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Letter to the Editor

High-resolution wide-band Fast Fourier Transform spectrometers

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ABSTRACT

We describe the performance of our latest generations of sensitive wide-band high-resolution digital Fast Fourier Transform Spectrometer (FFTS). Their design, optimized for a wide range of radio astronomical applications, is presented. Developed for operation with the GREAT far infrared heterodyne spectrometer on-board SOFIA, the eXtended bandwidth FFTS (XFFTS) offers a high instantaneous bandwidth of 2.5 GHz with 88.5 kHz spectral resolution and has been in routine operation during SOFIA's Basic Science since July 2011.
We discuss the advanced field programmable gate array (FPGA) signal processing pipeline, with an optimized multi-tap polyphase filter bank algorithm that provides a nearly loss-less time-to-frequency data conversion with significantly reduced frequency scallop and fast sidelobe fall-off. Our digital spectrometers have been proven to be extremely reliable and robust, even under the harsh environmental conditions of an airborne observatory, with Allan-variance stability times of several 1000 seconds.
An enhancement of the present 2.5 GHz XFFTS will duplicate the number of spectral channels (64*k*), offering spectroscopy with even better resolution during Cycle 1 observations.

Key words. Instrumentation: spectrographs – Techniques: spectroscopic

1. Introduction

Until the recent past signal processing instruments for radio-astronomical spectroscopy were highly dedicated developments, customized to the individual scientific application (Fig.1). Digital auto-correlators have been widely-used in the radio-astronomical communities since the detection in 1963 of the first interstellar molecule at radio wavelength, the hydroxyl radical OH (Weinreb et al. 1963), with the auto-correlation technique (Weinreb 1963). In a late version, the array auto-correlator serving the CHAMP heterodyne array (Wiedenhöver 1998; Kasemann et al. 2006) used the high-performance (*Canaris*) CMOS chip for a maximum bandwidth of 1 GHz with 1024 lags. In parallel, acousto-optical spectrometers (AOS) have been widely used, with comparable bandwidth limitations (Cole 1968; Schieder et al. 2003). For high spectral resolution applications, with limited bandwidth requirements, chirp transform spectrometers (CTS) are in operation (Hartogh 1997). The early back-end concept of GREAT, when defined almost 10 years ago, was consequently based on a suite of wide-band (1 GHz) AOS (with 1 MHz channel spacing) and – for high resolution applications – CT-spectrometers (200 MHz, 56 kHz resolution) only.

Then, less than a decade ago, the exploding computing power of high-performance field programmable gate array (FPGA) chips and the rapidly increasing sampling rate of commercially available analog-to-digital converters (ADC) revolutionized the field, and *Fourier transform* spectroscopy became possible. In this process, the down-converted intermediate frequency signal of the coherent receiver is first sampled at high resolution, then – in the FPGA – the Fast Fourier Transform (FFT) is calculated and the spectra are summed (see Klein et al. 2006b for details and a visualization of the Wiener-Khinchin theorem).

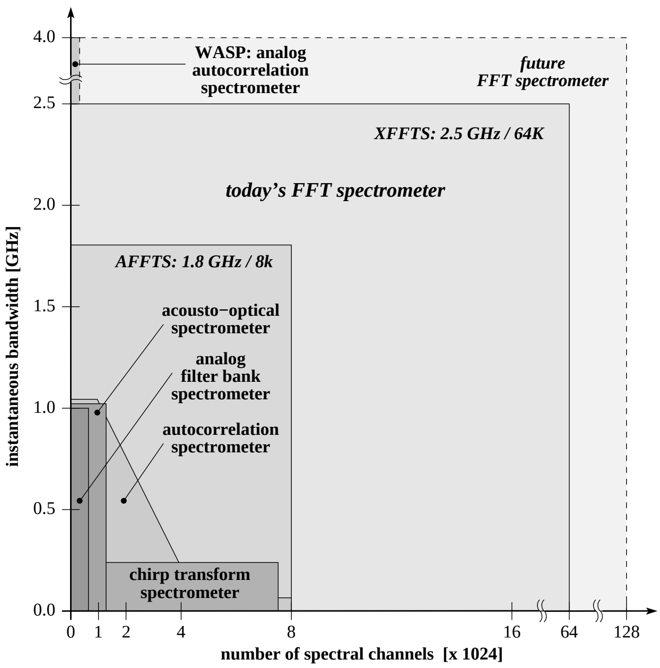

Fig. 1. Comparison of different spectrometer types in terms of instantaneous bandwidth and spectral channel number applied in radio astronomy. Only FFT spectrometers provide both wide bandwidth and high-frequency resolution because of their impressive number of independent spectral channels (Klein et al. 2006a).

