ENGR-2350
Embedded Control

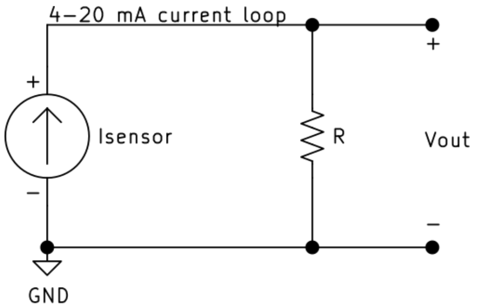
Data Acquisition: ADC

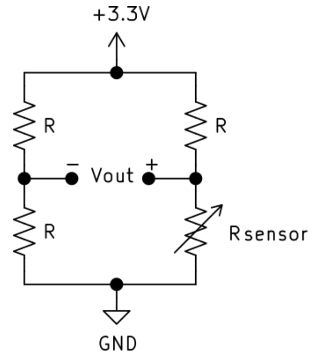
Data Acquisition

Need more than just plain Digital Inputs to perform most control applications (input → output):

- Temperature INPUT to control Heater
- Distance INPUT to control Drive power
- Speed INPUT to control Cruise control
- Light level INPUT to control screen brightness
- Pressure INPUT to control relief valves
- Tilt INPUT to control game character movement
- Etc.

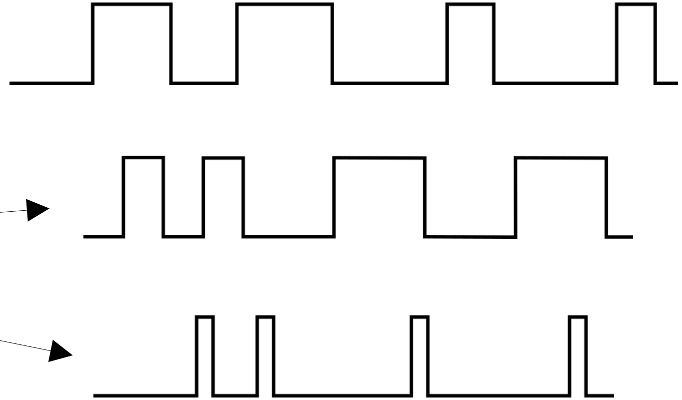
Data Acquisition





Additional Types of Input Data:

- **Analog Voltages and Currents:**
  - Sensors may output analog voltage directly.
  - Converted 4-20 mA current loops
  - Variable resistance + Bridges
- **Time/Frequency Based Signals:**
  - Pulse width modulated (PWM)
  - Frequency modulated (FM)
  - Delay based signals
- More...



Data Acquisition: Methods

Analog Voltages:

- Analog-to-Digital Converters (ADC):
  - Maps an **Analog** voltage to a **Digital** number
  - Conversion range limited to **Reference Voltages**
  - Loss of information due to **Quantization**
  - Limited **Sampling** speed

Time/Frequency Based Signals:

- Timer **Capture: Last Lecture**

Analog-to-Digital Converter (ADC)

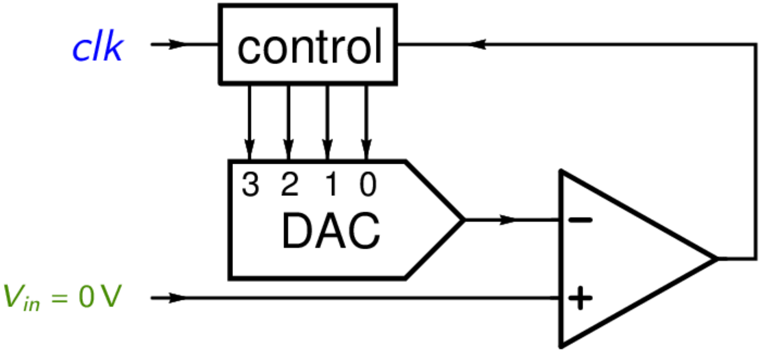
Analog-to-Digital Converters (ADC)

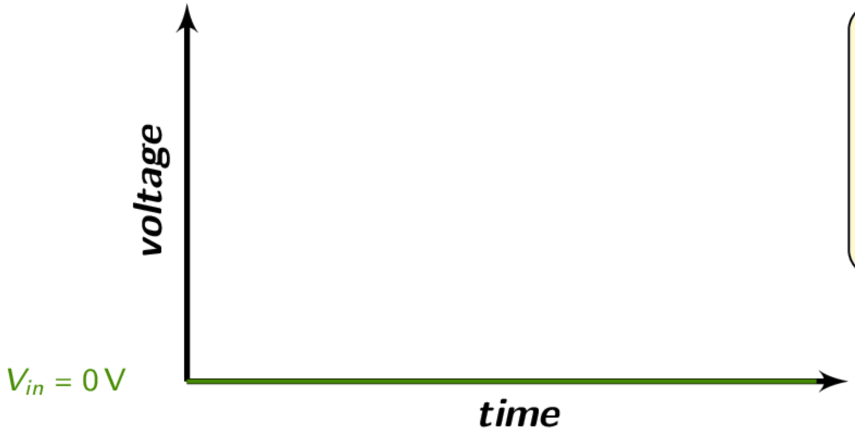
- Convert an analog voltage to a digital value.
  - E.g., 1.3 V → 4362 [ADC unit: LSb]
- How? Many different ways...
  - Most common:
    Successive Approximation Register ADC
    - Work from MSb to LSb, testing if “guess” is too high/too low

Successive Approximation – example of a 4-bit ADC

SAR ADC

https://en.wikipedia.org/wiki/Successive-approximation_ADC





Resolution:

$5\,V \times 1/2$	2.5000 V
$5\,V \times 1/4$	1.2500 V
$5\,V \times 1/8$	0.6250 V
$5\,V \times 1/16$	0.3125 V
...	
$5\,V \times 1/1024$	0.0049 V

ADC: Mapping (typical)

- Conversion Mapping (uint16_t output):
  - Single-Ended Mode

$$N_{\text{ADC}} = 2^{N_{\text{bits}}} \frac{V_{\text{in}+} - V_{\text{Ref}-}}{V_{\text{Ref}+} - V_{\text{Ref}-}} \qquad V_{\text{Ref}-} \leq V_{\text{in}+} < V_{\text{Ref}+}$$

  - Estimated Voltage: $\hat{V}_{\text{in}+} = \frac{N_{\text{ADC}}}{2^{N_{\text{bits}}}} \left(V_{\text{Ref}+} - V_{\text{Ref}-}\right) - V_{\text{Ref}-}$

ADC: Mapping (typical)

- Conversion Mapping (uint16_t output) if $V_{\text{Ref}-} = 0$
  - Single-Ended Mode

$$N_{\text{ADC}} = 2^{N_{\text{bits}}} \frac{V_{\text{in}+}}{V_{\text{Ref}+}} \qquad 0 \leq V_{\text{in}+} < V_{\text{Ref}+}$$

  - Estimated Voltage:

$$\hat{V}_{\text{in}+} = \frac{N_{\text{ADC}}}{2^{N_{\text{bits}}}} V_{\text{Ref}+}$$

ADC: Example Conversions

- Single-Ended Conversion Mapping Example:

$$V_{\text{in}+} = 1.3\text{V} \quad V_{\text{R}+} = 3.3\text{V} \quad V_{\text{R}-} = 0\text{V} \quad N_{\text{bits}} = 14$$

$$N_{\text{ADC}} = 2^{14}\frac{1.3 - 0}{3.3 - 0} = 6454.3 \rightarrow \boxed{6454}$$

Output is always an integer!

- Quantization Error:

$$6454 = 2^{14}\frac{\hat{V}_{\text{in}+} - 0}{3.3 - 0} \rightarrow \hat{V}_{\text{in}+} = 1.299939\text{V} \qquad \text{error} = 61\ \mu\text{V}$$

ADC: Example Conversions

- Single-Ended Conversion Mapping Example:

$$V_{\text{in}+} = 1.3\text{V} \quad V_{\text{R}+} = 3.3\text{V} \quad V_{\text{R}-} = 0\text{V} \quad \boxed{N_{\text{bits}} = 8}$$

$$N_{\text{ADC}} = 2^8 \frac{1.3 - 0}{3.3 - 0} = 100.848 \to 100$$

- Quantization Error:

$$100 = 2^8 \frac{\hat{V}_{\text{in}+} - 0}{3.3 - 0} \to \hat{V}_{\text{in}+} = 1.289\text{V} \qquad \text{error} = 11\ \text{mV}$$

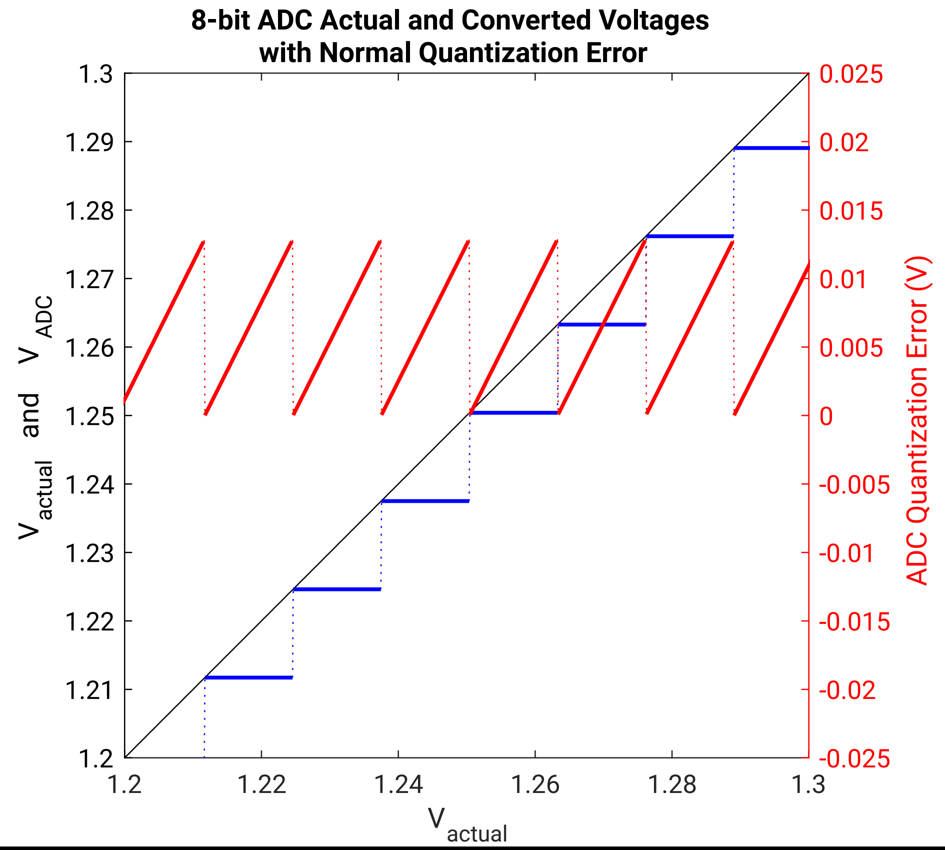
ADC: Mapping (typical)

