of coaxial cables [8].

The announcements of new ADCs with even higher sample rates ($f_s \geq 10$ GS/s) and wider analogue input bandwidth, together with the still increasing processing power of future FPGA chips (e.g., XILINX Virtex-6 family), make it very likely that FFTS can be further pushed to broader bandwidth in the next years.

REFERENCES

[1] S. Stanko, B. Klein, J. Kerp, "A Field Programmable Gate Array Spectrometer for Radio Astronomy", A&A, Vol. 436, pp.391-395, 2005.

[2] B. Klein, S.D. Philipp, I. Krämer, C. Kasemann, R. Güsten, K.M. Menten, "The APEX Digital Fast Fourier Transform Spectrometer", A&A, Vol. 454, pp. L29-L32, 2006.

[3] B. Klein, S.D. Philipp, R. Güsten, I. Krämer, D. Samtleben, "A new generation of spectrometer for radio astronomy: Fast Fourier Transform Spectrometer", Proc. of the SPIE, Vol. 6275, pp. 627511, 2006.

[4] R. Güsten, et al., "Submillimeter Heterodyne Arrays for APEX", Proc. of the SPIE, Vol. 7020, pp. 702010-702010-12, 2008.

[5] B. Klein, I. Krämer, S. Hochgürtel, R. Güsten, A. Bell, K. Meyer, V. Chetik, "The Next Generation of Fast Fourier Transform Spectrometer", Proc. of the 19. ISSTT, 2008.

[6] R. Güsten, et al., "APEX: the Atacama Pathfinder Experiment", Proc. of the SPIE, Vol. 6267, pp. 626714

[7] S. Heyminck, R. Güsten, P. Hartogh, H.-W. Hübers, J. Stutzki, U.U. Graf, „GREAT: a first light instrument for SOFIA", Proc. of the SPIE, Vol. 7014, pp. 701410-701410-7, 2008

[8] S.J.C. Yates, A.M. Baryshev, J.J.A. Baselmans, B. Klein, R. Güsten, "Fast Fourier Transform Spectrometer readout for large arrays of Microwave Kinetic Inductance Detectors"