Stanko et al. (2005) performed successful astronomical observations already in August 2004 at the 100m-telescope with a first fully digital Fast Fourier Transform spectrometer (though at that time limited to just 2 × 50 MHz bandwidth and 1024 (1*k*) spectral channels). Only shortly later, the rapid advances in digital signal processing (DSP) hardware made it possible to develop the first wide-band FFT spectrometers with already 1 GHz bandwidth (Benz et al. 2005; Klein et al. 2006b). In 2007 our Array FFTS (AFFTS) with up to 1.8 GHz bandwidth and 8*k* channels saw first light (Klein et al. 2008), and here we present the latest product of these amazing advances in DSP: the XFFT spectrometer for GREAT[1] now analyzes 2.5 GHz of instantaneous bandwidth in 32*k* spectral channels (Fig. 2).

With the availability of the first samples of once again faster analog-to-digital converters and new FPGAs with still increasing processing capabilities (Fig. 2), present-day FFT spectrometers meet all requirements of high-resolution spectroscopy in radio astronomy and beyond, thereby replacing traditional spectrometers. The FFTS provide wide bandwidth with very fine spectral resolution at comparatively low production costs. The high dynamic range of today's ADCs with 8/10-bit allows observing strong continuum sources and bright maser lines without signal loss. The FFT spectrometers operate very stably with long Allan-variance times (Klein et al. 2008); they are calibration- and aging free and perform extremely reliable in the harshest environments. The generic approach of our signal processing pipeline allows generating FPGA cores with different bandwidths and/or spectral resolution on a short time scale.

In this paper we describe the hardware and the FPGA signal processing of the AFFTS and XFFTS developed for APEX[2] and GREAT (Heyminck et al. 2012). First we discuss the goal and design of the Array FFT Spectrometer (Sect. 2), followed by a description of our latest development – the XFFTS – in Section 3. In Section 4 we outline the FPGA signal processing and the polyphase filter bank algorithm as well as the spectral behavior and frequency response of our processing pipeline. Section 5 summarizes the technical details of the two spectrometers and their configuration and performance during now worldwide field operations (Section 6). Finally, we present an outlook on on-going and future FFTS developments (Sect. 7).

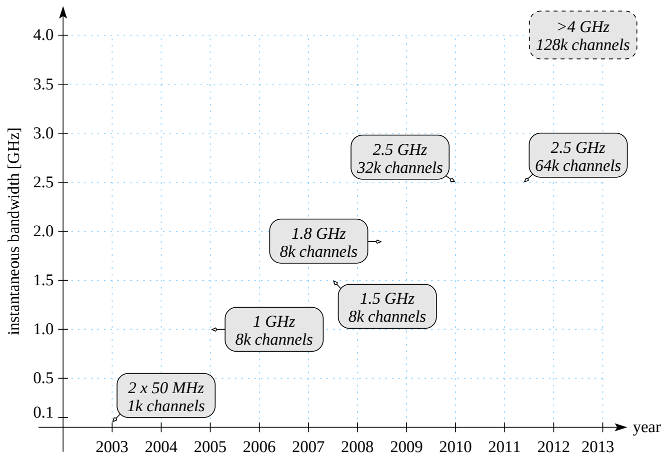

Fig. 2. Overview of the FFTS developments at the Max-Planck-Institut für Radioastronomie. In the last 8 years it was possible to improve the instantaneous bandwidth by a factor of 50 while processing 64 times more spectral channels. The dashed box marks the design goals for our next generation of FFTS.

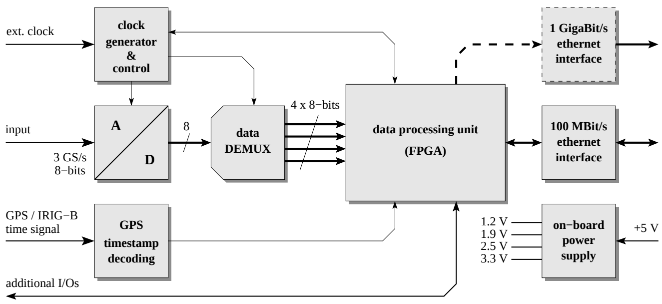

Fig. 3. Block diagram of the 1.5 GHz bandwidth AFFTS digitizer/analyzer board. The board can be equipped with a single- or dual-input ADC (National ADC083000 or ADC08D1500). The optional GigaBit-ethernet interface allows high-speed data acquisition with transfer rates of up to 90 MBytes/s, which are required for pulsar/transient search or to readout MKIDs – Microwave Kinetic Inductance Detectors.