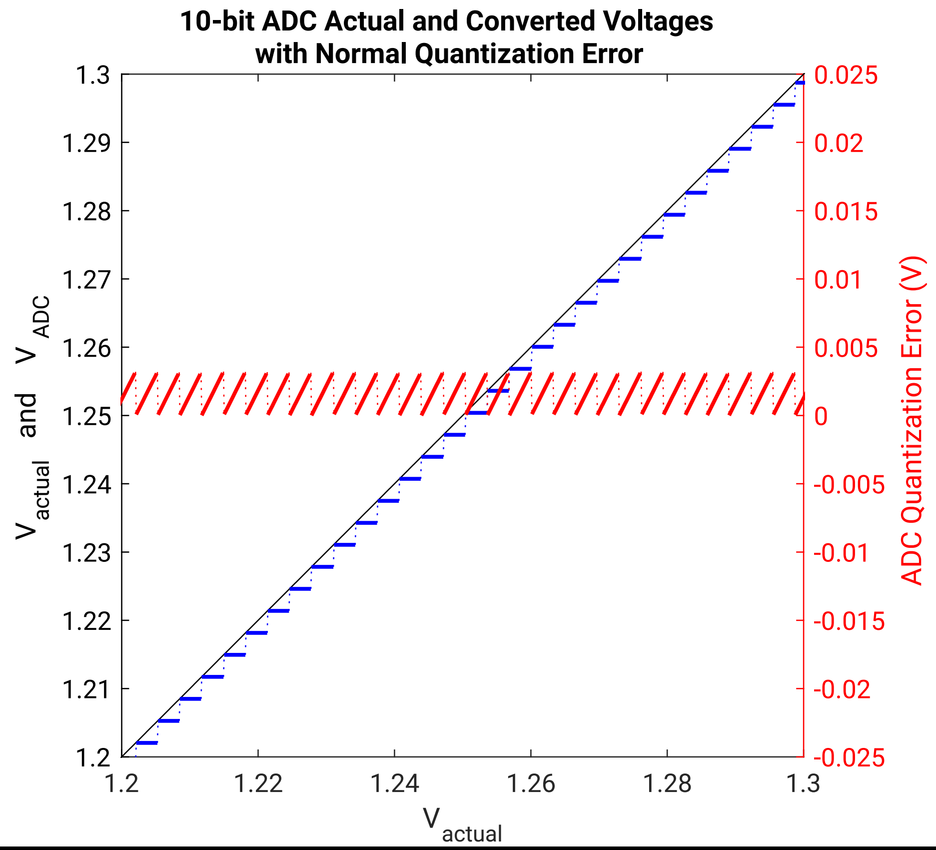
- Conversion Mapping (uint16_t output):
  - Differential Mode (Voltage between two inputs)

$$N_{\text{ADC}} = 2^{N_{\text{bits}}-1} \frac{V_{\text{in}+} - V_{\text{in}-}}{V_{\text{Ref}+} - V_{\text{Ref}-}} + 2^{N_{\text{bits}}-1} \qquad V_{\text{Ref}-} \leq V_{\text{in}-}, V_{in+} < V_{\text{Ref}+}$$

  - Estimated Value: $\hat{V}_{\text{in}+} - \hat{V}_{\text{in}-} = \left(\frac{N_{\text{ADC}}}{2^{N_{\text{bits}}-1}} - 1 \right) (V_{\text{Ref}+} - V_{\text{Ref}-}) + V_{\text{Ref}-}$

ADC: Quantization Error (Vref 3.3V)





ADC: Quantization Error

- Quantization Error is the error between the actual and the converted digital value:

$$Q_{\text{error}} = V_{\text{in+}} - \hat{V}_{\text{in+}}(N_{\text{ADC}})$$

- No quantization error when no rounding (e.g.):

$$N_{\text{ADC}} = \lfloor 123.00... \rfloor = 123 \rightarrow Q_{\text{error}} = 0, V_{\text{in+}} = \hat{V}_{\text{in+}}\left(N_{\text{ADC}}\right)$$

- Maximum value occurs at maximum rounding (e.g.):

$$N_{\text{ADC}} = \lfloor 123.99\ldots \rfloor = 123 \rightarrow Q_{\text{error}} = \max, \quad V_{\text{in+}} = \hat{V}_{\text{in+}}(N_{\text{ADC}} + 1)$$

$$\max(Q_{\text{error}}) = \hat{V}_{\text{in+}}(N_{\text{ADC}} + 1) - \hat{V}_{\text{in+}}(N_{\text{ADC}}) = \hat{V}_{\text{in+}}(1)$$

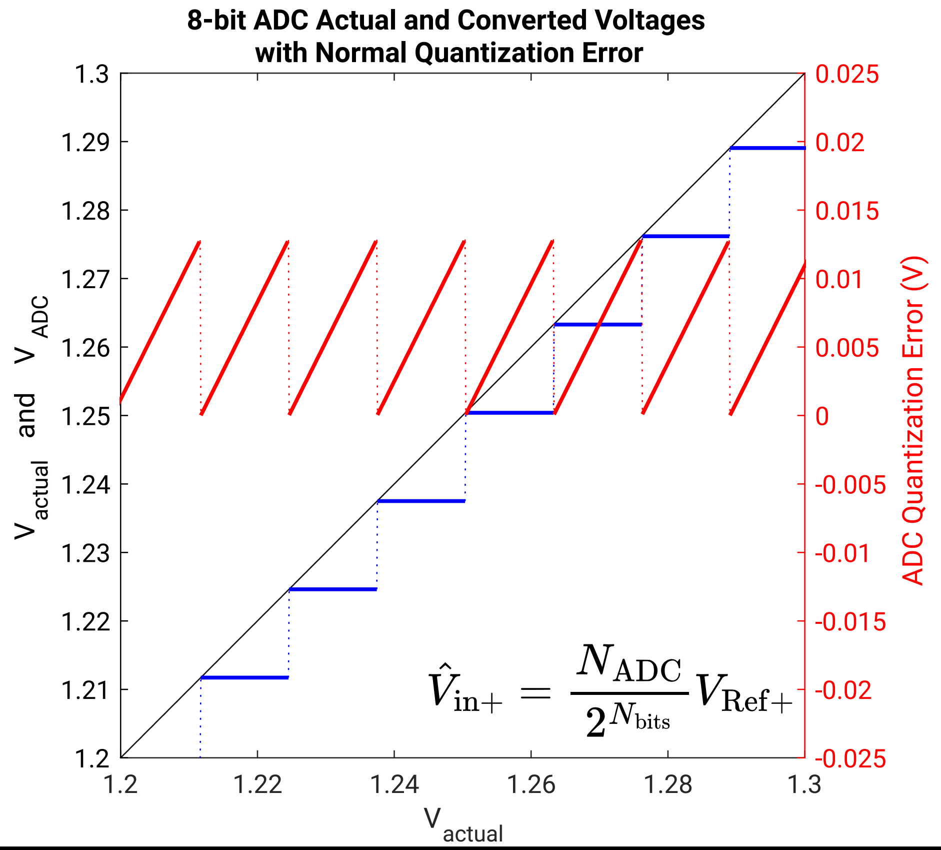
ADC: Quantization Error

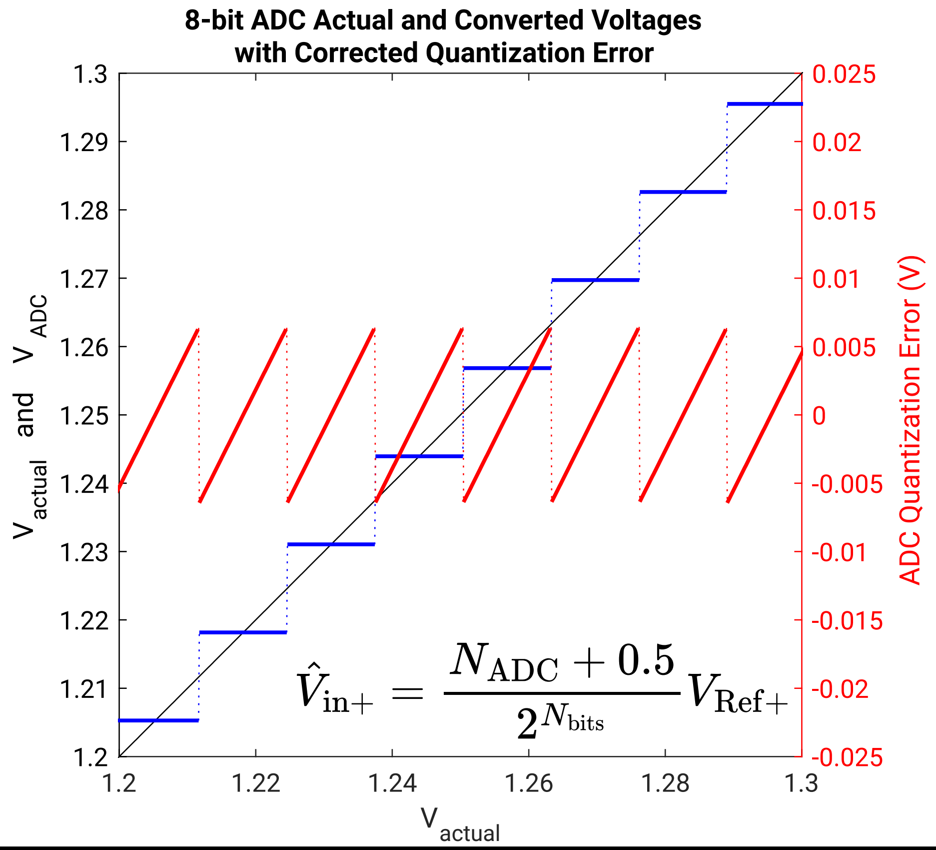
- Simple software change to reduce maximum quantization error:
  - Modify estimated voltage equation to add voltage offset of ½ the ADC resolution:

$$\hat{V}_{\text{in+}} = \frac{N_{\text{ADC}}}{2^{N_{\text{bits}}}} V_{\text{Ref+}} \longrightarrow \hat{V}_{\text{in+}} = \frac{N_{\text{ADC}} \mathbf{+0.5}}{2^{N_{\text{bits}}}} V_{\text{Ref+}}$$

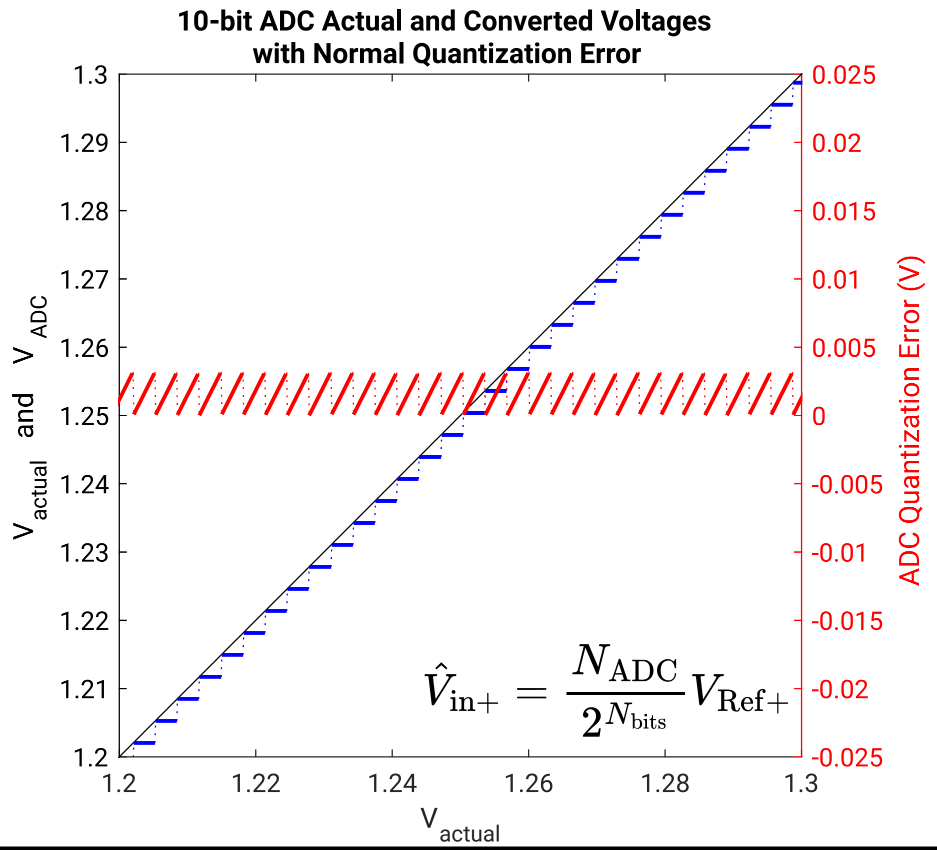
$$0 \leq Q_{\text{error}} < \hat{V}_{\text{in+}}(1) \longrightarrow -\frac{\hat{V}_{\text{in+}}(1)}{2} \leq Q_{\text{error}} < \frac{\hat{V}_{\text{in+}}(1)}{2}$$

