



CR1000Xe Resolution – Effective Number of Bits

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1. Introduction

Resolution determines the smallest change in a measured quantity that can be detected by an instrument. High-resolution measurements enable detailed analysis, precise control, and accurate monitoring.

The CR1000Xe is a high-resolution measurement system. To understand the measurement engine in the CR1000Xe, it is important to know what effective number of bits (ENOB) is and how bits impact an analog-to-digital converter (ADC).

2. Bits of resolution

Analog measurement systems have some type of analog-to-digital converter (ADC). To convert an analog signal into digital data the ADC will sample the analog input and quantify the signal into discrete digital values. This involves dividing the range of the analog signal into a finite number of levels (quantization levels). The higher number of quantization levels in a measurement system means it has a finer resolution.

The resolution of an ADC is specified in the number of digital bits (quantization levels) it has available to process an analog signal. For example, a 12-bit ADC has 2^{12} (4096) discrete levels, while a 24-bit ADC has 2^{24} (16,777,216) levels. While the ADC is specified in the number of digital bits, this does not guarantee that all bits are available to process an analog input.

All the other electrical components that make up measurements system (e.g., power supplies, communication ports, multiplexers ...) generate electrical noise that can be detected by the measurement engine. This means the noise of the system may not allow the measurements to effectively use all the available bits of the ADC. To represent how many bits of the ADC output are useful, the term effective number of bits (ENOB) is used.

2.1 Resolution calculations

To calculate measurement resolution, the Input Range, full span of values that your measurement system can capture, must be known.

- Example Calculation using ADC Bits

$$\frac{\text{Input Range}}{\text{ADC Bits}} = \frac{10 \text{ V}}{2^{12}} = 2.44 \text{ mV}$$

This equation shows that for a 12-bit ADC with an input range of 10 volts, the smallest change in input voltage that can be detected (the resolution) is 2.44 millivolts.

- Example Calculation using ENOB Bits

$$\frac{\text{Input Range}}{\text{ENOB}} = \frac{10 \text{ V}}{2^{10.678}} = 6.1 \text{ mV}$$

This equation shows that if the ENOB is used to calculate the resolution of the ADC, the smallest change in input voltage that can be detected is 6.1 millivolts.

3. Effective number of bits (ENOB)

ENOB represents how many bits of the ADC output are useful, considering the effects of noise and other imperfections. The ENOB can be calculated, but in addition to knowing the input range the system noise must also be known.

3.1 ENOB equation

$$\text{Effective Number of Bits} = \frac{\log\left(\frac{\text{Measurement Range}}{\text{Measured Noise}}\right)}{\log(2)}$$

3.1.1 SNR (signal-to-noise-ratio) calculation

$$\frac{\text{Measurement Range}}{\text{Measured Noise}}$$

This ratio tells you how many times larger the measurement range is compared to the noise level. A larger ratio indicates that the signal is much greater than the noise, leading to a higher resolution.

3.1.2 Logarithm of ratio

$$\log\left(\frac{\text{Measurement Range}}{\text{Measured Noise}}\right)$$

The logarithm of the SNR quantifies the dynamic range of the measurement system. It represents how many orders of magnitude the measurement range exceeds the noise level.

A higher logarithm value indicates a larger dynamic range, meaning that the signal is significantly stronger compared to the noise, which leads to higher resolution.

3.1.3 Convert to logarithm base 2

$$\frac{\log(\text{Ratio})}{\log(2)}$$

Taking the logarithm of the SNR and dividing it by the $\log(2)$ converts this ratio into bits. The base 2 logarithm is used because digital systems operate in binary (bits).

4. Example calculation

4.1 Variables

- Measurement Range = ± 5000 mV
- Measured Noise = 0.001 mV (1 μ V)
- Equation

$$\frac{\log\left(\frac{10000 \text{ mV}}{0.001 \text{ mV}}\right)}{\log(2)} = ENOB$$