2. AFFTS – the Array FFT Spectrometer

To serve the operation of our single pixel detectors (a.o. GREAT), but in particular to process the ~ 50 GHz signal bandwidth of mid-sized heterodyne arrays like CHAMP+/APEX (Güsten et al. 2008) or EMIR/IRAM (Carter et al. 2012), and the future upGREAT for SOFIA, in 2007 we launched the development of a 1.5 GHz bandwidth digitizer-/analyzer-board: the Array FFT Spectrometer (AFFTS).

The development goal was to design a compact and robust digital spectrometer board that can be produced inexpensively with simply commercially available components. The 100 × 160 mm sized AFFTS-board combines a National 3 GS/s ADC (ADC08300) and a Xilinx Virtex-4 SX55 FPGA. The wide analog input bandwidth of the 8-bit ADC enables one to sample the input signals at baseband (DC to 1.5 GHz) or in the second Nyquist zone (1.5 – 3.0 GHz). The boards include a standard 100 MBits/s ethernet interface, which simplifies the combination of many boards into an Array FFTS via a common ethernet switch. A block diagram of the AFFT-board is presented in Figure 3. The spectrometer board operates from a single 5 Volt source and dissipates less than 20 Watt, depending on the actual configuration of bandwidth and number of spectral channels. Precise time stamping of the processed spectrum is realized by an on-board GPS/IRIG-B time decode circuit. Furthermore, the 10-layer digital board includes a programmable ADC clock synthesizer for a wide range of bandwidth configurations (0.1 – 1.8 GHz), making the spectrometer flexible for different observing requirements and receiver characteristics.

3. XFFTS – the eXtended bandwidth FFTS

With the availability of first samples of E2V's 5 GS/s 10-bit ADC in mid 2009, we commenced the development of the wide-band XFFTS board (Klein et al. 2009). The goal was a digitizer-analyzer-board with broader bandwidth and higher spectral res-

[1] GREAT is a development by the MPI für Radioastronomie and the KOSMA / Universität zu Köln, in cooperation with the MPI für Sonnensystemforschung and the DLR Institut für Planetenforschung.

[2] APEX is a collaboration between the Max-Planck-Institut für Radioastronomie, the European Southern Observatory, and the Onsala Space Observatory.

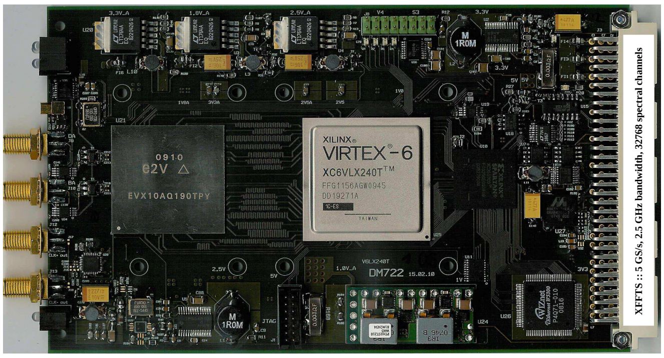

Fig. 4. XFFTS board that uses E2V's fastest 4 × 1.25 GS/s 10-bit ADC and the high-performance Xilinx Virtex-6 LX240T FPGA. By applying time interleave techniques, the four 1.25 GS/s ADCs can be combined into two 2.5 GS/s or one 5 GS/s converter. The XFFTS allows analyzing an instantaneous bandwidth of 2.5 GHz with 32*k* spectral channels. Depending on the processing set-up and the input signal level, the board consumes 20 – 25 Watt.

Fig. 5. Photograph of the 19-inch XFFTS-crate, equipped with eight XFFTS-boards (hence processing 20 GHz signal bandwidth) and one FFTS-controller unit. The modular concept allows combining multiple crates to build large FFT spectrometer arrays.

olution than provided by the AFFT to analyze the instantaneous bandwidth of the GREAT HEB receivers (> 2 GHz) in one monolithic part. To realize an adequate number of spectral channels, we designed the new XFFTS board around the high-performance Xilinx Virtex-6 LX240T FPGA. This device is able to process a continuous data flow of 6 GBytes/s in a polyphase filter bank with 32768 spectral channels.