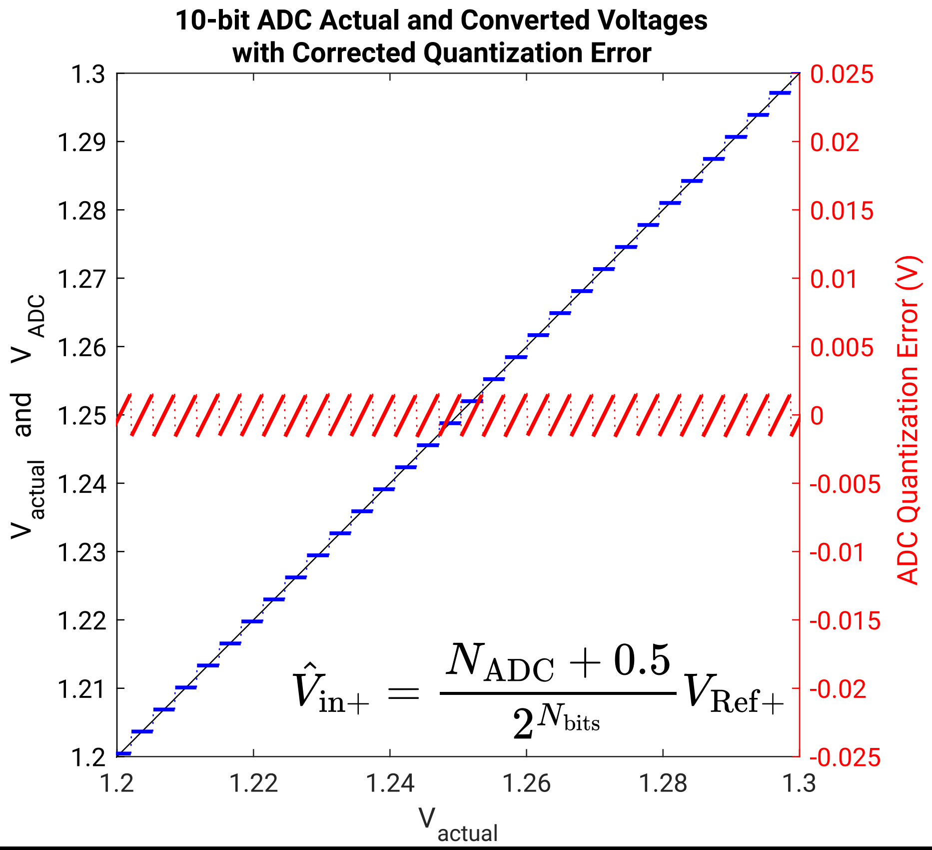
ADC: Quantization Error (Vref 3.3V)





ADC: Quantization Error (Vref 3.3V)

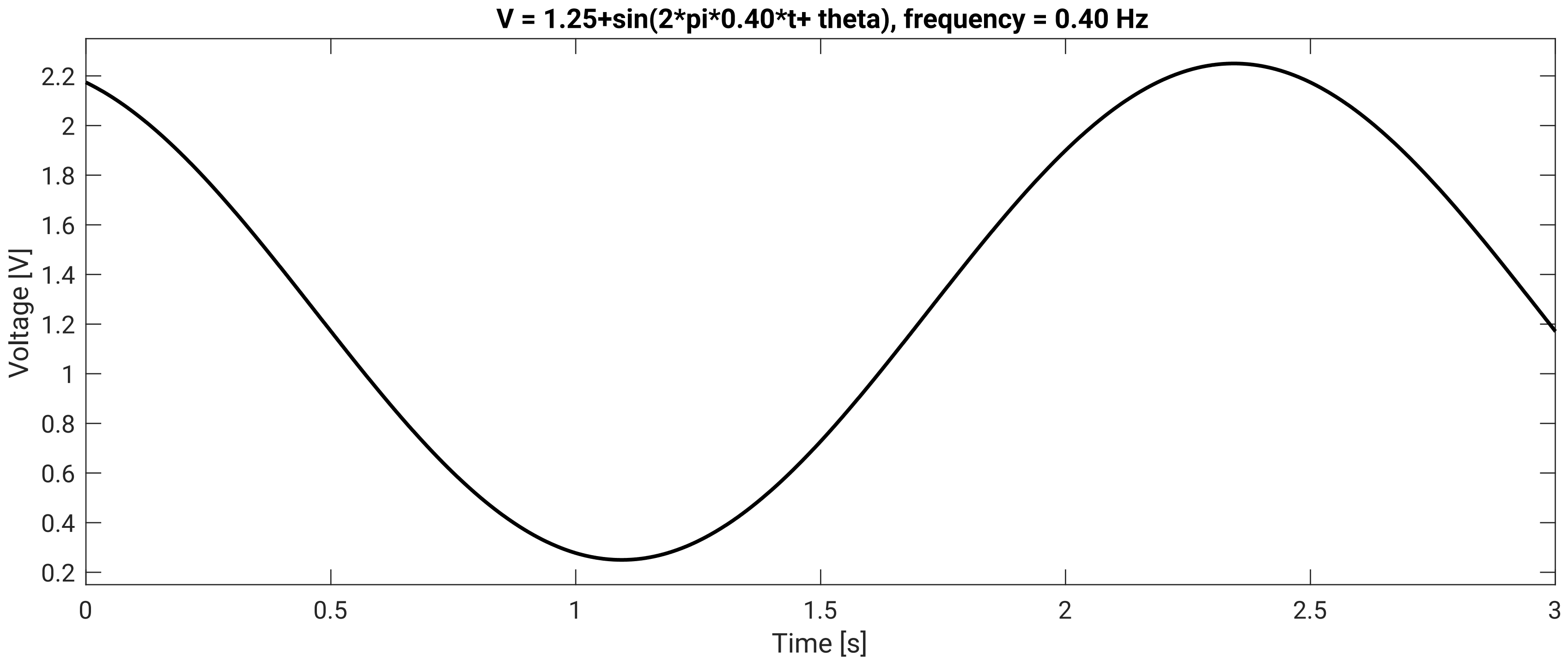




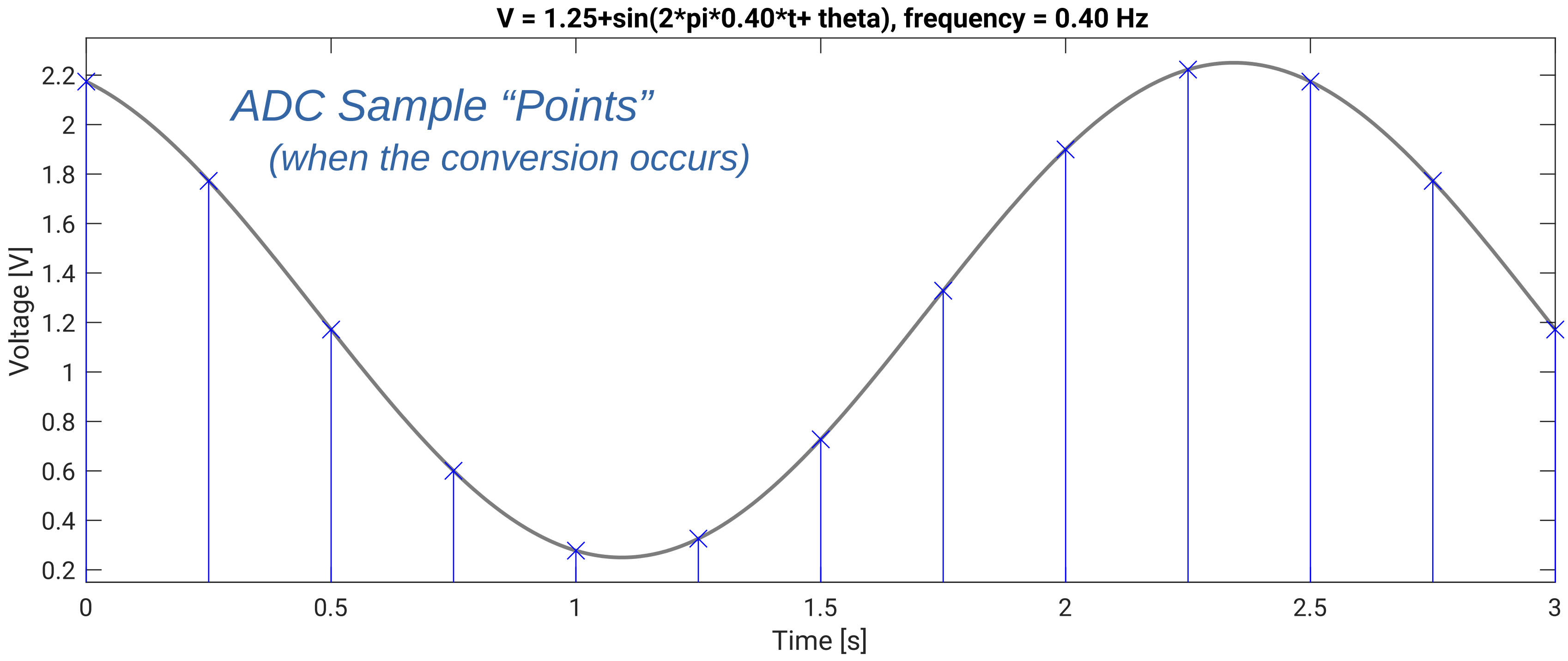
ADC Sampling Rate Issues

- Measuring near-DC (constant) voltages is easy
- Signals that vary with time may not be represented well with an ADC...