4.2 Calculation steps

- Calculate the SNR:
$$\frac{10000 \text{ mV}}{0.001 \text{ mV}} = 10 \text{ million}$$
- Take the logarithm (base 10) of the SNR:
$$\log(10 \times 10^6) = 7$$
- Convert this using the logarithm base 2:

$$\frac{7}{\log(2)} = 23.2534$$

4.3 Result

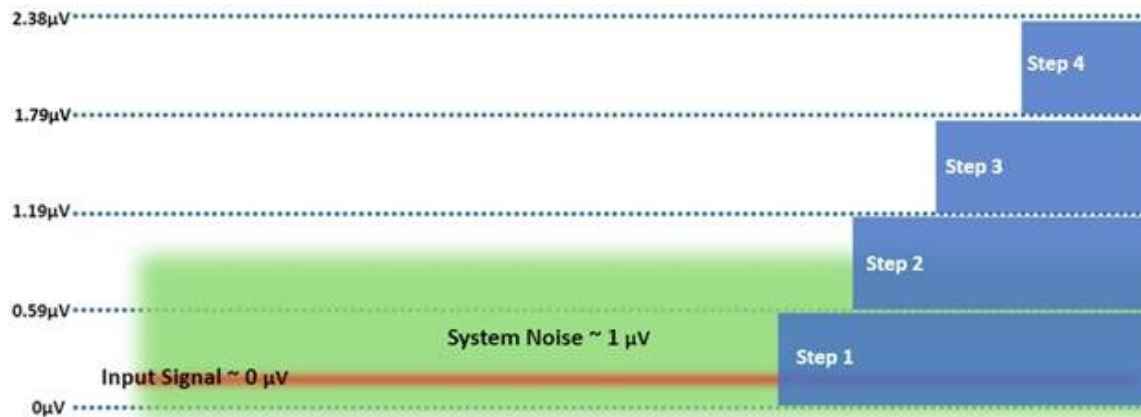
The measured effective number of bits (ENOB) is approximately 23.25. This means the ADC effectively has around 23.25 bits of resolution when accounting for noise, even if it might be a 24-bit ADC.

On a 24-bit ADC the estimated resolution would be:

$$\frac{10000 \text{ mV}}{2^{24}} = 0.596 \mu\text{V}$$

When the ENOB is used the actual resolution of the system would be:

$$\frac{10000 \text{ mV}}{2^{23.2534}} = 1.000 \mu\text{V}$$



5. CR1000Xe application

5.1 Theory

The CR1000Xe is equipped with a 24-bit ADC and offers three selectable analog input ranges: $\pm 5000 \text{ mV}$, $\pm 1000 \text{ mV}$, and $\pm 200 \text{ mV}$. The $\pm 5000 \text{ mV}$ range can handle a wider span of signals but offers less precision compared to the $\pm 200 \text{ mV}$ range. The CR1000Xe is designed to allow a little headroom around each range. The actual ranges are: $\pm 5406.7 \text{ mV}$, $\pm 1062.25 \text{ mV}$, and $\pm 212.01 \text{ mV}$.

5.1.1 Estimated resolution

$$\pm 5000 \text{ mV Range Resolution} = \frac{10813.4 \text{ mV}}{2^{24}} = 644.52 \text{ nV}$$

$$\pm 1000 \text{ mV Range Resolution} = \frac{2124.5 \text{ mV}}{2^{24}} = 126.63 \text{ nV}$$

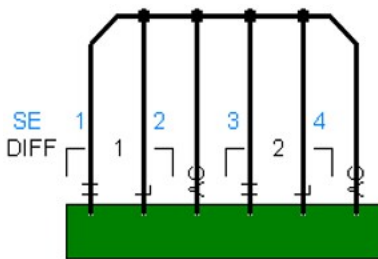
$$\pm 200 \text{ mV Range Resolution} = \frac{424.02 \text{ mV}}{2^{24}} = 25.27 \text{ nV}$$

5.2 Measuring the effective number of bits (ENOB)

5.2.1 Hardware setup

To measure the noise all analog input channels are connected to the signal ground.

Ideally signal ground should be 0 Volts. When the analog inputs are measured, the noise in the system will cause signal to deviate from the expected 0 Volts. The larger the signal deviates from 0 Volts effectively reduces the number of available bits to perform the analog-to-digital conversion.



5.2.2 `VolDiff()` and `VolSE()`

The two CRBasic functions used to measure the system noise are: `VolDiff()` and `VolSE()`. Both instructions contain parameters that change the effect noise has on a measurement, which will in turn impact the ENOB.

- F_{N1}

Notch frequency filtering. A slower notch frequency results in longer averaging intervals, effectively smoothing out variations in the signal over time. This can help mitigate the effects of random fluctuations or interference, leading to more stable and consistent measurements. Averaging over longer intervals effectively increases the effective resolution of the measurement system. This is particularly beneficial in situations where the signal is weak or noisy, as it allows finer details to be captured with greater precision.