Because E2V's 5 GS/s ADC is not a monolithic converter but a fourfold 1.25 GS/s ADC, the four ADCs have to be time-interleaved to synthesize the behavior of a 5 GS/s converter. The main challenges with time-interleaving are accurate phase alignment of sampling-clock edges between channels, and compensation for manufacturing variations that inherently occur between ICs. Accurately matching the gain, offset, and clock phase between separate ADCs is very challenging, especially because these parameters are frequency-dependent (McCormack 2009). For the XFFTS we developed an adaptive FPGA-based calibration routine that measures an injected fixed frequency continuous wave line and calculates the best parameter for gain, offset, and clock phase. Applying this optimized calibration scheme, no interleaving artifacts are noticed, even in long integrations.

Similar to the AFFTS, the XFFTS-board includes the GPS/IRIG-B time decoder unit and a low-jitter on-board ADC synthesizer. In Figure 4 we show a photo of the 12-layer XFFTS board. Up to eight XFFTS-boards can be housed in one 19" FFTS-crate together with power supplies (4 × 5 Volt,

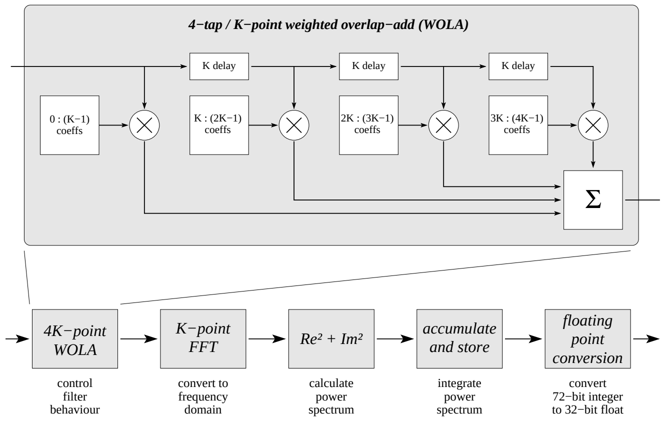

Fig. 6. Block diagram of the polyphase filter bank (PFB) signal processing pipeline. The PFB not only produces a flat response across the passband, but also excellently suppresses of out-of-band signals.

20 Amperes) and one FFTS-controller (Fig. 5). The latter is responsible for the distribution of global synchronization signals, e.g., the reference clock for the ADC synthesizer, or the GPS/IRIG-B timing information. In addition, the controller displays housekeeping information such as board IP numbers, temperatures of the ADC and FPGA chips and the power level of the IF inputs. All controller informations are also available by ethernet, making a completely remote operation of the XFFTS possible.
To serve the need for spectroscopy with even higher spectral resolution, we enhanced the present XFFTS by replacing the FPGA with the substantially more complex Xilinx Virtex-6 SX315T chip to implement 64*k* spectral channels.

4. Advanced FPGA signal processing

As described in Klein et al. (2006a), the complete signal processing pipeline for converting time-sampled data into an integrated power spectrum fits on a single complex FPGA chip. The advanced spectrometer core for our FFTS-boards is an in-house development by MPIfR and based on a generic VHDL[3] approach, which uses Xilinx's IP core-generator to configure the pipeline-FFTs. This allows a maximum of flexibility in FFT-length, FFT-bit-width, and processing speed. Unlike the commonly 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. Figure 6 illustrates the polyphase filter bank (PFB) signal processing in the FPGA: After the polyphase filter that we implemented as a pipeline version of the weighted overlapp-add (WOLA) method (Crochiere & Rabiner 1983), the FFT is realized using a highly parallel architecture to achieve the very high data rates of 3 GBytes/s (AFFTS) and 6 GBytes/s (XFFTS). The next step of the signal processing includes converting the complex frequency spectrum to a power density representation and successive accumulation of these results by an adjustable time-period. This accumulation step has the effect of averaging a number of power spectra, thereby reducing the background noise and improving the detection of weak signal parts. In addition, this step also reduces the huge amount of data pro-