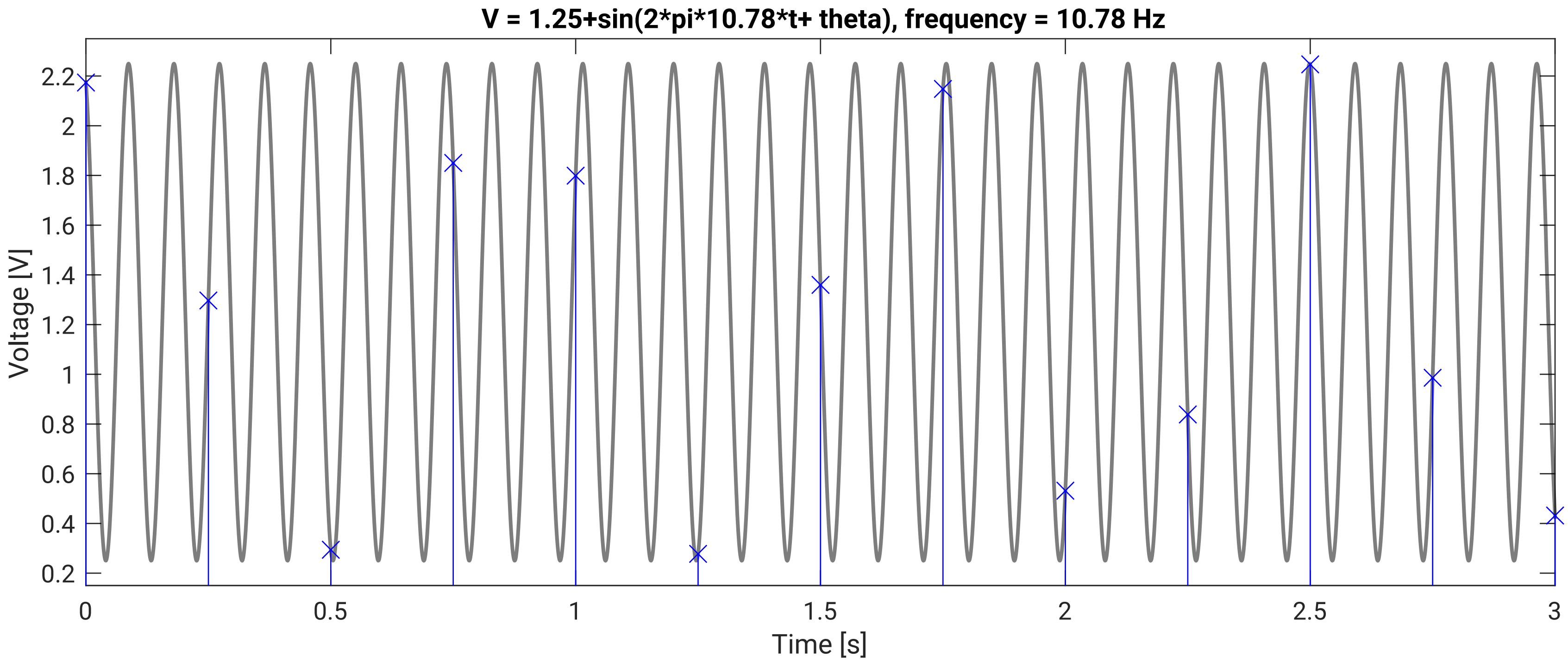
ADC Sampling Rate Issues



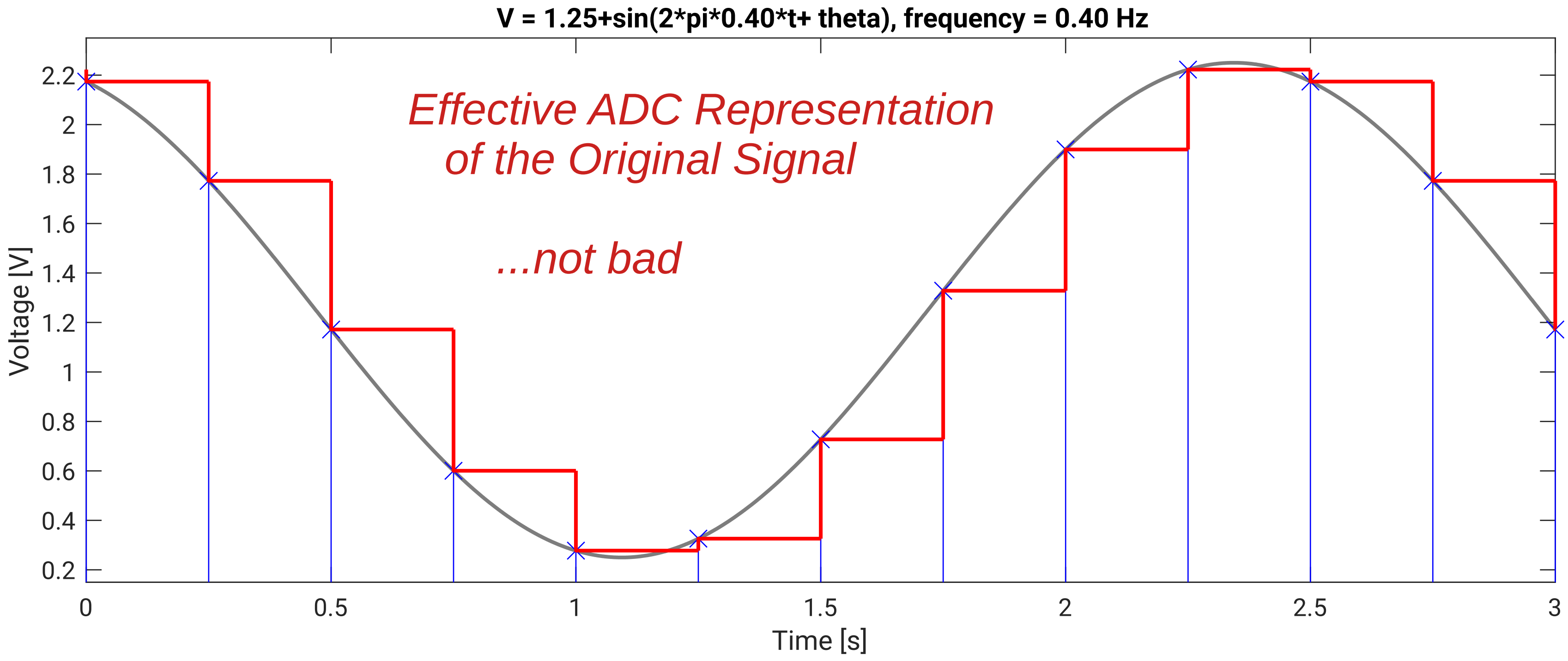
ADC Sampling Rate Issues



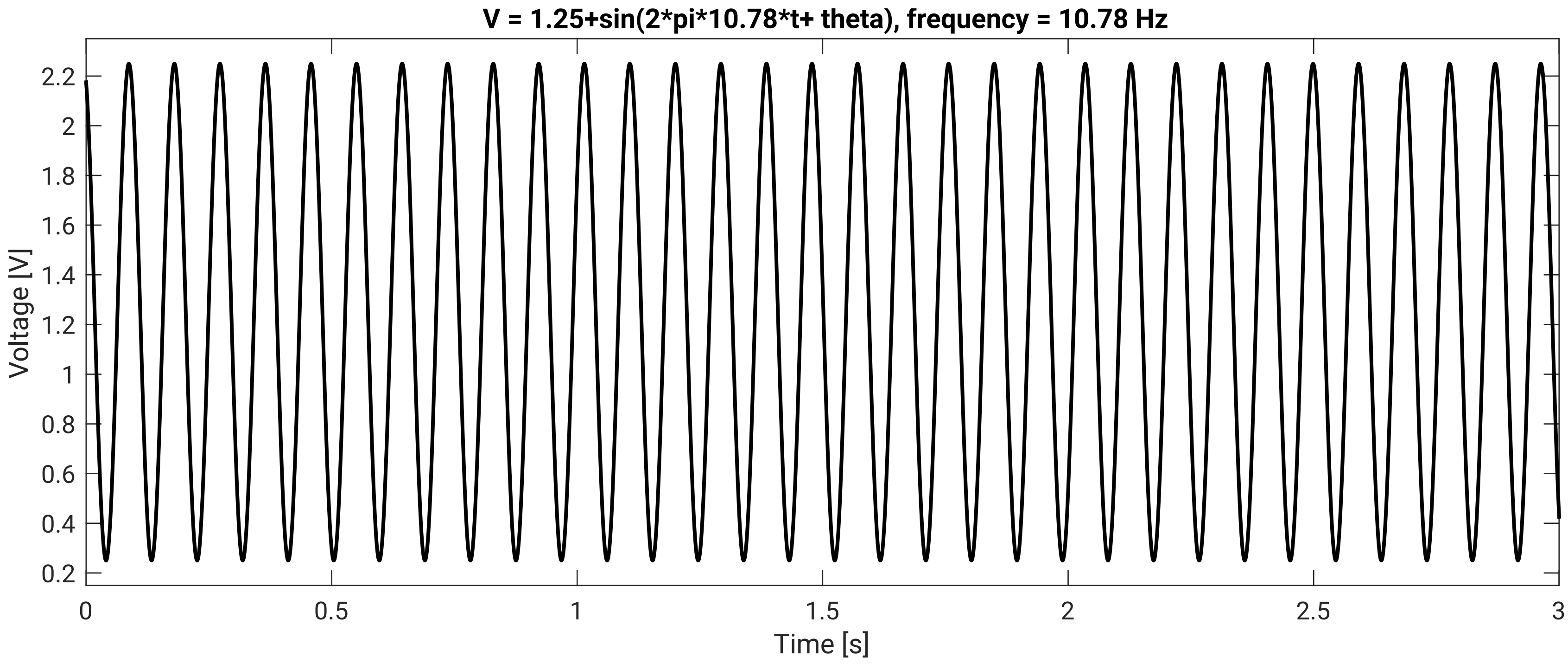
ADC Sampling Rate Issues



ADC Sampling Rate Issues

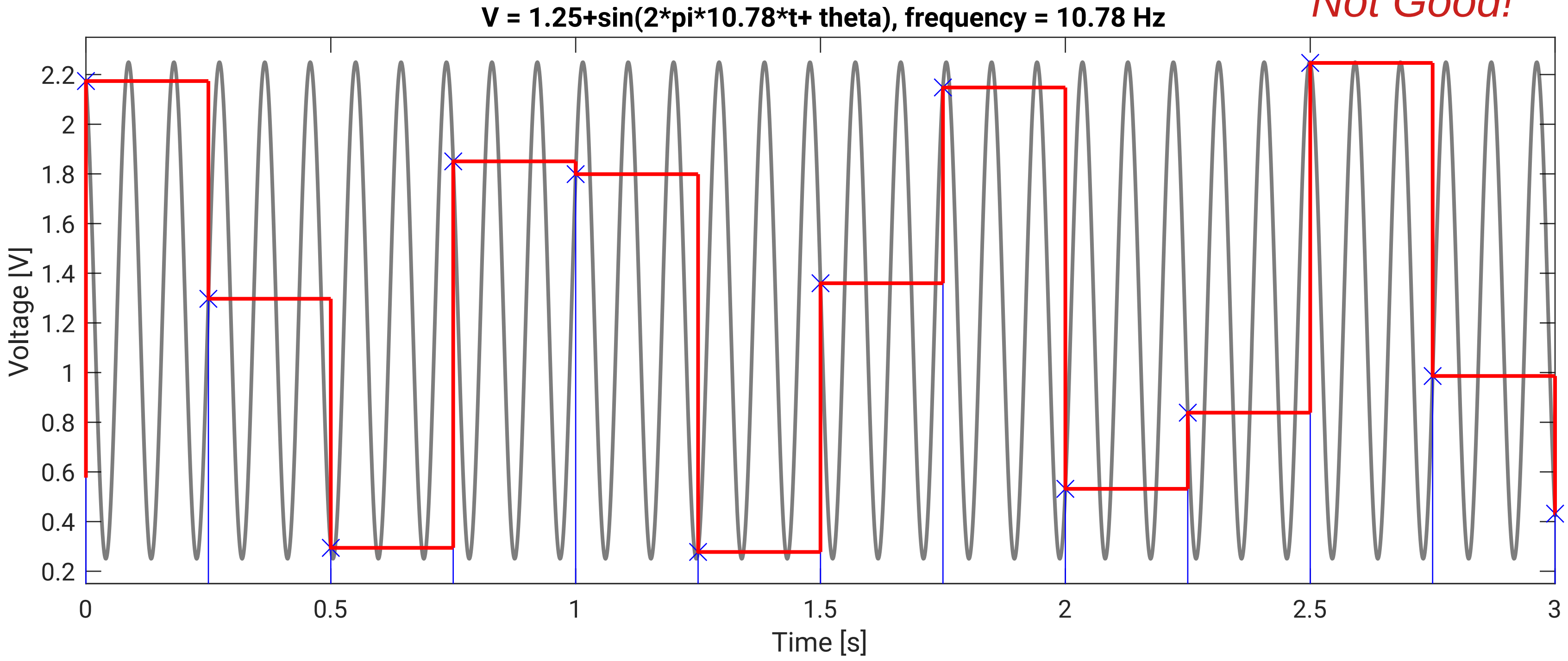


ADC Sampling Rate Issues



ADC Sampling Rate Issues

Not Good!



