Analog-to-digital conversion beyond 20 bits

Applications, architectures, state of the art, limitations, and future prospects

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Abstract— Analog-to-digital converters with resolution exceeding 20 bits are widely available today. They exist in two forms – flexible laboratory instruments and monolithic integrated circuits. We present an overview of application fields for such digitizers, the hardware architectures that implement them, and their limitations. We review the state of the art by comparing the best-performing devices reported in scientific literature, as well as those available commercially. Our focus is particularly on integrated circuit solutions, and among our aims are the disambiguation of the multiple performance metrics in use, as well as the presentation of a clear perspective on basic performance trade-offs. Finally, we provide a discussion on the future prospects for high-resolution digitizing measurement systems.

Keywords—*analog-to-digital, ADC, high-resolution, 20-bit, LHC, HL-LHC*

I. INTRODUCTION

Modern electronics is predominantly digital. The progress in the development of microprocessors, digital memory, and programmable logic is best exemplified by Moore’s law [1]. First stated in 1965, the law predicts exponentially increasing complexity and remains valid to this day. In the meantime, analog electronic devices have seen an altogether different path of development. In many aspects, they have reached physical and technical limitations that are difficult to overcome by conventional means. In precision mixed-signal circuits, the optimization of circuit area or power dissipation usually dictates a shift of complexity from the analog to the digital domain [2]. However, this approach has its limits too. Getting the best of both worlds requires a good understanding of the interfaces between them and the limitations they impose on the flow of information.

Non-electrical quantities of natural or artificial origin can have extremely high intrinsic dynamic range. In many cases, the first bottleneck in a measurement chain occurs due to the sensor or transducer. The electrical quantities at the output of a sensor are subject to the same constraints faced by the subsequent analog processing stages: the inevitable presence of noise and range limits imposed by device physics, technology, or convention. In certain cases, the sensor presents a challenge for the subsequent chain – for instance in photometry [3], magnetometry [4], or seismic instrumentation [5]. All practical analog signal conditioning stages (amplifiers, filters, etc.) are yet another information channel with limited capacity. Dynamic

range bottlenecks are frequently avoided on the system level by methods such as sub-ranging, compensation, fine-coarse measurement, or nonlinear conversion. Yet, there are applications where such solutions are not optimal – for instance, when dealing with dynamic signals of considerable bandwidth, or where high linearity and stability are required throughout the full measurement range.

Analog-to-digital converters (ADCs) are the final, and sometimes ultimate bottleneck in the signal chain. One of the major trade-offs in digitization is between speed and resolution. It is due to a number of technical and quasi-fundamental limitations in the analog domain, such as noise, clock jitter, and supply voltages [6]. Several ADC architectures, as well as their multiple variations, have been developed and optimized to address specific application requirements. The scope of this work is on devices having nominal resolution beyond 20 bits, or dynamic range in excess of 120 dB. Such ADCs are normally used to sample signals with a limited bandwidth in the range of kHz or below. The dominant performance limitation in these converters is excess noise, often modelled as an equivalent input-referred generator of thermal noise [6]. High-resolution ADCs exist in different forms, but in this work we are mostly concerned with commercial monolithic integrated circuits (ICs).

II. APPLICATIONS

A brief summary of the application fields for high-resolution ADCs, together with their specific requirements, is given in Table I. One common feature, apart from the obvious need for high dynamic range, is the relatively low importance of power dissipation in such devices. This fact is in marked contrast with the scientific aspect of ADC design, where typically a composite figure-of-merit that includes power dissipation is optimized on the system level [6].

TABLE I. APPLICATION FIELDS OF HIGH-RESOLUTION DIGITIZERS

Application field	Signal bandwidth	Main requirements	Examples
Audio	20 Hz – 20 kHz	low distortion low noise	[7]
Seismology / geophysical surveying	near-DC to 10^2 - 10^3 Hz	low distortion	[5]

Industrial instrumentation	near-DC	EMI robustness resolution provisions for signal conditioning stability	[7] [8]
Voltage metrology	DC	voltage range $\geq \pm 10V$ linearity stability	[9] [10]
Electrical power metrology	DC to $10^3 - 10^4$ Hz	linearity stability	[9] [11] [12]
High-precision current control	near-DC	voltage range $\geq \pm 10V$ resolution linearity stability	[13] [14]

Audio ADCs are exclusively of the $\Sigma\Delta$ type and are typically not useful for other applications due to their very poor DC characteristics [7].