- **Reverse Differential [VolDiff()]**

Reversed differential measurements allow for better rejection of common-mode noise. Common-mode noise is noise that appears simultaneously and identically on both signal lines. By reversing the polarity of one of the signal lines and taking the difference between them, common-mode noise components cancel out, while the desired signal is preserved.

Measure Offset [VoltSe()]

Measure Offset has two options:

Option 1 – True. The ground offset voltage is measured before conducting the actual measurement on the analog channel. The ground offset voltage is subtracted it from the sensor measurement.

Option 2 –False. The offset voltage correction can be performed from background calibration. In this mode, the system automatically calibrates and corrects for offset voltage during background calibration processes.

- **Input Range**

The span of voltage levels that an analog measurement system can accurately process.

5.2.3 Test matrix

The manipulation of each of these parameters potentially yields a different ENOB. The following table shows the combinations that have been tested.

FN1	VoltDiff () RevDiff = True	VoltDiff () RevDiff = False	VoltSe () MeasOff = True	VoltSe () MeasOff = False
15000 Hz	Test 1*	Test 4	Test 7	Test 10
±5000				
±1000				
±200				
60/50 Hz	Test 2	Test 5	Test 8	Test 11
±5000				
±1000				
±200				
5 Hz	Test 3	Test 6	Test 9	Test 12
±5000				
±1000				
±200				

*Test will be used as an example.

5.2.4 CRBasic Code Example of Test 1

- Block 1 - Measurement Tasks

```
Const REPS = 8
Const START_CH = 1
Const SETTLING_TIME = 2000
Const FN1 = 15000
Const DIFF_REVERSAL As Boolean = true

VoltDiff (mV_5000(), REPS, mV5000, START_CH, DIFF_REVERSAL, SETTLING_TIME,
FN1, 1, 0)
VoltDiff (mV_1000(), REPS, mV1000, START_CH, DIFF_REVERSAL, SETTLING_TIME,
FN1, 1, 0)
VoltDiff (mV_200(), REPS, mV200, START_CH, DIFF_REVERSAL, SETTLING_TIME, FN1,
1, 0)
```

- START_CH = 1 and REPS = 8

All differential channels will be measured. This is intended to capture the noise across all the channels not just an individual channel.

- SETTLING_TIME = 2000

The measurement settling time is set to 2000 μ S (2 mS). Anecdotally, this is enough time to ensure the effects of multiplexing channels to the ADC does not interfere with the measurement. This value most likely could be faster.

- FN1 = 15000 and DIFF_REVERSAL = TRUE

These are the test parameters of the `VoltDiff()` instruction that are being tested. They have the potential to influence how much noise is measured.

- Block 2 – Data Collection

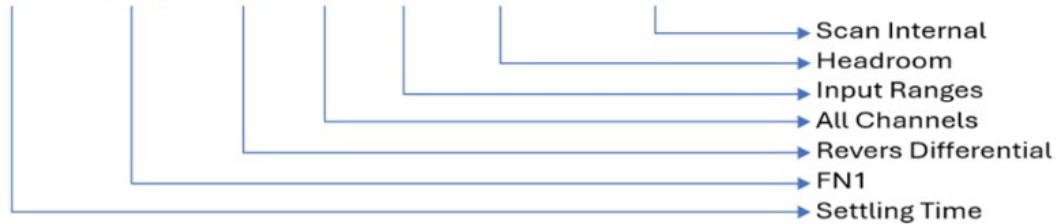
```
Const SCAN_TIME = 150
Const SAMPLES = 60

DataTable (calc_table,2,-1)
  DataInterval(0,SCAN_TIME * SAMPLES,mSec,10)
  StdDev (REPS,mV_5000(),IEEE4,0)
  StdDev (REPS,mV_1000(),IEEE4,0)
  StdDev (REPS,mV_200(),IEEE4,0)
EndTable
```

- **SCAN_TIME = 150**

This sets the data loggers main scan interval to 150 mS. The 150 mS scan interval is based on how long it takes to complete the measurement tasks without skipping scans.

$$((((2 \text{ mS} + \frac{1}{15000}) \times 2) \times 8) \times 3) + 50 \text{ mS} = 150 \text{ mS}$$



- **SAMPLES = 60**

The number of measurements recorded in the data table before processing the effective number of bits (ENOB). A sample size of 60 appears to yield a sufficient data set. While increasing the number of samples can enhance data quality, the improvement is likely to be marginal.