ADC Sampling Rate Issues

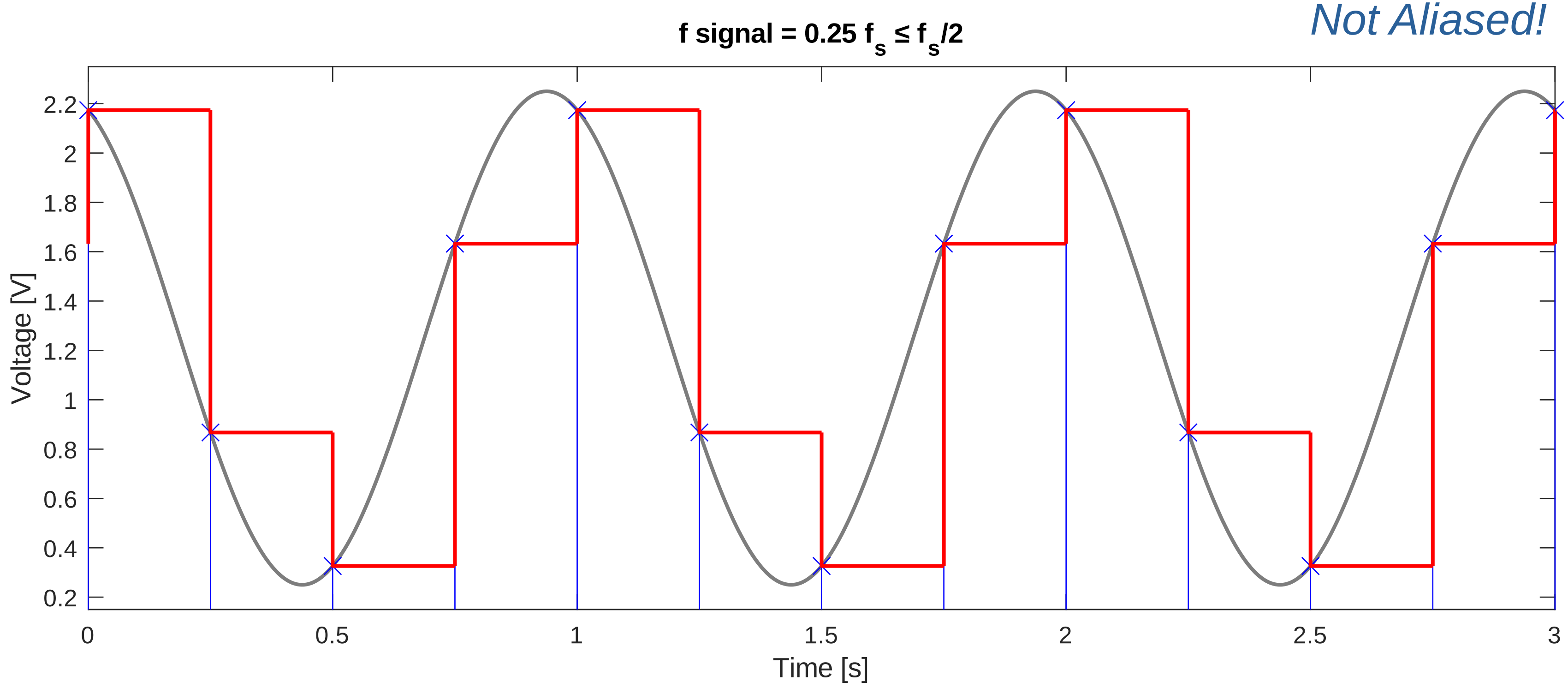
- Measuring near-DC (constant) voltages is easy
- Signals that vary with time may not be represented well with an ADC.
  - “High speed” signals cannot be represented well!
    - High Speed: Relative to the ADC sampling rate
    - ADC sampling rate should be 2 * highest frequency
      - This is the “Nyquist Rate”

ADC Sampling Rate Issues

- ADC sampling rate, f_s , should be 2 * highest frequency
  - This is the "Nyquist Rate"
- Any signals with frequencies ≥ $f_s / 2$ will "Alias"
  - "Alias" – any/all frequencies in a signal *after measurement* will look like a frequency ≤ $f_s / 2$
  - $f_s / 2$ is known as the "Nyquist Frequency", or the maximum frequency able to be measured.

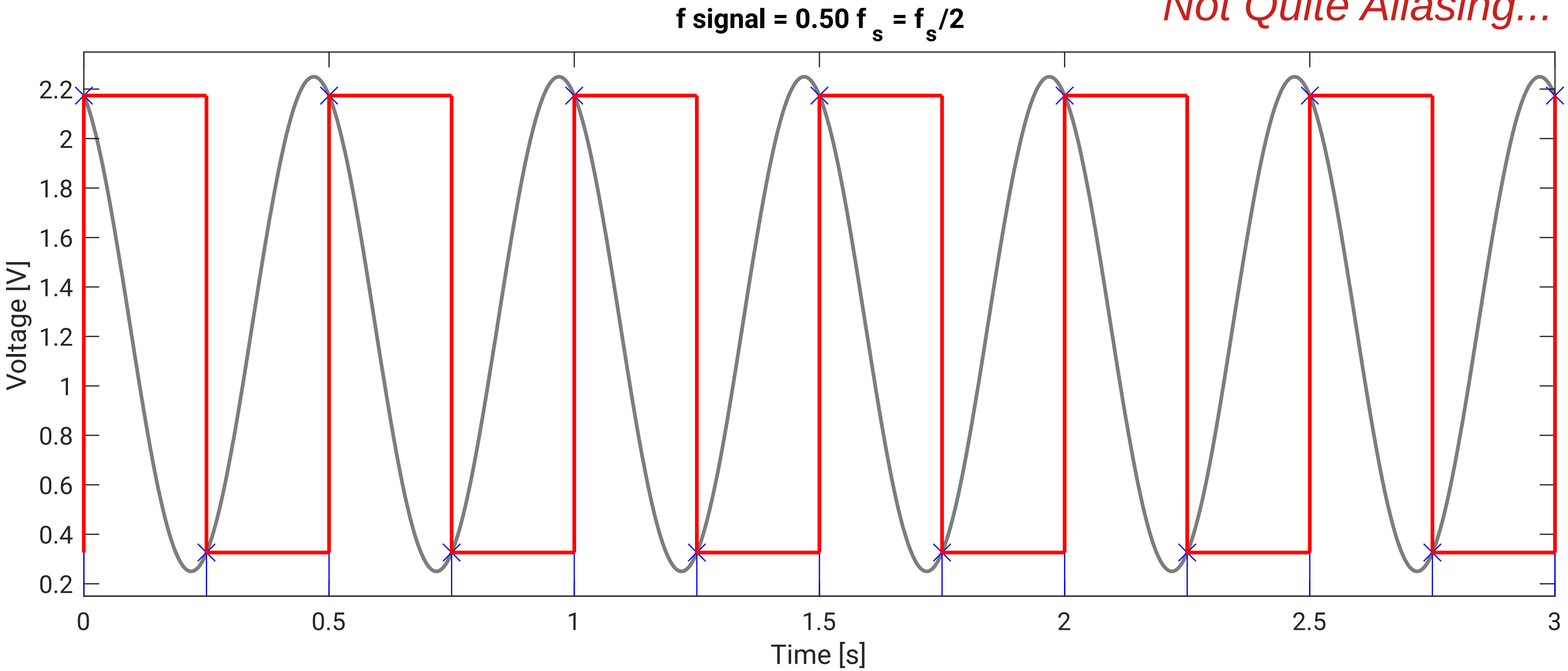
ADC Aliasing Example

Not Aliased!



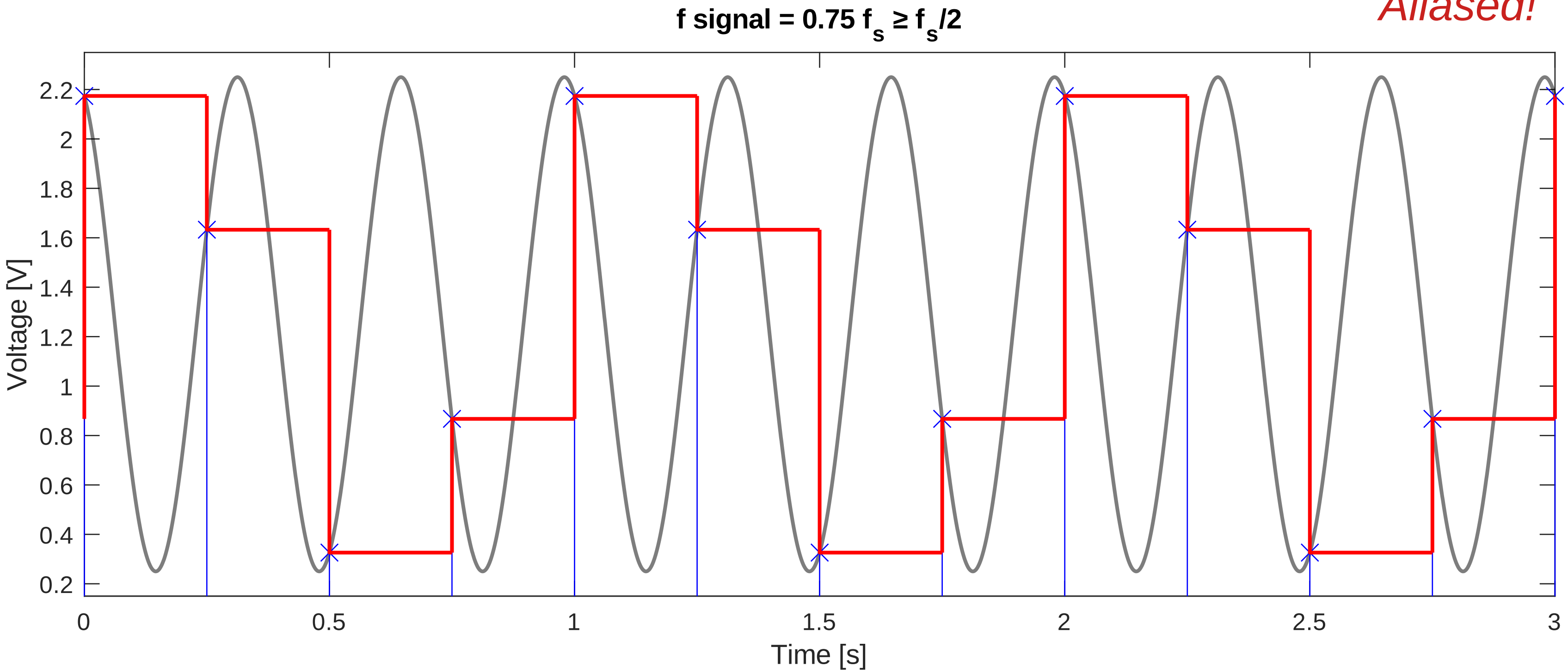
ADC Aliasing Example

Not Quite Aliasing...