The instruments used in **seismology and geophysical surveying** require high dynamic range and linearity, but less bandwidth than audio. The DC performance is not of prime importance, although the low frequencies near DC may be of interest. Some unique requirements may apply, for example an extreme temperature range. Presently, there are seismic sensors with such high dynamic range, that even a very high-resolution ADC presents a bottleneck in the acquisition system [5].

In **industrial sensor instrumentation**, the suppression of EMI is one of the main objectives. Therefore, standard and well-proven techniques such as bridge circuits, ratiometric measurement, 4-wire connections and balanced/differential signaling are commonplace [7]. The manufacturers of modern integrated ADCs for industrial applications offer such features with the aim to ease the overall system design. Many ADCs have built-in analog multiplexers, programmable gain amplifiers (PGAs), 50/60 Hz notch filters and self-calibration capabilities. Digital signal processing techniques are common as well, thanks to the high availability and configurability of digital resources. Typical sensors that require high-resolution digitization include pressure and force gauges, weight cells, resistive thermometers, and thermocouples.

The digitizing devices suitable for **metrology** are primarily designed for stability, i.e. low variation of parameters with time and environmental factors. The static errors are less important, as they are subject to calibration. DC voltage metrology requires devices that can be used with 10 V-output transfer standards and calibrators. One important advantage of having such wide voltage range is the reduced effect of thermal EMFs generated inadvertently at the contact points of dissimilar metals due to temperature gradients (Seebeck effect). This effect presents one of the most challenging limitations of DC and near-DC voltage measurements.

The **scientific applications** of high-resolution ADCs are very diverse. They include the readout of sensors [5] [8] [15], intrinsically low-noise devices like superconducting interferometers (SQUIDs) [16], particle accelerator beam instrumentation [17], digital integrators for pickup coil-based

magnetic measurements [18] and quench detection in superconducting magnets [19]. Such applications are often driven by highly specific requirements that cannot be summarized.

High-precision current control for accelerator magnets [14], as a sub-field of scientific applications, is particularly demanding. The simultaneous requirements for stability, linearity, and resolution are high, since they all determine the overall control loop performance. The response to dynamic signals is important, but the requirements are relaxed in comparison with the static set point regime. Dynamic limitations exist due to other parts of the control loop - the load (magnet) and the actuator (power converter). Operation within a closed feedback loop also sets a limit on the measurement latency and the available time for signal processing.

The work we present is triggered by the needs of the High Luminosity LHC project [20] at CERN.

III. HIGH-RESOLUTION ADC ARCHITECTURES

There are presently three common architectures that implement high-resolution ADCs: (A.) multi-slope integrating, (B.) Sigma-Delta, and (C.) Successive Approximation Register (SAR). Their basic topologies are shown in Fig. 1.

Fig. 1. Architectures implementing high-resolution ADCs: A.) multi-slope integrating; B.) Sigma-Delta; C.) SAR

Conceptually, the three architectures are very similar – they are all based on a closed-loop circuit topology with a DAC in the feedback path and at least one low-resolution ADC (or comparator) in the loop. Architectures (A.) and (B.) also share similarities in the way they process information – both of them use the analog input signal to modulate a quantity that is later recovered by digital means. In contrast, SAR is simply a way to “invert” a DAC by incorporation into a feedback loop. As such, it has the least complex topology and most intuitive operation. Another common feature is that all three architectures have their digital logic operating at frequencies well above the sampling rate or output data rate (ODR). Their differences are summarized in Table II.

TABLE II. COMPARISON OF THE THREE HIGH-RESOLUTION ADC ARCHITECTURES

	Multi-slope integrating	Sigma-Delta	SAR
<i>In-loop DAC resolution</i>	> 1 bit	≥ 1 bit	N bits (nominal res.)
<i>Error signal</i>	$\varepsilon \rightarrow 0$ at EOC ^a	$\int_t \varepsilon(t) dt \rightarrow 0$	$\varepsilon < \pm 1/2$ LSB at EOC
<i>Speed</i>	slowest	mid-range to fast	fastest
<i>Latency</i>	single cycle	determined by digital filter	single cycle
<i>Unique features</i>	synchronization to power line frequency	quantization noise shaping	easy to multiplex and interleave
<i>IC realizations</i>	no	yes	yes
<i>Typical representatives</i>	Keysight 3458A Fluke 8508A Keithley 2182A	AD7177-2 ADS1281 MAX11210	AD7767 LTC1280-24 MAX11905

^a. End of Conversion

Multi-slope integrating ADCs are known to engineers and scientists mainly in the form of high-grade tabletop digital voltmeters (DVMs), such as the 8.5-digit devices HP/Agilent/Keysight 3458A and Fluke 8508A. Presently, there are no monolithic IC realizations of this architecture. Lower-resolution dual-slope integrating ADCs do exist in IC form, but their performance does not approach the 20-bit level.