- **calc_table**

The primary responsibility of the data table is to calculate the standard deviation for the number of samples/measurements. The standard deviation of the noise is used to quantify the SNR, which in turn determines the effective resolution or ENOB of the measurement system. Lower noise levels (as indicated by a lower standard deviation) lead to higher SNR and better resolution.

- **Block 3 – ENOB Calculation**

```
'mv5000 range
Const FMR_MV5000 = 10813.4

For i = 1 To REPS
    Std_mv5000(i) = calc_table.mV_5000_Std(i,1)
Next i

AvgSpa (AvgStdDev_mv5000, REPS, Std_mv5000())
ENOB_mv5000 = (LOG(FMR_MV5000/(AvgStdDev_mv5000))) / LOG(2)
```

- **FMR_MV5000 = 10813.4**

Full Measurement Range for the ± 5000 mV input option. As previously described, the ± 5000 mV full measurement range is ± 5406.7 mV.

- **Std_mv5000**

This array stores the output of the calc_table. Each element of the Std_mv5000() array corresponds to the calculated standard deviation measured for individual analog differential channels.

- **AvgStDev_mV5000**

The average standard deviation across all analog inputs is represented by this variable, ensuring that each channel is considered collectively rather than individually.

- **ENOB_mv5000**

The effective bits of resolution measured for the ± 5000 mV input range. This also incorporates the associated notch frequency and reverse differential parameters.

6. Data from testing

Table 6-1: Measured effective number of bits				
FN1	VoltDiff () RevDiff = True	VoltDiff () RevDiff = False	VoltSe () MeasOff = True	VoltSe () MeasOff = False
15000 Hz	Test 1	Test 4	Test 7	Test 10
± 5000	20.344	19.942	19.378	19.863
± 1000	20.115	19.603	19.151	19.643
± 200	19.096	18.654	18.155	18.492
60/50 Hz	Test 2	Test 5	Test 8	Test 11
± 5000	24.136	23.644	23.157	23.597
± 1000	23.922	23.413	22.818	23.47
± 200	22.948	22.405	21.923	22.322
5 Hz	Test 3	Test 6	Test 9	Test 12
± 5000	25.926	25.19	24.98	25.075
± 1000	25.714	24.84	24.579	24.88
± 200	24.599	23.953	23.252	23.672

Table 6-2: Measured effective resolution				
FN1	VoltDiff () RevDiff = True	VoltDiff () RevDiff = False	VoltSe () MeasOff = True	VoltSe () MeasOff = False
15000 Hz	Test 1	Test 4	Test 7	Test 10
±5000	8.12 μ V	10.735 μ V	15.87 μ V	11.339 μ V
±1000	1.87 μ V	2.667 μ V	3.649 μ V	2.59 μ V
±200	0.757 μ V	1.028 μ V	1.453 μ V	1.15 μ V
60/50 Hz	Test 2	Test 5	Test 8	Test 11
±5000	0.586 μ V	0.824 μ V	1.156 μ V	0.852 μ V
±1000	0.134 μ V	0.19 μ V	0.287 μ V	0.183 μ V
±200	0.052 μ V	0.076 μ V	0.107 μ V	0.081 μ V
5 Hz	Test 3	Test 6	Test 9	Test 12
±5000	0.17 μ V	0.282 μ V	0.327 μ V	0.306 μ V
±1000	0.038 μ V	0.071 μ V	0.085 μ V	0.069 μ V
±200	0.017 μ V	0.026 μ V	0.042 μ V	0.032 μ V

6.1 CR1000Xe summary

The CR1000Xe ADC is a 24-bit sigma-delta converter. This type of ADC oversamples the input signal and applies noise shaping to achieve high resolution. It consists of three main components:

Oversampling – Sample the input at a significantly higher rate than the expected output rate. For example, sampling 256 times the desired rate could theoretically increase the effective resolution by 2 to 4 bits.

Averaging – Averaging the oversampled measurements and outputting at the desired rate will reduce the impact of system noise. The more samples you average the more the noise is reduced.

Advance Filtering – The FN1 (first notch filter) is used to further improve the resolution by filtering out noise. The sigma-delta modulation can shape the noise spectrum, pushing noise to higher frequencies where it can be filtered out.