[3] VHDL: Virtual Hardware Description Language

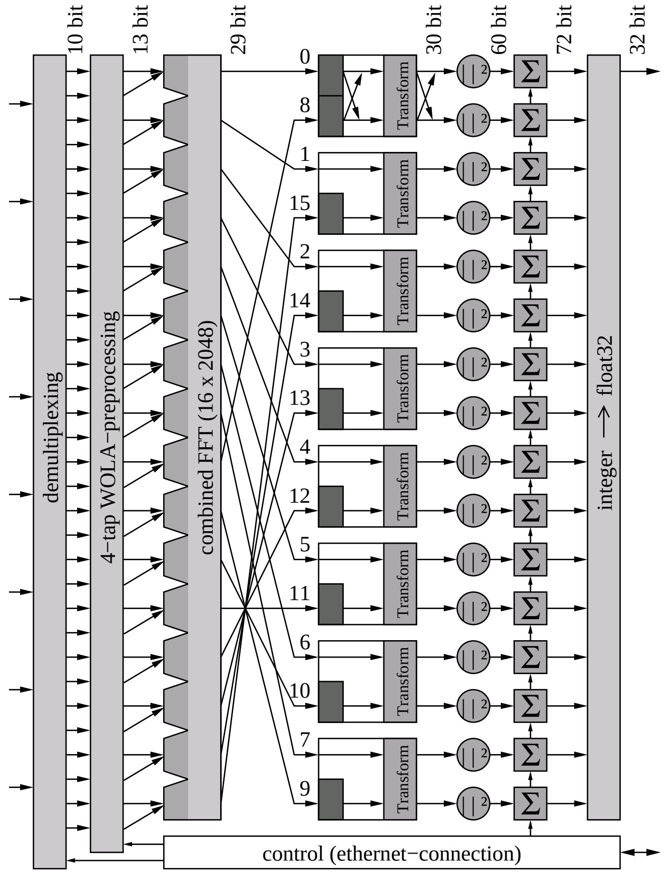

Fig. 7. 32k spectrometer design with a combined 32768-points FFT (16 × 2048), running on a Xilinx Virtex6 LX240T FPGA. Data width grows by $log(4) + 1$ bits in four-tap WOLA, by $log(32768) + 1$ bits in 32768-points FFT, by 1 bit during channel transformation and is doubled by squaring.

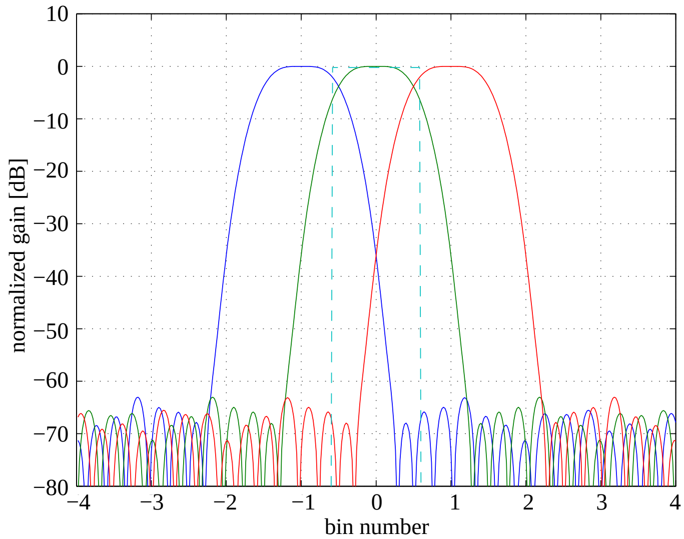

Fig. 8. Frequency response of the polyphase filter bank signal processing pipeline. The diagram shows three adjacent frequency bins in logarithmic scale measured with the 32k channel XFFTS. The dashed lines illustrate the equivalent noise bandwidth (ENBW) for the corresponding spectral bin.

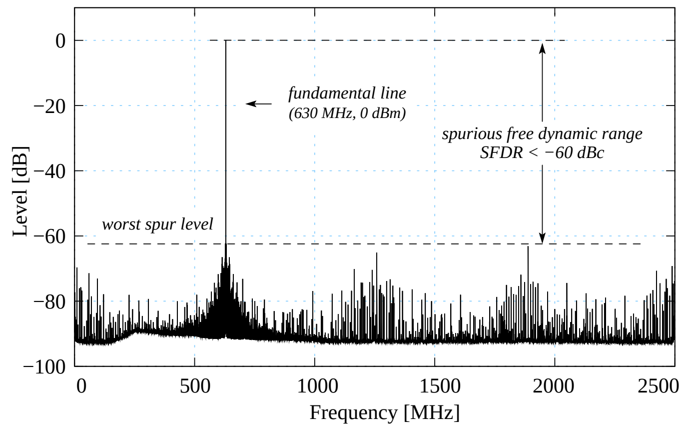

Fig. 9. Measured spurious free dynamic range (SFDR) of the XFFTS with E2V's 10-bit 5 GS/s ADC for a fundamental line injected at 630 MHz. Over the whole 2.5 GHz bandwidth the SFDR is below −60 dBc, perfectly confirming the vendor specifications for this ADC.

duced by the prior processing stages and eases any subsequent interfacing for the data analysis.