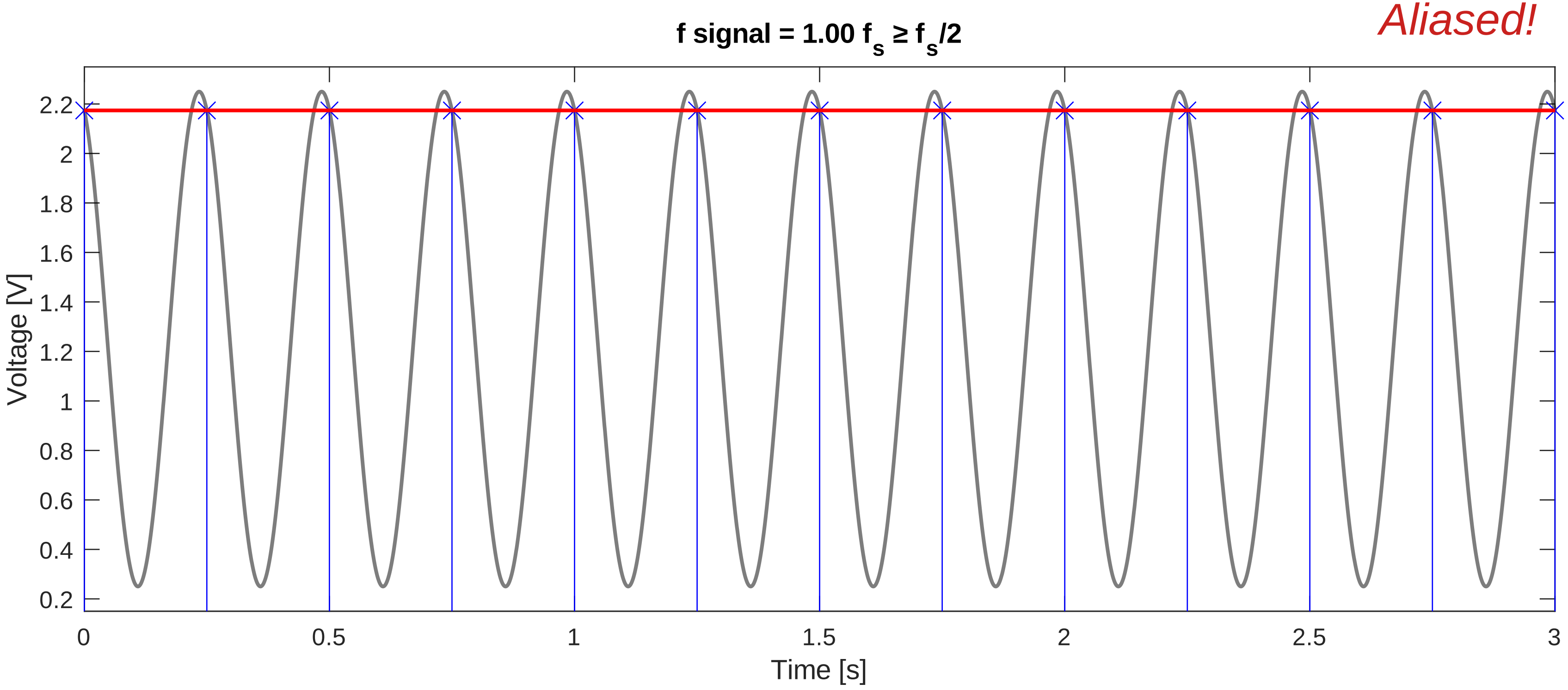
ADC Aliasing Example

Aliased!



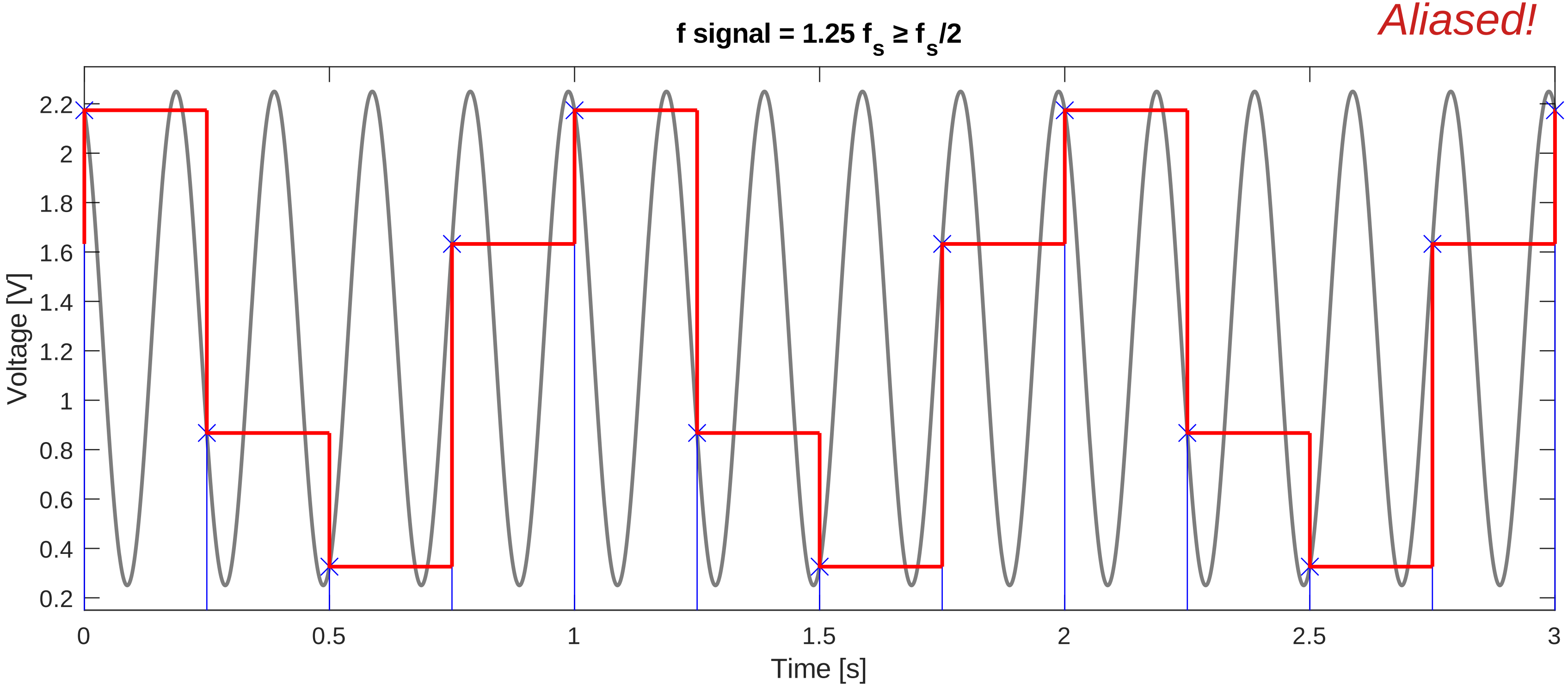
ADC Aliasing Example

Aliased!



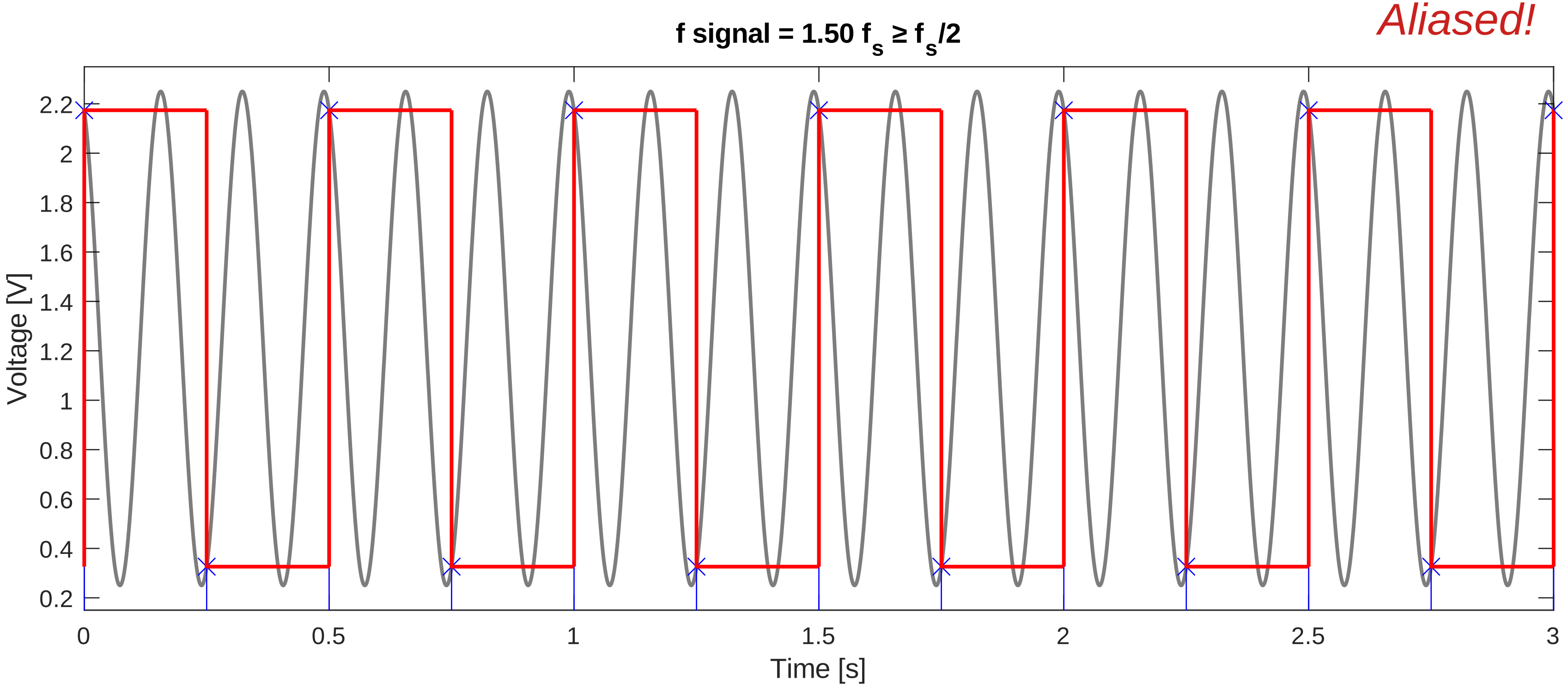
ADC Aliasing Example

Aliased!



ADC Aliasing Example

Aliased!



MSPM0G3507 ADC: **ADC12**

- MSPM0G3507 has two SAR ADCs: **ADC0, ADC1**
  - 16* input channels and configurable conversions
  - Selectable resolution: **8**, **10**, or **12** bits
  - **Single-Ended** only (no **Differential** inputs)
  - Voltage references selectable from **1.4 V**, **2.5 V**, **3.3 V** or provided externally through VREF+ pin**

* Not all 16 channels on each ADC are available on a pin
** VREF+ pin is not accessible by default on the LaunchPad DevBoard