Most high-resolution ADCs today are of the Sigma-Delta type. They include devices published in scientific literature, commercial digitizer systems, and commercial ICs. There are many variations of the architecture [21], but the highest-resolution devices are typically based on single- or multi-bit modulators of 3rd or 4th order operating at oversampling ratios of $\approx 10^2$ - 10^4 . The highest effective resolution figures are achieved within narrow frequency bands, where the noise of the in-loop quantizer is suppressed to very low levels, and where other noise mechanisms dominate. A variation of the Sigma-Delta architecture, known as *incremental ADC*, has also been reported in scientific literature as a viable solution for high-resolution high-accuracy digitization [22]. However, to the best of our knowledge, there are no commercial devices based on it.

SAR ADCs are the big winner of CMOS technology scaling [23]. It is due to their simplicity and inherent scalability, as well as the fact that a typical SAR realization does not require any

linear analog stages; all functional blocks can be implemented using switched capacitors and charge redistribution techniques. As a result, SAR devices cover a very broad range on the ADC landscape, either in standalone form, or as building blocks for other architectures (pipelined and time-interleaved converters). In the recent years, the SAR architecture has presented very competitive high-resolution ICs as well. However, to reach effective resolution figures beyond 20 bits, they must operate in oversampling mode. Some ICs have built-in provisions for it, while for others it has to be implemented in external logic.

IV. DEFINITIONS AND PERFORMANCE METRICS

A. Overview

The lack of standardization in the field of high-resolution ADCs, as well as the diverging application goals, have resulted in the existence of multiple ways to define and quantify performance. In this section we review the commonly used metrics. We note that authors of scientific articles, books, and technical documentation often do not make clear distinction between the terms, or use them interchangeably.

The quantities given below refer either to the full-scale peak-to-peak range $V_{FS(p-p)}$, or the RMS value of a full-scale sine wave $V_{FS(RMS)}$. In practice, there may be degradation of *SNR* or *SINAD* for signals that approach the range limits; at this point we ignore such effects and assume maximum *SNR* at 0 dBFS.

- Signal-to-Quantization Noise Ratio (*SQNR*)

$$SQNR [dB] = 10 \log_{10} \frac{P_{signal}}{P_{quant. noise}} = 6.02N + 1.76$$

- Signal-to-Noise Ratio (*SNR*) [6]

$$SNR [dB] = 10 \log_{10} \frac{P_{signal}}{P_{quant. noise} + P_{excess noise}}$$

- Signal-to-Noise and Distortion ratio (*SINAD*) [24]

$$SINAD [dB] = 10 \log_{10} \frac{P_{signal}}{P_{noise} + P_{distortion}}$$

- Effective Resolution (*ER*)

$$ER [bits] = \log_2 \left(\frac{V_{FS(p-p)}}{V_{noise(RMS)}} \right)$$

- Noise-Free Code Resolution (*NFCR*)

$$NFCR [bits] = \log_2 \left(\frac{V_{FS(p-p)}}{V_{noise(p-p)}} \right) = ER - 2.7 \text{ bits}^*$$

*valid for 1000 samples, assuming noise with Gaussian distribution

- *SNR* bits [6]

$$SNR \text{ bits} [bits] = \frac{SNR [dB] - 1.76}{6.02}$$

- Effective Number of Bits (*ENOB*) [24]

$$ENOB [bits] = \frac{SINAD [dB] - 1.76}{6.02}$$

B. Signal-to-noise ratios

$SQNR$ is the signal-to-noise ratio for a full-scale pure sine wave digitized by an ideal N -bit Nyquist-rate ADC. Any practical ADC has *excess noise*, which leads to the common SNR metric. $SINAD$ is yet stricter, as it includes distortion products due to non-linearity of the digitizer. In the context of high-resolution ADCs, it may be impractical or even impossible to measure directly $SINAD$ due to the lack of sine wave generators with sufficiently low distortion [25]. For any practical ADC with $N > 20$ bits, excess noise dominates over quantization and determines SNR at high data rates. Oversampling, decimation, and filtering provide a way to gain equivalent resolution that matches or exceeds the nominal.