All signal processing steps use unrounded computations to prevent a loss of sensitivity during the calculations. The data bandwidth after each processing unit is equal to the data bandwidth before plus the logarithm of the number of summed values: $log(4)$ bits in the four-tap WOLA and $log(N)$ in the N-point FFT and channel-transformation unit. Two extra bits are spent to compensate for window-multiplication and to prevent an overflow by the twiddle-multiplication in the FFT. The power builder doubles the data width and up to 72 bits are finally reserved for each channel of the integrated power spectrum. Last step in the processing pipeline is the conversion from integer representation (AFFTS: 64-bit, XFFTS: 72-bit) to 32-bit floating-point format. The spectrometer design of the 32k channels XFFTS core with the bit-width in each stage is illustrated in Figure 7. Hochgürtel & Klein (2008) give a more detailed discussion concerning the internal FPGA signal processing and the resources consumed in the FFTS cores.

We optimized our polyphase filter coefficients for spectroscopic observations. The design goal was to find a good trade-off between the frequency resolution and an optimum use of the limited FPGA resources, particularly the on-chip block-memory. The equivalent noise bandwidth (ENBW) is generally used to characterize the spectral resolution. The ENBW is the width of a fictitious rectangular filter such that the power in that rectangular passband is equal to the integrated response of the actual filter. In all our FFTS, the ENBW is adjusted to 1.16× the channel spacing, which is the total bandwidth of the spectrometer divided by the number of spectral channels. Figure 8 illustrates the measured frequency response of three adjacent frequency bins for a four-tap polyphase filter bank and the corresponding ENBW for the central bin in logarithmic scale. The measurements shows a relatively flat passband behavior and a suppression better than −60 dB for out-of-band signal fractions. The spurious free dynamic range (SFDR), the intensity ratio of the fundamental signal to the strongest spurious signal in the power spectrum, was measured to be below −60 dBc across the 2.5 GHz bandwidth of the XFFTS (Figure 9). Following the above definition of the ENBW, the spectral resolution of our AFFTS and XFFTS with default FPGA core is 212 kHz and 88.5 kHz, respectively (Tables 2, 4).

Table 1. Hardware specifications of the **AFFTS** board

ADC sample rate (default / max)	3 GS/s / 3.6 GS/s
Full-scale input power	0 dBm (630 mVpp)
Input impedance	50 Ω
ADC analog input bandwidth (−3 dB)	0.1 – 3 GHz
ADC input resolution (quantisation)	8 Bit
ADC sampling jitter (10 μs record)	< 500 fs r.m.s.
ENOB (full bandwidth)	7 Bits @ 748 MHz
Spurious-free dynamic range (SFDR)	> 43 dBc @ 1498 MHz
Differential nonlinearity (typ)	0.25 LSB
Integral nonlinearity (typ)	0.35 LSB
FPGA data processing unit	XILINX Virtex-4 SX55
GPS/IRIG-B time decoder	1 kHz, AM modulated
GPS/IRIG-B accuracy (decoding)	< 50 μs
On-board ethernet interface	IEEE 802.12, ≤ 20 MBits/s

Table 2. Specifications of the **AFFT**-processing pipeline

Signal processing / algorithm	polyphase filter bank (PFB)
Processing bandwidth	1.5 GHz (default)
Spectral channels	8192 (8*k*) @ 1.50 GHz
	16384 (16*k*) @ 750 MHz
Channel separation	183 kHz @ 1.5 GHz
Spectral resolution (ENBW)	212 kHz @ 1.5 GHz
Internal FPGA signal processing	64-bit precision
On-board integration time	max. 5 s
Spectral dump time	20 ms @ 8*k* channels
Spectroscopic Allan-variance	~ 4000 s

Table 3. Hardware specifications of the **XFFTS** board

ADC sample rate	max 5 GS/s
Full-scale input power	-2 dBm (500 mVpp)
Input impedance	50 Ω
ADC analog input bandwidth	0.1 – 3.8 GHz (−3 dB)
ADC input resolution (quantization)	10 Bit
ADC sampling jitter (10 μs record)	< 500 fs r.m.s.
ENOB (full bandwidth)	7.2 Bits @ 1.2 GHz
Spurious-free dynamic range	> 55 dBc @ 1.2 GHz
Differential nonlinearity (typ)	0.3 LSB
Integral nonlinearity (typ)	0.8 LSB
FPGA data processing unit	XILINX Virtex-6 LX240T
GPS/IRIG-B time decoder	1 kHz, AM modulated
GPS/IRIG-B accuracy	< 50 μs (decoding)
On-board ethernet interface	IEEE 802.12, ~ 10 MBytes/s
Optional gigabit ethernet interface	IEEE 802.3, ~ 90 MBytes/s