ADC12

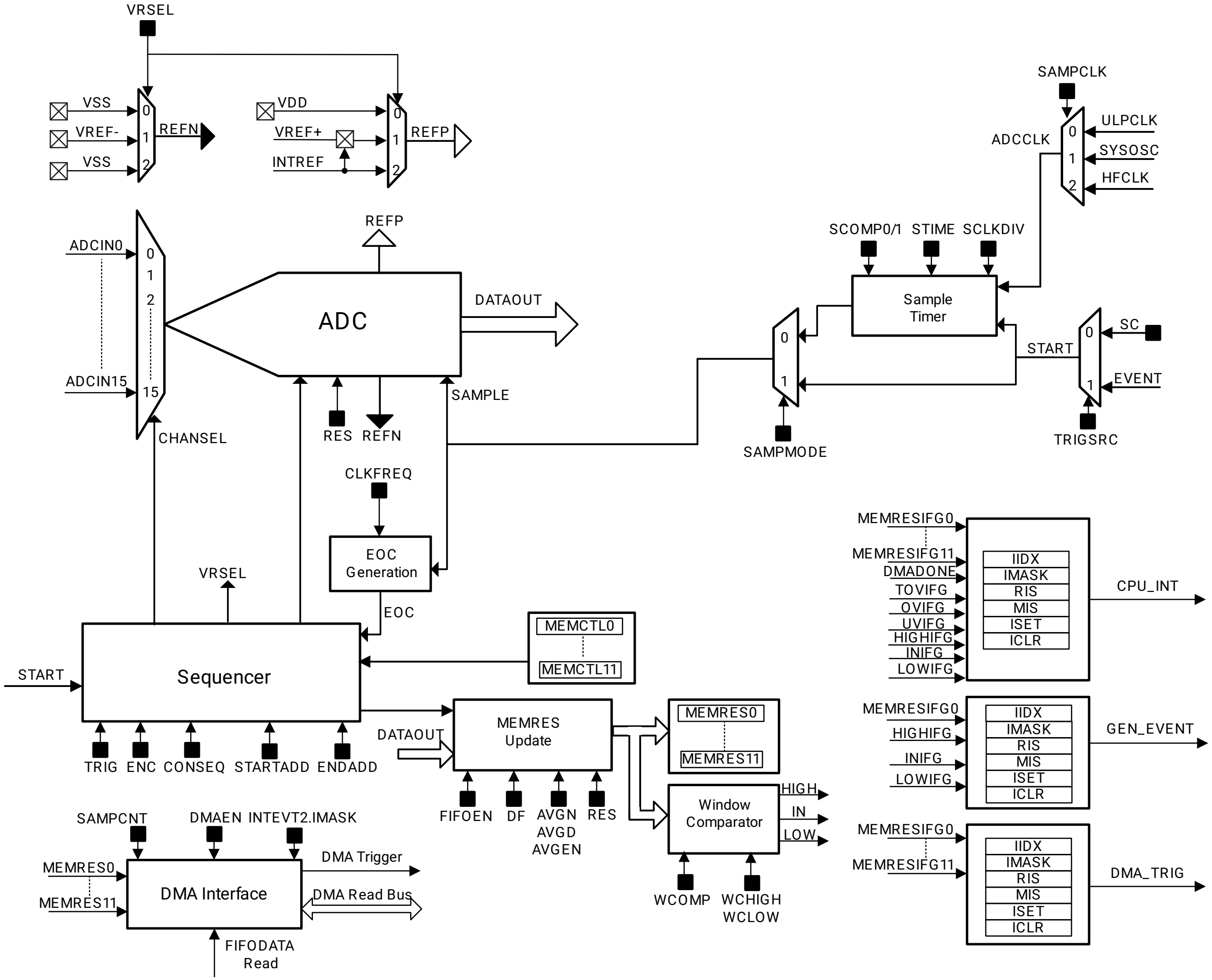


Figure 12-1. ADC Block Diagram

ADC12

Reference Voltage Selection

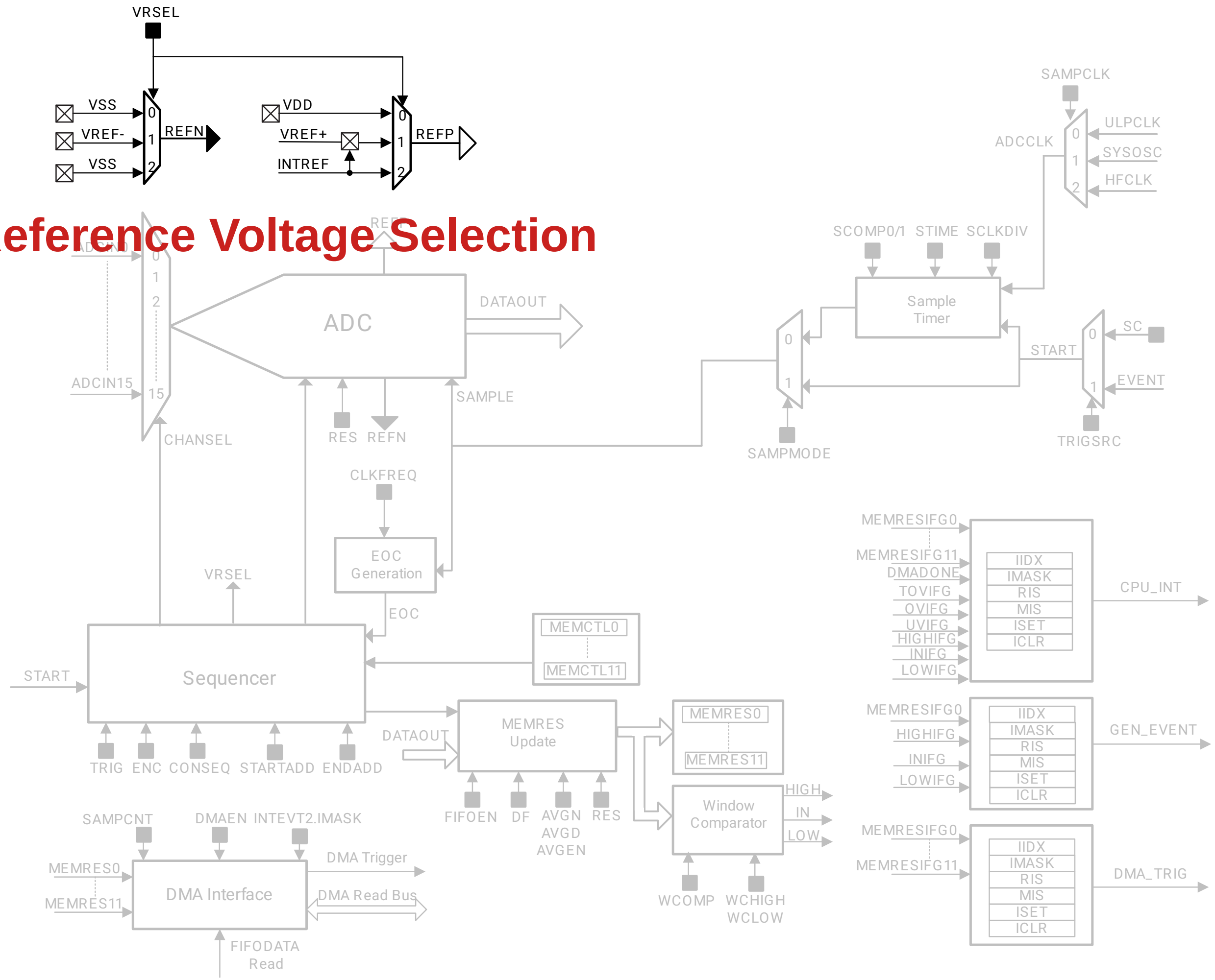


Figure 12-1. ADC Block Diagram

ADC12

Channel Selection

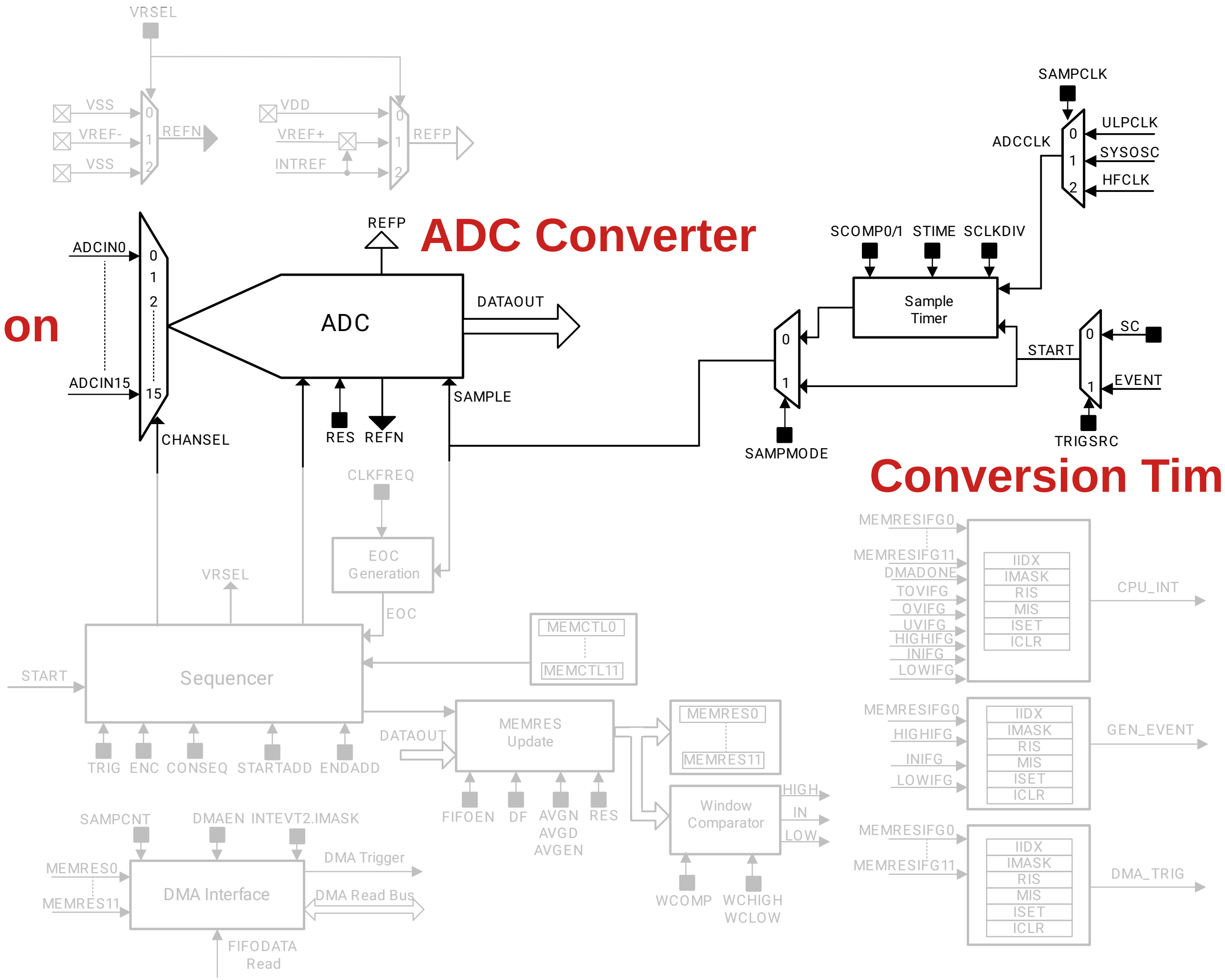


Figure 12-1. ADC Block Diagram

ADC12

Conversion Control

ADC "Memories"