The overall effect of integrating oversampling, averaging, and filtering enhances the SNR thereby increasing the ENOB, reaching or exceeding 25 bits with a 24-bit ADC. In the data from testing, there are a few conditions where the CR1000Xe ENOB exceeds the 24-bit ADC.

The CR1000Xe uses a 12 V buck-boost power input regulator, operating within a voltage range of 10 to 36 volts. The ENOB was measured at both extremes of this input range. In theory, bucking or boosting the voltage could generate additional system noise. However, it was observed that when the input regulator was either bucking or boosting, there was no change in the measurement results.

Appendix A. CRBasic program for Test 1

CRBasic Example 1: CRBasic program for Test 1

```
'CR1000X
'Analyze noise and offset on all Analog input channels.
'Calculate the Effective Resolution
'To perform this test, you need to know the Full Measurement Range in mV (FMR)

' mV5000
'   max 5406.7
'   min -5406.7
'   full range = 10813.4mV

' mV1000
'   max 1062.25mV
'   min -1062.25mV
'   full range = 2124.5mV

' mV200
'   max 212.01mV
'   min -212.01mV
'   full range = 424.02mV

'Setup - Wire all diff channels to ground.

Const SCAN_TIME = 150
Const REPS = 8
Const START_CH = 1
Const SETTling_TIME = 2000
Const FN1 = 15000
Const DIFF_REVERSAL As Boolean = true

Const FMR_MV5000 = 10813.4 'see notes above
Const FMR_MV1000 = 2124.5 'see notes above
Const FMR_MV200 = 424.02 'see notes above
Const SAMPLES = 60

Public mV_5000(REPS)
Public mV_1000(REPS)
Public mV_200(REPS)
```

CRBasic Example 1: CRBasic program for Test 1

```

Public AvgStDev_mv5000
Public AvgStDev_mv1000
Public AvgStDev_mv200

Public ENOB_mv5000
Public ENOB_mv1000
Public ENOB_mv200

Public Tdone

Dim Std_mv5000(REPS)
Dim Std_mv1000(REPS)
Dim Std_mv200(REPS)
Dim i

DataTable (calc_table,2,1000)
  DataInterval(0,SCAN_TIME*SAMPLES,mSec,10)
  StdDev (REPS,mV_5000(),IEEE4,0)
  StdDev (REPS,mV_1000(),IEEE4,0)
  StdDev (REPS,mV_200(),IEEE4,0)
EndTable

BeginProg

  Scan(SCAN_TIME,mSec,10,0)

  VoltDiff (mV_5000(),REPS,mV5000,START_CH,DIFF_REVERSAL,SETTLING_TIME,FN1,1,0)
  VoltDiff (mV_1000(),REPS,mV1000,START_CH,DIFF_REVERSAL,SETTLING_TIME,FN1,1,0)
  VoltDiff (mV_200(),REPS,mV200,START_CH,DIFF_REVERSAL,SETTLING_TIME,FN1,1,0)

  CallTable calc_table

  If calc_table.output(1,1) AND calc_table.record(1,1) > 0 Then

    'mv5000 range
    For i = 1 To REPS
      Std_mv5000(i) = calc_table.mV_5000_Std(i,1)
    Next i

    AvgSpa (AvgStDev_mv5000,REPS,Std_mv5000())
    'VIN = Full Measuremnt Range
    'Bits = LOG(VIN/STDev)/LOG(2)
    ENOB_mv5000 = (LOG(FMR_MV5000/(AvgStDev_mv5000))) /LOG(2)

    'mv1000 range
    For i = 1 To REPS
      Std_mv1000(i) = calc_table.mV_1000_Std(i,1)

```

CRBasic Example 1: CRBasic program for Test 1

```
Next i

AvgSpa (AvgStDev_mV1000,REPS,Std_mv1000())
'VIN = Full Measuremnt Range
'Bits = LOG(VIN/STDev)/LOG(2)
ENOB_mv1000 = (LOG(FMR_MV1000/(AvgStDev_mV1000))) /LOG(2)

'200mV range
For i = 1 To REPS
  Std_mv200(i) = calc_table.mV_200_Std(i,1)
Next i

AvgSpa (AvgStDev_mV200,REPS,Std_mv200())
'VIN = Full Measuremnt Range
'Bits = LOG(VIN/STDev)/LOG(2)
ENOB_mv200 = (LOG(FMR_MV200/(AvgStDev_mV200))) /LOG(2)

Tdone = 1

EndIf

NextScan
EndProg
```


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