Table 4. Specifications of the **XFFT**-processing pipeline

Signal processing / algorithm	polyphase filter bank (PFB)
Processing bandwidth	2.5 GHz (default)
Spectral channels	32768 (32*k*) @ 2.5 GHz
Channel separation	76.3 kHz @ 2.5 GHz
Spectral resolution (ENBW)	88.5 kHz @ 2.5 GHz
Internal FPGA signal processing	72-bit precision
On-board integration time	max. 5 s
Spectral dump time	20 ms @ 32*k* channels
Spectroscopic Allan-variance	~ 4000 s

5. Specification and performance

In Tables 1 and 3 we compile the hardware specifications and the achieved performances of the AFFTS and XFFTS boards. The corresponding specifications of the signal processing pipeline are listed in Tables 2 and 4.

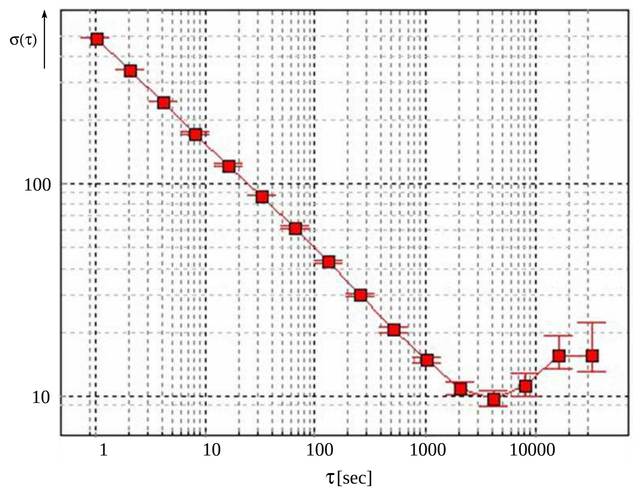

Fig. 10. Remarkable stability of the FFTS is illustrated in this Allan-variance plot. The spectrum of a laboratory noise source was integrated and processed in the AFFTS. The spectroscopic variance between two ~ 1 MHz (ENBW) wide frequency channels, separated by 800 MHz within the band, was determined to be stable on a time scale of ~ 4000 s.

To illustrate the performances of the spectrometer boards, we plot in Figure 10 the result of an Allan-variance test, emphasizing the remarkable stability of the AFFTS on a timescale of ~ 4000 s. Similar stability results were demonstrated for the 2.5 GHz XFFTS.

6. FFT spectrometers in operation

The MPIfR FFT spectrometers[4] are in use now at several radio telescopes worldwide. Here we describe the configuration and performance of a few of these installations.

6.1. AFFTS

At the APEX telescope an array-FFT spectrometer is in flawless routine operation since spring 2008 (Güsten et al. 2008). In its current configuration it provides a total bandwidth of $32 \times 1.5 = 48$ GHz with 256*k* ($32 \times 8k$) spectral channels. By uploading a special FPGA processing core and new ADC synthesizer settings the configuration can be extended to 58 GHz (32×1.8 GHz) total bandwidth. This spectrometer is connected to CHAMP$^+$, a 2×7 pixel heterodyne array operating in the 350 and 450 μm atmospheric windows (Güsten et al. 1998).

An AFFTS with 24 processing boards has been successfully commissioned at the IRAM 30m-telescope in July 2011, covering 32 GHz of total bandwidth with 200 kHz spectral resolution. A flexible IF spectrum-slicer, built by IRAM, allows one to observe either four parts of the IF bands with 200 kHz resolution and 8 GHz bandwidth each, or eight parts of the IF bands with 50 kHz resolution and 1.82 GHz bandwidth each.

For two years, an AFFTS with 16 units is in routine operation at the MPIfR 100m Effelsberg telescope. Owing to the lower operating frequencies of this telescope, the spectrometer covers

[4] Owing to the high demand we outsourced the production and distribution of our standard AFFTS and XFFTS. Both spectrometers are manufactured in licence by Radiometer Physics GmbH, Germany (http://www.radiometer-physics.de).