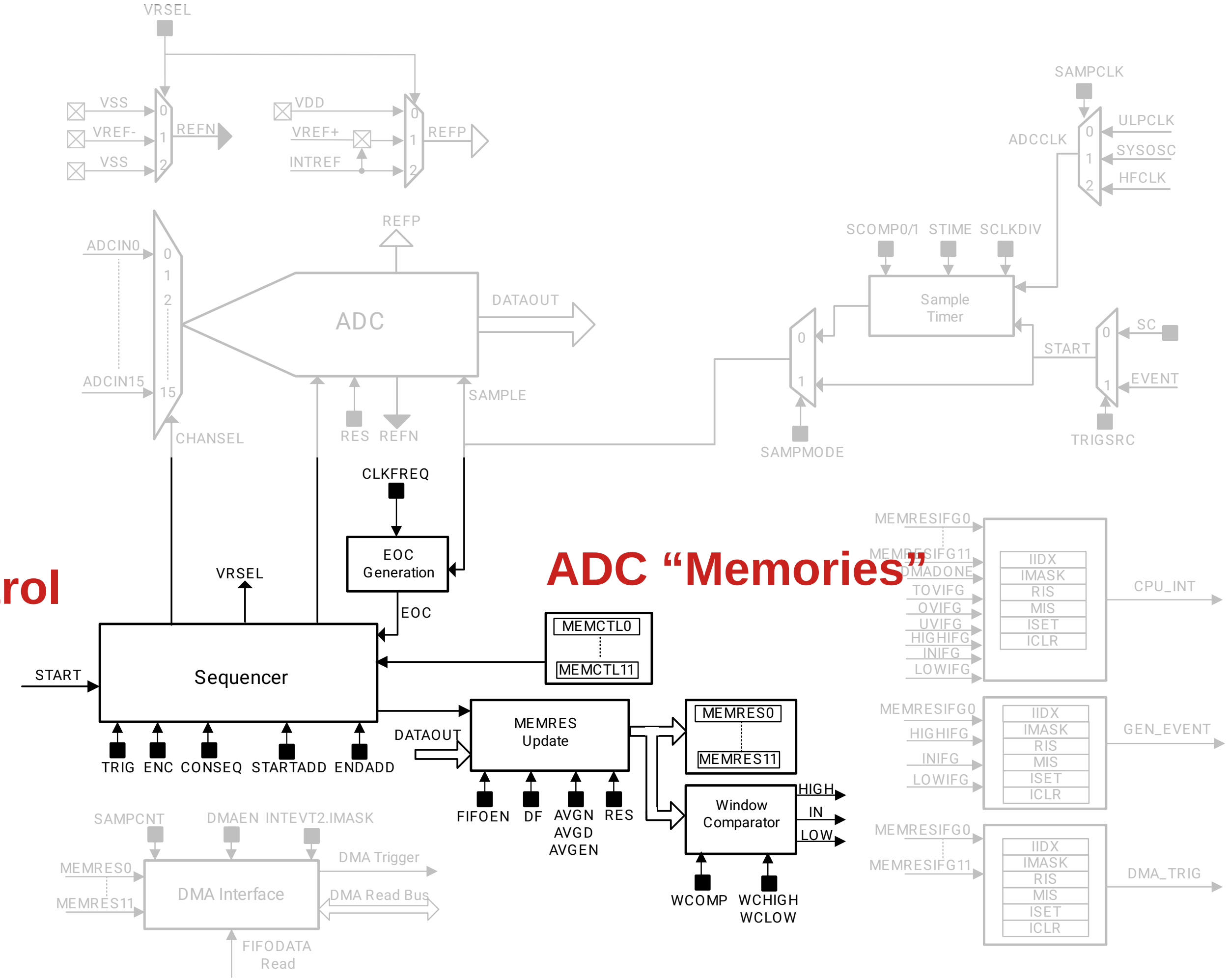


Figure 12-1. ADC Block Diagram

ADC12

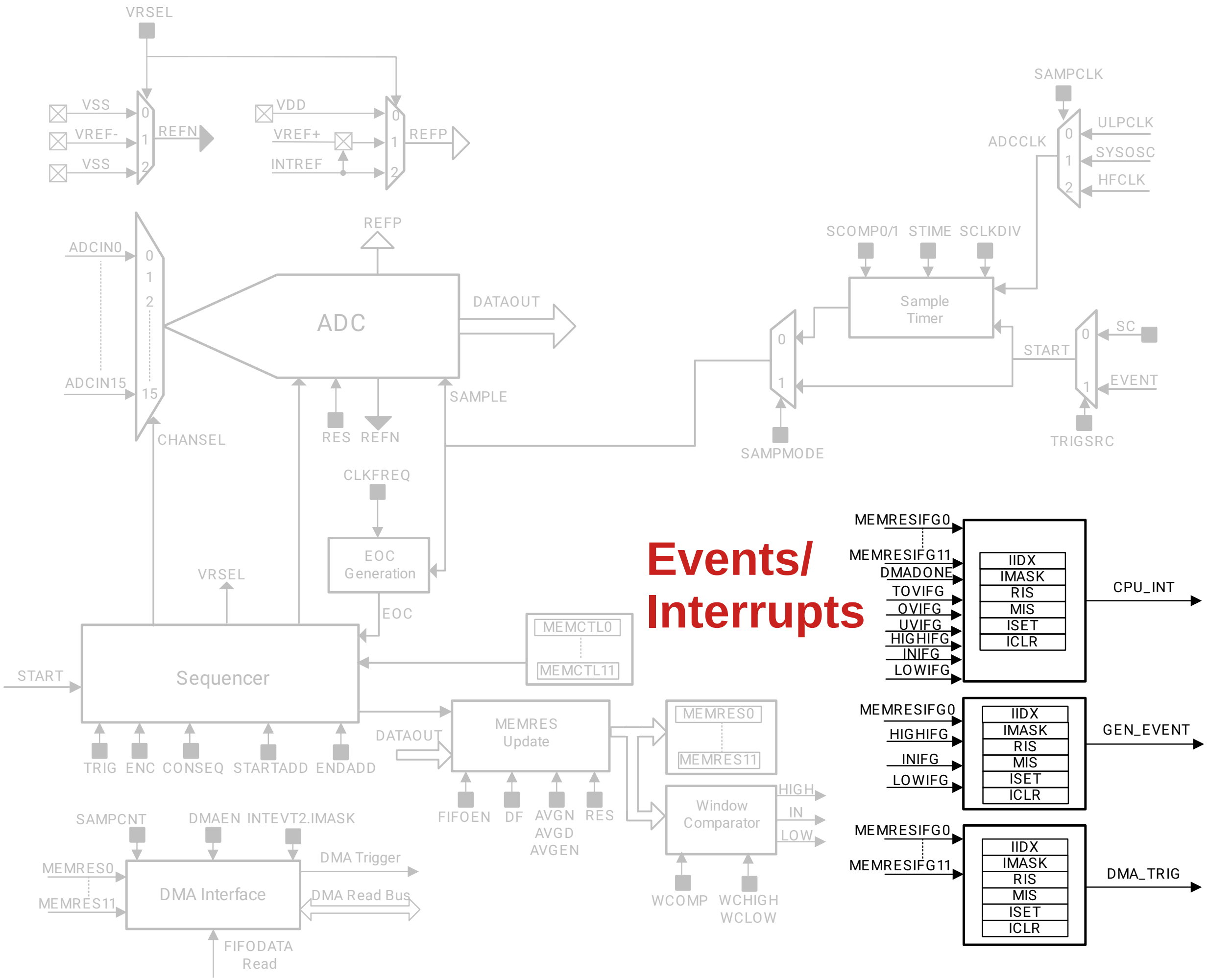


Figure 12-1. ADC Block Diagram

ADC12

Hardware Data Management

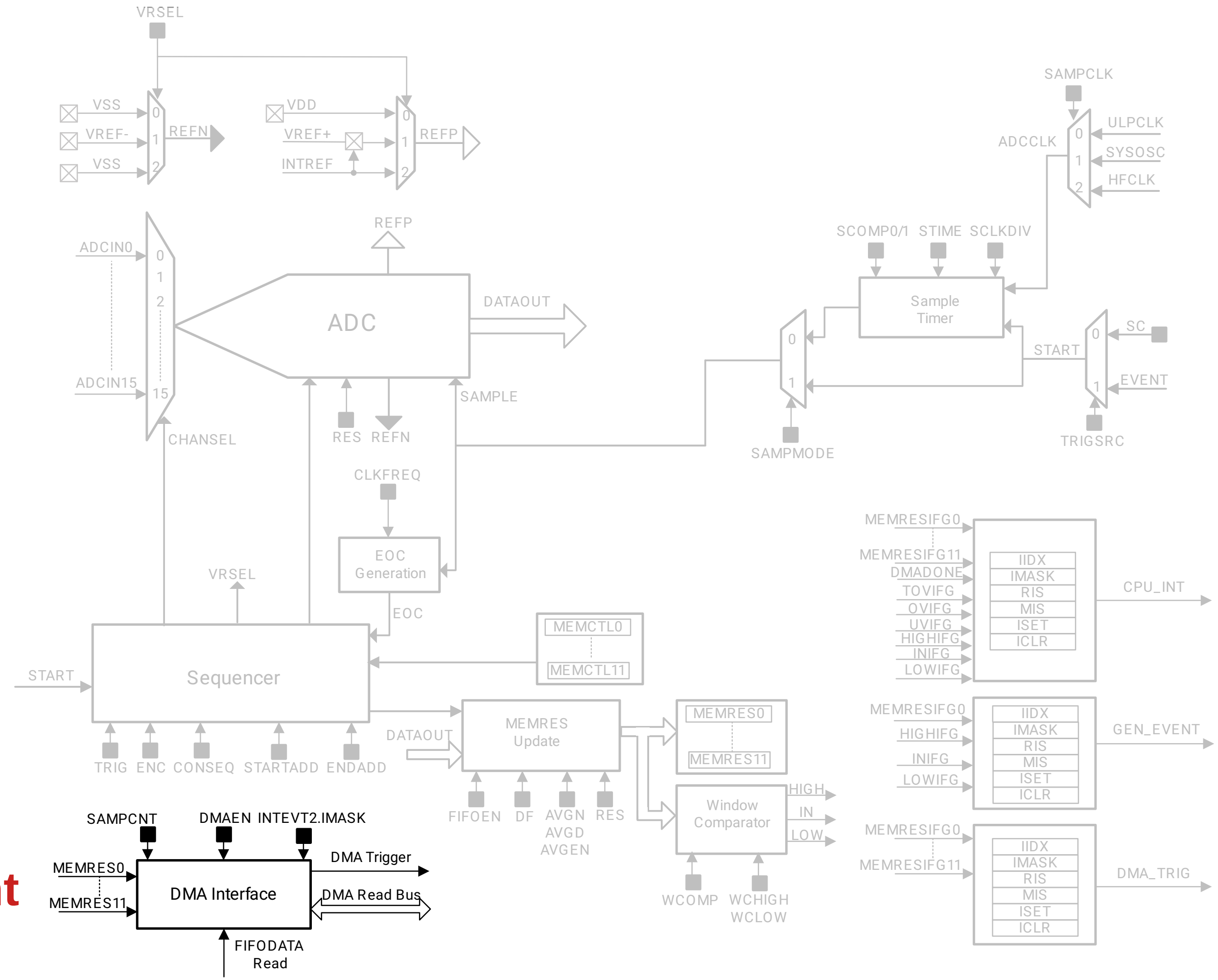


Figure 12-1. ADC Block Diagram

ADC12 Configuration

- Conversion timing (ADC Clock)*
- Resolution (8, 10, 12)
- Triggering modes:
  - Firmware requests single conversions
  - Continuously occurring conversions
  - Event triggered conversions
- Setup of Voltage Reference Value(s)/Source(s)

* Our EmCon HAL will take care of this; usually has to be configured

ADC12 Configuration

- Channel Selection:
  - ADC Memories (one per conversion) MEMx
  - ADC Input Channel
  - GPIO Analog Peripheral Function
  - Selection of available VREF for each channel
  - Individual Channel Triggering
  - Sampling Time*

* Our EmCon HAL will take care of this; usually has to be configured

ADC12: Mapping

- Quantization Minimization is part of ADC12 conversion!
- Conversions always single-ended with $V_{\text{Ref}-} = 0$

$$N_{\text{ADC}} = 2^{N_{\text{bits}}} \frac{V_{\text{in}+}}{V_{\text{Ref}+}}$$

$$0 \leq V_{\text{in}+} < V_{\text{Ref}+}$$

  - Estimated Voltage:

$$\hat{V}_{\text{in}+} = \frac{N_{\text{ADC}}}{2^{N_{\text{bits}}}} V_{\text{Ref}+}$$

Up Next...

- Lab 3: PWM and Encoders for use on Car
- Quiz 2: March 30th:
  - PWM, Encoders.
  - Timer Compare and Capture modes
  - H-bridge use
- Activity 12: ADC Activity (Maybe using DAC as well...)