C. Equivalent Resolution

The four given ways to specify equivalent resolution count on different assumptions. ER and $NFCR$ do not assume a dynamic signal; they are simply a way to refer excess ADC noise to the full-scale range. As such, they have no directly corresponding SNR -like quantities, and are normally measured with shorted ADC inputs, i.e. a 0 V noiseless DC input voltage. In some cases, excess noise is dependent on the DC input level [9] [16]; this effect is not reflected in the basic effective resolution metrics, but may be given separately in the form of plots, tables, etc.

In contrast, SNR_{bits} and $ENOB$ assume a full-scale sine wave test signal. These metrics correspond directly to SNR and $SINAD$; they are essentially a way to lump together the converter non-idealities into the “quantization noise” of an equivalent ideal Nyquist-rate ADC.

D. Noise

Sometimes manufacturers specify the ADC excess noise separately from other metrics. It can be given in different forms: input-referred RMS noise voltage, input-referred noise spectral density, output-referred noise relative to 1 LSB, or output noise referred to the full-scale range (e.g. ppm_{rms}). The true noise of the ADC core should be distinguished from the input-referred noise floor of any preceding stage. In case the ADC has a built-in PGA, the relevant noise specification is given for unity gain setting, or bypassed PGA. Knowing the input-referred noise density allows one to calculate the integrated RMS noise within a given bandwidth, and thus estimate the noise-limited SNR or equivalent resolution at different data rates. This approach is particularly useful when digital post-processing, e.g. custom filtering with decimation, is implemented in external logic. The RMS noise values given in datasheets can be converted to noise density using the equivalent noise bandwidth of the used digital filter, which is usually of the $sinc^n$ type. For a given filter type, this bandwidth is a fixed fraction of the ODR.

E. Static errors and drifts

Many applications require not only high resolution, but also an accordingly good accuracy. It is quantified by a number of DC parameters. They can be subdivided into static errors, drifts, linear, and non-linear ADC transfer function parameters. The parameters are either referred to the input or the output, and they can be given in absolute or relative units. The drift terms are given in input-referred absolute or relative units per degree

Celsius. In some cases, the temperature dependence of non-linearity is given, either as worst-case INL as a function of temperature, or in plot form of INL versus code, with temperature as a parameter.

V. STATE OF THE ART

A summary of the best ADCs reported in scientific literature in terms of dynamic range is given in Table III. Table IV compares the absolute noise floor and metrology-relevant DC characteristics of a number of commercial high-resolution ADCs. Fig. 2 shows a plot of noise-limited SNR versus bandwidth both for commercial and scientific ADCs.

TABLE III. BEST-PERFORMING ADCs REPORTED IN SCIENTIFIC LITERATURE

Publication	Noise floor [$nV/\sqrt{Hz}$]	Full-scale range [V_{pp}]	Note
Pett [13], [14]	200	20	$\Sigma\Delta$, 3 rd order, single-bit
Gao et al. [5]	10	20	Multibit $\Sigma\Delta$ built out of a 16-bit DAC
Naiknaware, Fiez [26]	4	2.6	Integrated CMOS $\Sigma\Delta$ with CDS
Qu et al. [27]	9±2	0.632	NI PXI-4462 ($\Sigma\Delta$) with CDS

TABLE IV. NOISE, DRIFT AND NONLINEARITY OF SOME HIGH-PERFORMANCE COMMERCIAL ADCs

ADC	Type	N [bits]	Noise floor [$nV/\sqrt{Hz}$]	Offset drift [ppb/ °C]	Gain drift [ppm/ °C]	INL (typ) [ppm]
AD7177-2	SD	32	30 ^a	±8	±0.4	±1
ADS1256	SD	24	120	±20	±0.8	±3
ADS1262	SD	32	110	±0.1	0.5	3
ADS1281	SD	32	110	6	0.4	0.6
AD7190	SD	24	280 ^a	±0.5	±1	±5
LTC2440	SD	24	70	±2	0.2	5
CS5532	SD	24	70	±1	±2	±15
ISL26104	SD	24	120	±30	±0.1	±2
MAX11210	SD	24	250 ^b	5	0.05	±10
LTC2508-32	SAR	32	50	±14	±0.05	±0.5
LTC2380-24	SAR	24	30 ^b	9	0.05	0.5
AD7767	SAR	24	60	1.5	0.4	3