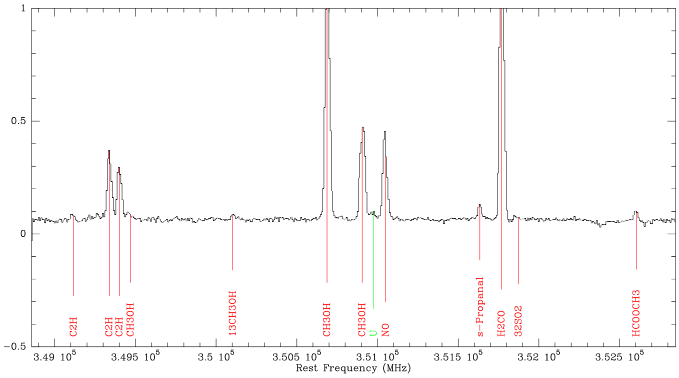

Fig. 11. Two 2.5 GHz XFFT boards combined, with 500 MHz overlap, to create a 4 GHz-wide spectrometer. The sample spectrum, part of a Galactic Center line survey (Güsten, priv comm.), shows the upper sideband of the sideband separating APEX/FLASH$^+$ receiver.

bandwidths of 500, 300, and 100 MHz per board only, but with 16*k* spectral channels each by applying a high-resolution FPGA core.

For GREAT laboratory tests and the Early Science flights, a two-board AFFTS was used in a 750 MHz and 1.5 GHz bandwidth configuration (Heyminck et al. 2012).

6.2. XFFTS

A first version of the 2.5 GHz XFFTS has been successfully commissioned in 2010 at the APEX telescope. In combination with a flexible IF signal processor, four XFFTS boards cover a bandwidth of 2×4 GHz bandwidth with a spectral resolution (ENBW) of 88.5 kHz and 500 MHz overlap in the band center. This setup allows one to observe the upper and lower sideband of the re-modeled sideband separating FLASH$^+$ receiver at the same time (Fig. 11).

Since July 2011, two XFFTS boards – in standard configuration – are in regular operation with GREAT, providing 2.5 GHz bandwidth with a spectral resolution of 88.5 kHz (ENBW). Even under the harsh environmental conditions at facilities such as APEX or SOFIA, the FFT spectrometers have proven to be extremely reliable and robust.

Finally, at the 100m Effelsberg telescope, a two-unit XFFTS has been successfully commissioned at the end of 2011, with remote switchable FPGA configurations for high-resolution spectroscopy at 2 GHz, 500 MHz, and 100 MHz bandwidths.

7. Conclusions and outlook

We briefly summarize the advantages of our high-resolution wide-band Fast Fourier Transform spectrometers:

- FFT spectrometers provide high instantaneous bandwidth (1.5 GHz, 2.5 GHz) with many thousands of frequency channels, thus offering wide-band observations with high spectral resolution.
- The implemented polyphase filter bank algorithm provides a nearly loss-free time-to-frequency transformation with significantly reduced frequency scallop, less noise bandwidth expansion, and faster sidelobe fall-off.
- FFTS have been demonstrated to operate extremely stable due to exclusive digital signal processing. Allan-variance stability times of several 1000 seconds have been achieved routinely.
- FFTS require only small volume, mass, and power budgets – ideal for operation at high-altitude observatories (e.g., APEX at 5100-m) as well as on airborne observatories such as SOFIA.
- Production costs are low compared to traditional spectrometers because only commercial components and industrial manufacturing are used.
- The superior performance, high sensitivity and reliability of our FFT spectrometers have been demonstrated at many telescopes word-wide.

The announcements of new ADCs with even higher sample rates ($f_s \geq 10$ GS/s) and wider analog input bandwidth, together with the still increasing processing capability of future FPGA chips (e.g., the Xilinx Virtex-7 series), make it very likely that FFT spectrometers can be extended to even broader bandwidth with adequate numbers of spectral channels in the near future. Our next FFTS development will be the design of a spectrometer with instantaneous bandwidth ≥ 4 GHz and up to 128*k* spectral channels, aiming at operational readiness in time for the commissioning of our upGREAT detector array in 2013/14[5] .
In current FFTS applications an IF processor is needed for down-mixing the receiver signals to baseband. However, these analog processors are time-consuming to build, not calibration- and aging-free, and cost-intensive. The notification of a new class of track-and-hold amplifiers, operating at GHz frequencies, will allow direct sampling of the intermediate frequency of current and future heterodyne receivers by bandpass-sampling techniques, with much reduced complexity and reduced costs.

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[5] The projected development time is based on a time-to-science figure-of-merit of ∼18 months that we have demonstrated during previous implementations of new DSP opportunities. Timely injection of new science opportunities is essential for the success of a PI instrument like GREAT, flying cutting-edge technologies on-board an expensive mission. For a technology that still advances according to Moore's growth law our highly specialized approach ensures probably better, faster realization than designs based on hardware building blocks from a DSP developer platform like CASPER (see, e.g., Parsons et al. 2005, 2009 about their philosophy to support broader community applications with open hardware architectures and open signal processing libraries).

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