Estimated, assuming ^a BW = ODR/3; ^b BW = ODR/2

VI. LIMITATIONS

A. Signal range

Most high-resolution integrated ADCs have differential inputs. This feature allows for a full-scale range equal to twice the reference voltage. A *de facto* standard for external reference voltage of commercial high-resolution ADCs is 5V; therefore, most converters have a full-scale range of 10 V_{pp} . The devices

Fig. 2. Comparison of high-resolution scientific and commercial ADCs in terms of SNR and SNR-equivalent resolution (*SNR bits*)

reported in scientific literature usually do not follow the same pattern – they exhibit either application-specific [5], or technology-limited ranges [26]. When the range of the measured signal does not match the ADC input full scale, the analog input conditioning stages must either amplify or attenuate the signal. Special care must be taken to ensure that the scaling of the input signal and reference voltage does not degrade the system dynamic range, linearity, and other aspects of performance.

B. Noise

Broadband noise is the main resolution-limiting factor at data rates above a few Hz. This noise usually has frequency-independent (white) spectral density, because it has fundamental origins (thermal or shot noise). It is relatively easy to reduce the broadband noise contribution of the reference voltage to negligible levels by low-pass filtering; the remaining figure is the intrinsic noise floor of an ADC core. For devices with a built-in PGA, the overall input-referred noise is minimized at moderately high PGA gain. However, in this regime the system dynamic range is degraded, due to the reduced full-scale input range.

Low-frequency (flicker, $1/f$) noise is the main limiting factor for measurements at longer time scales, corresponding to narrowing the measurement bandwidth down to a few Hz or less. Fig. 2 shows that certain devices have a very low $1/f$ noise corner frequency. This fact is either due to special features like built-in auto-zeroing or chopping stages, or is a merit of the circuit realization. Techniques like correlated double sampling (CDS) can be employed to effectively suppress $1/f$ noise [26], at the expense of extra circuitry and added latency [27].

C. Reference voltage source

Some integrated-circuit ADCs contain a built-in bandgap reference voltage source. Although they have seen much progress in recent years, their performance is not comparable to external buried-zener references in terms of noise, temperature dependence, and long-term drift. The unchallenged leader in this distinctly stagnated field is still the LTZ1000, with specified temperature coefficient of 0.05 ppm/°C and long-term stability better than $1 \text{ ppm}/\sqrt{kHr}$ [28].

D. Drift and Linearity

Many high-resolution integrated ADCs exhibit excellent temperature stability. The typical offset drift is in the range of nV/°C, which corresponds to part-per-billion (ppb) levels of the full scale. Gain drift is significantly worse, but for some devices it is well below 1 ppm/°C, therefore not far from the drift of the best available reference voltage source. For ultimate performance, an external temperature-stabilizing loop may be employed [13].

The best specified INL levels are below 1 ppm. It is not realistic to expect significant decrease in this figure due to process improvement alone; advanced techniques like large-scale dither [15] or multi-point calibration can improve linearity.

VII. DISCUSSION

It is nowadays possible to build digitizers for demanding applications that are based on commercial integrated high-resolution ADCs [8] [9] [11] [12] [16] [18]. However, reaching

a level of accuracy comparable to the resolution beyond 20 bits remains a difficult task that requires careful consideration of many system-level factors. Furthermore, even though ADCs with nominal resolution of 24 bits are prolific, few parts can actually achieve *SNR*-equivalent resolution beyond 24 bits.

It is hard to predict the rate of improvement in resolution and accuracy for commercial high-resolution ADCs, as their segment is not subject to the strongest market pressure. The dominance of the Sigma-Delta architecture is evident, although a number of SAR ADCs are catching up. Customized and hybrid digitizers [5] [27] are still capable of achieving higher dynamic range than fully integrated solutions.

The most demanding high-resolution applications could benefit from the unique analog signal processing capabilities of some sensors and circuits. Piecewise linear or non-linear analog stages have been used for range compression in systems with low accuracy requirements [29]. Sensors with periodic output could perform dynamic range folding, effectively relieving the ADC bottleneck. This approach has been demonstrated with SQUIDS [4] [30], and has been proposed for magneto-optical current sensors based on the Faraday effect [31].

We would like to point out that in the case of dynamic signals, the above-mentioned methods are essentially ways to exchange bandwidth for dynamic range. As such, they complement a number of established and well-known information-processing techniques (modulation, oversampling, dithering) that are at the very heart of existing high-resolution ADC technologies. One common feature of such techniques is that they all rely on digital post-processing. An information-theoretic approach to the problem of digitization could shed more light on the optimal use of analog and digital resources in high-performance signal acquisition systems.

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